Shared-Separation: Empirical Results and Theoretical Implications

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ABSTRACT

The concept of free flight is intended to provide increased flexibility and efficiency throughout the global airspace system. This idea could potentially shift aircraft separation responsibility from air traffic controllers to flight crews creating a 'shared-separation' authority environment. A real-time, human-in-the-loop simulation study was conducted using facilities at the National Aeronautics and Space Administration (NASA) Ames Research Center and the Federal Aviation Administration (FAA) William J. Hughes Technical Center. The goal was to collect data from controllers and pilots on shared-separation procedures, information requirements, workload, and situation awareness.

The experiment consisted of four conditions that varied levels of controller and flight crew separation responsibilities. Twelve controllers and six pilots were provided with enhanced traffic and conflict alerting systems. Results indicated that while safety was not compromised, pilots and controllers had differing opinions regarding the application of these new tools and the feasibility of the operational concept. These results are discussed within the theoretical framework of the Hollnagel (1993) Contextual Control Model. Future research in the shifting of separation authority and the requirement for intent information is recommended.

INTRODUCTION

The free flight concept, as described by the RTCA Task Force 3 (1995) suggests placing more responsibility on flight crews to maintain safe separation from other aircraft in the National Airspace System. This idea could potentially shift aircraft separation responsibility from air traffic controllers to flight crews creating a 'shared-separation' authority environment. Possible benefits include more flexibility to manage flight operations, plus improved safety through enhanced conflict detection and resolution capabilities, and redundant traffic monitoring procedures.

BACKGROUND

A variety of studies have examined the effects of free flight operations on controllers and pilots. Endsley, Mogford, Allendoerfer, Snyder, and Stein (1997) and Endsley (1997) reported that controllers acting as passive monitors during free flight may show a decrease in situation awareness, an increase in workload due to different responsibilities, and have problems making timely interventions. They indicated that communications might significantly increase under free flight conditions due to the need to obtain pilot intent information. Galster, Duley, Masalonis, and Parasuraman (2001) reported a free flight study in which traffic densities and the presence of self-separating aircraft were varied. It was shown that it was difficult for controllers to notice the self-separating maneuvers of pilots. While controllers detected nearly 100% of conflicts under moderate traffic, their conflict detection performance dropped to only 50% under high density traffic. Metzger and Parasuraman (1999) performed a study manipulating traffic densities and locus of control (i.e., active or passive). Passive control consisted of the controller detecting the conflict, but refraining from providing a resolution strategy. In the active control locus, controllers detected conflicts and provided resolution strategies. In the high-density condition, controllers took twice as long to detect conflicts in the passive compared to the active control condition.

Corker, Gore, Fleming and Lane (2000) investigated the impact of shifts in separation authority between controllers and pilots. In this study, the Jacksonville Air Route Traffic Control Center (ARTCC) controller participants worked traffic in four different conditions: current traffic, direct-to route request (where aircraft flew direct to their feeder fix close to their destination airport), 20% of traffic self-separating, and 80% of traffic self-separating. The controllers were instructed that in the cases of self-separation, they had authority to cancel free flight whenever they felt safety was compromised. Results indicated that controller subjective workload was affected by the free flight control conditions. Specifically, Corker et al. (2000) reported that when the majority of the aircraft were managing their own separation, the subjective workload ratings for the controllers were higher. That increase in workload appeared to be directly related to the increase in communication requirements necessary to accomplish the controllers' management of airspace. The controllers reported that they needed to communicate with the aircraft to determine its intent, knowledge they felt was vital to accomplishing their tasks. Finally, the data from this investigation revealed that the controllers cancelled free flight for an average of about 20% of the aircraft in the condition where 20% were self-separating, while about 9% of the aircraft were canceled in the condition with 80% of the aircraft self-separating.

While there have been studies done on air issues, ground issues, and the supporting tools individually, there is a need to investigate how all the elements might work together in a shared-separation environment. This, in addition to mixed fidelity levels of past studies, provided the motivation to conduct a high fidelity study that considered the tools, environments, and issues from a fully integrated perspective. The Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the Volpe National Transportation Systems Center began a collaborative research effort to evaluate the potential for shared-separation in an environment in which both controllers and pilots have decision support tools for conflict detection. A high fidelity, real-time, human-in-the-loop simulation study was completed in February 2000. The concept exploration study, termed the Air-Ground Integration Experiment (AGIE), was co-sponsored by the FAA (AAR-100, ASD-130, and ATP-400) and the NASA Advanced Air Transportation Technologies Project. This study was the first successful experiment in which both the flight deck and air traffic control (ATC) were simulated with high fidelity. A Cockpit Display of Traffic Information (CDTI) prototype, developed by NASA Ames Research Center (ARC), was the airborne conflict alerting tool. The CDTI included embedded conflict alerting logic that predicted the probability of an encounter with another aircraft. The ground-based conflict probe and trial-planning tool was the User Request and Evaluation Tool (URET).

This paper describes the results of the AGIE study as they relate to shared-separation, and interprets these results, along with some of the earlier studies, in terms of the Hollnagel Contextual Control Model (Hollnagel, 1993, 2000). In addition, the paper discusses work by Hoffman et al. (2000) in which some of the potential task changes of controllers in free flight are examined.

THE AIR-GROUND INTEGRATION EXPERIMENT (AGIE)

Participants

Air Traffic Controllers. Three groups of four Certified Professional Controllers (CPCs) from Memphis ARTCC (ZME) participated in the simulation. Each group was divided into two, two-member teams (a radar and radar-associate controller) and participated for three days. All CPCs were qualified to control traffic in the sector they operated during simulation.

B747-400 Pilots. Three flight crews, consisting of both captains and first officers, flew the Boeing 747-400 flight simulator located at NASA ARC. The participants were qualified Boeing 747-400 pilots. Each crew participated for two days.

Research Facilities and Equipment

The simulation test bed integrated facilities and equipment from the FAA William J. Hughes Technical Center (WJHTC) and NASA ARC. WJHTC facilities and equipment included ARTCC simulation facilities with URET, pseudo-aircraft systems (PAS) and target generation laboratories, a simulation pilot laboratory, voice communication systems, and audio and video recording systems. NASA ARC was linked to the WJHTC via the Crew

Vehicle Systems Research Facility which included the NASA ARC Boeing 747-400 flight simulator and the flight crew displays and tools. Those tools included the alerting logic, a PAS laboratory, a voice communication system, and audio and video recording systems.

User Request Evaluation Tool. A ground-based conflict probe and trial-planning tool, URET, was available to the controller participants in this study. URET is currently installed as a prototype system and is in daily use at the Memphis and Indianapolis ARTCCs. The system's functionality consists of trajectory modeling, conformance monitoring and reconformance, current plan and trial plan processing, automated problem detection, interfaces with the Host and external data sources, and computer human interface. URET provides the controller five levels of automated problem detection alerts with a "look-ahead" time of approximately 20 minutes**.**

Flight Crew Displays and Tools. Traffic up to 120 nmi from the NASA simulator was represented on the flight deck navigation display (Figure 1). The Cockpit Display of Traffic Information-Alerting Logic (CDTI-AL) alert was triggered for the flight crews when the alerting logic predicted a pending violation of the protected zones (Yang & Kuchar, 1997). The word "ALERT" appeared in blue on the lower right hand corner of the display, along with the intruding aircraft's call-sign and the time to closest point of approach. All display features associated with the aircraft involved in a pending conflict (i.e., aircraft symbol, altitude readout, and call-signs) as well as the display changes related to the conflict appeared in blue. As crews solved a conflict and the threat probability reduced, the alert level degraded from the notification of the pending alert to a non-threat status.

Flight crews were able to select certain display features designed to aid them in self-separation. Crews could reduce clutter by toggling a button to de-select the traffic call-signs and ground speed of the aircraft. Another selectable feature was the temporal predictor. The predictor provided crews with an estimation, based on current aircraft state information, of where other aircraft would be relative to the own-ship up to ten minutes into the future (Figure 2). With the predictors, crews were able to determine which aircraft might create a potential conflict prior to an alert level indication.

Figure 1. CDTI-AL on the flight deck navigation display.

Figure 2. CDTI-AL depicting predictors selected to ten minutes.

Communications

Under all experimental conditions, current air-ground communication capabilities were simulated. During shared-separation operations, an air-air communication frequency was also available which allowed all pilots to directly communicate with each other. The controllers were able to (selectively) monitor but not transmit on the air-air frequency.

Scenarios

ZME was selected as the simulated enroute airspace since it is currently one of the locations where URET has been operationally fielded. Two adjoining ZME sectors, Sectors 44 and 21, were emulated for the experiment. Traffic scenarios were developed from field samples and emulated realistic moderate to high traffic densities. Data collection runs were 90 minutes long for the controller participants, plus 10 minutes warm-up time. Each run contained 16 planned conflicts for the controller participants. The pilot participants' data collection flight segments had a single planned conflict, and were approximately 20 minutes in duration, each of which was a part of the longer controller runs. The pilot participants were able to fly a total of three 20-minute flight segments during a single 90-minute run for the controllers. Therefore three of the conflicts in the 90-minute controller runs involved the NASA ARC simulator, and the remaining 13 conflicts for the controllers involved target generated aircraft controlled by simulation pilots.

Airspace

Sectors 21 (Conway High) and 44 (Pine Bluff High), both busy ZME high altitude sectors, were modeled. In the simulation, both sectors were fully emulated, except that in Sector 21, the airspace was expanded to include flight level (FL) 240 and above.

Experimental Conditions

The simulation consisted of four conditions defined by various levels of controller and flight crew separation responsibilities. The conditions were Current Operations (CO), Current Operations with CDTI-AL (CO:CDTI), Shared-Separation Level 1 (SS:L1), and Shared-Separation Level 2 (SS:L2). Each condition used a different set of procedures that reflected changing roles and responsibilities. Current standard separation rules of five nmi horizontal or 1000/2000 ft vertical as appropriate (i.e., 2000 ft above FL 290) were observed for all conditions. A within-subjects design was utilized where all pilot and controller participants were exposed to each condition.

Current Operations (CO): This condition simulated today's ATC environment; that is, the controller was responsible for separation assurance of all aircraft. URET was operational. Pilots did not have access to a CDTI-AL.

Current Operations with CDTI-AL (CO:CDTI): This condition simulated today's ATC environment with URET. In this condition, however, the pilots had CDTI-AL available to them. (The B747-400 simulator had a CDTI-AL prototype on the flight deck. All other target generated aircraft emulated this capability, and conflicts between these aircraft and their resolutions were scripted.)

Shared-Separation Level 1 (SS:L1)

This condition simulated all equipment and procedures of CO:CDTI with the following changes:

- All flight crews started SS:L1 responsible for their own separation (i.e., free flight).
- Flight crews were free to initiate any maneuver (i.e., change heading, altitude, speed, or any combination thereof) provided they first informed ATC.
- Flight crews were able to communicate with other flight crews on the air-air frequency. Controllers could monitor the air-air frequency as desired, but it was not required.
- Flight crews were instructed to use specific right-of-way rules to resolve conflicting situations.
- Flight crews could *cancel free flight*[1] of their own aircraft at any time.
- Controllers were instructed to issue *traffic alerts*[2] to the aircraft involved in a URET red alert.
- Controllers receiving a coordinated traffic alert were instructed to forward this to the subject

[1] For the procedures of this study, the *cancellation of free flight* was defined as the cancellation of shared-separation operations resulting in aircraft separation responsibility switching from pilots (air) back to controllers (ground).

[2] For the procedures of this study, *traffic alert* was defined as an advisory to an aircraft that was involved in a URET red alert.

aircraft unless that aircraft had already advised that a resolution was in progress.

- Controllers could only cancel free flight (for one or a pair of aircraft) if they had queried, or had knowledge of the intentions of, at least one of the aircraft. If they did cancel free fight, they were required to follow the cancellation with a control instruction. Also, only controllers could resume free flight.

Shared-Separation Level 2 (SS:L2)
This condition simulated all equipment and procedures of SS:L1 except for the following changes:

- Flight crews were not required to inform the controller before initiating any maneuver.
- Controllers were not required to issue traffic alerts to aircraft, but could do so.
- Controllers could not cancel free flight for any aircraft at any time.

DATA COLLECTION

Subjective and objective data were collected from participants, observers, the ATC environment, and the flight deck. Both the ground-side and air-side subjective data included workload, situation awareness ratings, experiences with shared-separation, traffic realism, and other details using post-run and debrief questionnaires.

RESULTS AND DISCUSSION

The results and discussion that follow are based on a small sample size. The scenarios were also simplistic (e.g., no severe weather, limited climbing and descending aircraft, no mixed equipage environment), since the intent was to identify issues in, rather than propose an operational concept for shared-separation.

Safety Measures. In all conditions, the minimum separation distance was defined as either five nmi horizontally or 1000/2000 ft vertically as appropriate. The pilot participants in this study did not violate minimum separation standards in any flight segment of any condition. Following each condition, the pilots and controllers were asked to rate the level of safety using that set of procedures and tools compared to current flight operations. See Figure 3 for mean and ±1 standard error of the mean (SEM) bars for the various conditions. In SS:L1 and SS:L2, pilot tasks and responsibilities increased (e.g., monitoring CDTI-AL, air-air communications, and detecting and resolving conflicts) beyond their normal activities, but, interestingly, they perceived these conditions as safer operations.

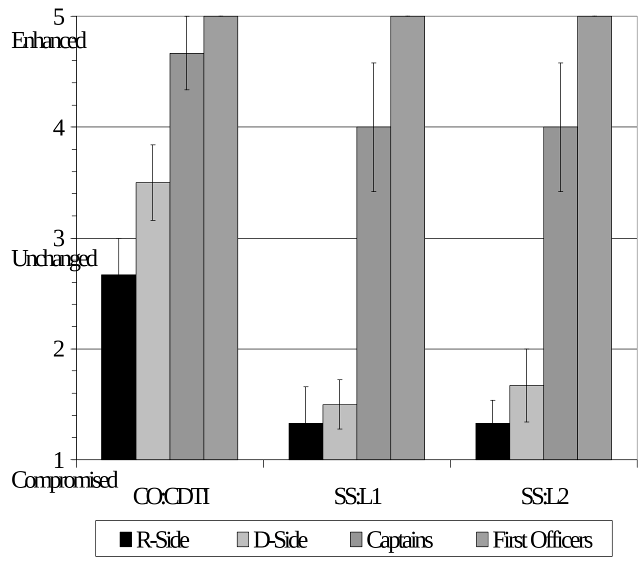

Figure 3. Controllers and pilot mean safety ratings.

However, controllers felt that CO and CO:CDTI were the safer operations and reported that SS:L1 and SS:L2 compromised safety. The fact that controllers cancelled free flight in SS:L1 and indicated that they would have cancelled in SS:L2 reinforces their concern for safety.

Conflict Resolution Strategies. Both controllers and pilots often used heading as part of their resolution strategy when responsible for separation, possibly because both air and ground traffic displays provide a clear depiction of heading changes. The controllers did use altitude to resolve resolutions in some cases where the pilots had the CDTI-AL. The pilots, however, only used altitude a few times. The controllers rarely used speed, whereas pilots frequently used speed changes. Pilots sometimes attempted maneuvering resolutions that took more time to enact and monitor, such as speed changes, or even more complicated strategies (e.g., speed and heading changes together).

Although the sample size is too small to draw definite conclusions, it appears that controllers resolved conflicts earlier than pilots. In the CO and CO:CDTI conditions, the two conditions in which the controllers always had separation authority, controllers achieved mean lateral separations of 10.5 nmi (SD = 3.5) and 11.0 nmi (SD = 2.8) respectively. In the SS:L2 condition, the pilot participants achieved a comparatively lower mean lateral separation of 6.2 nmi (SD = 1.1). Results for SS:L1 fell in between with mean lateral separations in the range of 8 to 9 nmi being achieved by both controllers and the pilots. The apparent preference for controllers to solve conflicts early was also reflected in their lower safety ratings for SS:L1 and SS:L2. Interestingly, when controllers cancelled free flight, they tended to only change the magnitude of the resolution (e.g., increased rate of turn) that was being executed by the pilots. This may be because the pilots' strategies were perceived as correct by the controllers but the magnitude was simply not enough to produce the separation the controllers felt was necessary.

Cancellation of Free Flight. In SS:L1, controllers were instructed they could cancel free flight for one or a pair of aircraft at a time. During the nine flight segments flown by pilot participants in this condition (three repetitions for each of the three flight crews), the controller teams cancelled free flight five times (56%). The mean lateral distance between the conflicting aircraft at the time of free flight cancellation by the controllers was 13.1 nmi (SD = 4.6). Runs of SS:L1 also included additional planned conflicts involving the WJHTC simulation pilots. Of the 39 additional conflicts not involving the flight crew participants, the controllers cancelled free flight 12 times (31%).

Pilot participants did not cancel free flight during SS:L1 or SS:L2 (nor were there any scripted cancellations by simulation pilots). The pilots seemed to feel that with the CDTI-AL they were able to maneuver safely to resolve conflicts. Conversely, controllers cancelled free flight in 17 of the 48 total conflicts (35%) in SS:L1.

Shared-Separation Procedural Considerations. The pilot and controller participants were asked their opinions about the time available for separation tasks and for coordination and communication tasks. In general, the time available for the separation tasks was rated as "adequate" by all the pilots across all the conditions, while the controllers felt there was slightly more time available in the CO and CO:CDTI conditions for separation. The controllers and pilots reported that the time allowed for coordination and communication tasks was at least adequate across all four conditions.

Air-Ground and Air-Air Communications. The data from the air-ground communications analyses revealed that the SS:L1 condition appeared to lead to the highest communications burden between the pilot and controller. This was partially affected by the requirement in this condition to have the flight crews inform the controllers prior to executing a conflict resolution maneuver. The requirement to inform controllers was based on the assumption that the controllers would want this information to maintain awareness of the traffic situation. Both the controllers and pilots stated that the air-air frequency was useful in SS:L1 and SS:L2. However, it was distracting at times for the radar (R-side) controllers and therefore not all the R-side controllers used it.

Workload. Subjective workload ratings were obtained from both pilots and controllers throughout all the conditions. Pilots were asked to rate their workload at the end of each flight segment within each run, while controllers were asked to rate their workload every five minutes during their 90-minute run for each condition. Overall, the workload ratings were rather low (see Figure 4). This may indicate the shared-separation tasks in this study did not present a significant challenge to either pilots or controllers in these lower complexity scenarios.

In general, based on subjective ratings, along with questionnaire and debriefing comments, controllers indicated that SS:L1 was the most workload intensive and difficult condition when compared to the other conditions. The reasons provided by the controllers included increased monitoring tasks, additional tasks to ensure that pilots were resolving conflicts in a safe and timely manner, and the need to plan multiple contingency resolutions for conflicts during SS:L1.

The mean ratings for pilot workload indicated a marginally higher workload for shared-separation conditions (i.e., SS:L1 and SS:L2) compared to the CO condition. Perhaps this was because CO was the only condition that did not have the additional display information provided by the CDTI-AL. Additionally, in the SS:L1 condition the flight crews had intent reporting tasks that were new, and both shared-separation conditions had separation tasks that were new. Similar to the controllers, the pilots also indicated they felt that SS:L1 was more workload intensive.

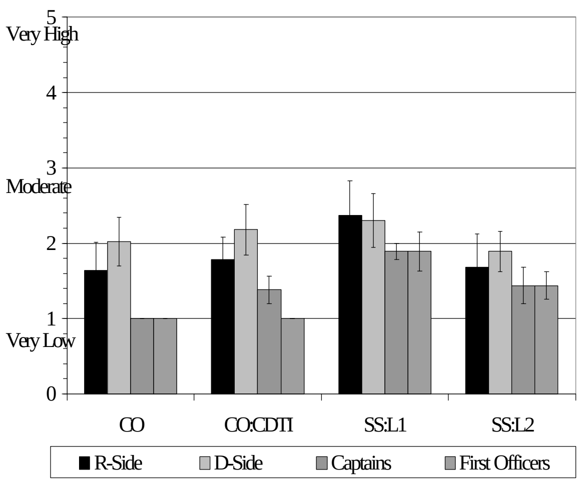

Figure 4. Controller and pilot mean workload ratings.

Situation Awareness. Figure 5 shows controller and pilot subjective ratings for the level of overall situation awareness for the four conditions. Controllers rated their situation awareness as relatively high with only small differences between the four experimental conditions. Although there was a large amount of variance in the flight crew data, pilots appeared to indicate that the shared-separation conditions provided more situation awareness than the CO and CO:CDTI conditions.

In SS:L2, informing the controllers about maneuvers was voluntary, and the pilots (both simulation and participant pilots) rarely provided this information. Therefore, one would have expected overall controller situation awareness in SS:L2 to be reduced, and the lack of noticeable change between the conditions was surprising. One would have also expected lower situation awareness in SS:L2 because the procedures seemed to result in the controllers being less directly engaged in conflict management tasks (especially since no pilots actually cancelled free flight and separation tasks were never shifted back to the controllers).

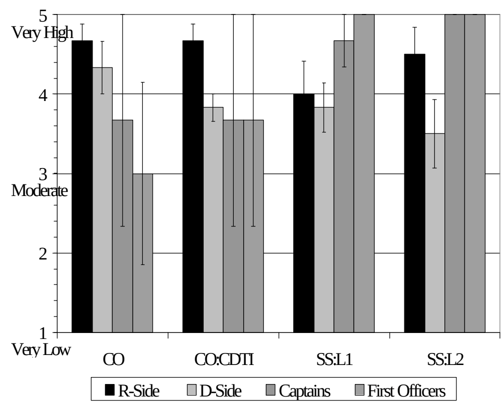

Figure 5. Controller and pilot mean ratings for overall situation awareness.

Additional Considerations. Controllers and pilots indicated that URET and CDTI-AL supported their activities well. However, in some cases, controllers felt that the URET alerts were too soon or too late. Controllers also strongly indicated that they would like to have pilot intent information earlier. At present, CDTI-AL provides alerts about 5 to 7 minutes prior to potential loss of separation, whereas URET provides alerts 13 to 17 minutes ahead. Perhaps having similar conflict alert look-ahead times would help pilots formulate and provide their intentions earlier for the controllers' needs.

THEORETICAL FRAMEWORK

Better understanding of some of these findings might be derived from Hollnagel, (1993, 2000) who describes the different cognitive processing strategies (control modes) adopted by operators in different environments. His framework considers human action to be interpreted as being determined by the situational context rather than by the inherent characteristics of human cognition. This is referred to as the Contextual Control Model (COCOM).

These decision-making strategies and control modes can be categorized in four ways:

- Scrambled decisions are made under high time pressure and in an almost haphazard manner, where the decision-maker does not have enough resources and time to investigate a range of decision alternatives. A majority of scrambled decisions are reactive rather than proactive.

- *Opportunistic decisions* are also made under time pressure, but the decision-maker has a little more time to investigate decision alternatives. In other words, the decision-maker looks for opportunities to make more efficient and effective decisions if and when possible.
- *Tactical decisions* are made with a slightly longer outlook. The decision-maker has more time to make effective and efficient decisions.
- *Strategic decisions* are made with a long-term perspective. The decision-maker has adequate or more than adequate time to make effective and efficient decisions, most of which are proactive rather than reactive.

The key distinguishing factors between these four types of decisions is the amount of control the decision-makers can command in the situation. From scrambled to strategic decisions, the decision-maker's mode of operation can be described as evolving from reactive to proactive.
However, these decision-making classifications, largely apply to one or a few operators who work very closely together.

Hollnagel defines four modes of control that depend on contextual factors, such as the number of goals being considered simultaneously, the amount of time available for planning, the amount of feedback on the effects of prior actions available, and the competency of the human in the particular situation. Of Hollnagel's four control modes, the highest two, tactical and strategic, best represent the pilot's or controller's preferred modes under normal conditions. Tactical control describes a situation in which planning is limited in scope or range by available time and/or incomplete knowledge and predictability of the environment. Strategic control may be effected when the operator is able to fully plan actions, including the global context, because the system behaves as predicted, and adequate time, feedback and expertise are available. Strategic control generally provides the most efficient and reliable performance. When dealing with the unexpected, the operator may be forced into a lower mode of control.

Control requires the ability to predict the future behavior of the system, which implies having a correct understanding of the situation. For the controller, this requires both the knowledge and interpretation of the current and near future trajectories of all aircraft under his/her control, and the knowledge and understanding of other relevant factors. These factors include those pertaining to the immediate situation, such as weather, and also to ongoing constraints, such as procedures and standards. Even once blessed with "perfect" situation awareness, a moment later an unexpected event can occur, pushing the controller into a reactive mode. These events can be routine and minor, such as a pilot mishearing a clearance, or major, such as an equipment failure. Planning for the unexpected may allow the operator to remain in the opportunistic control mode or better.

DISCUSSION

Previous shared-separation research can be interpreted using Hollnagel's COCOM. For example, Verma and Corker (2001) applied the COCOM framework to explain why controller workload was reported as higher under free flight conditions. They indicated that the controllers were attempting to use the tactical control mode under the higher uncertainty of free flight operations. Such a mismatch of control modes and operational context likely increased the controller workload. Another example is the Corker et al. (2000) study which indicated that shifting separation authority between pilots and controllers showed an increase in controller workload as the percentage of self-separating aircraft increased. It was explained that the controllers were trying to operate in a strategic mode while the operating context did not support this mode due to the high unpredictability in the system.

There are important similarities in the findings of the AGIE study and the Corker et al. (2000) study. In each study there appeared to be discomfort for the controllers when working traffic in the conditions where separation authority was shared with the flight deck. In both studies, this was evident in the cancellations of free flight, the reported higher workload, and the concern about ascertaining the intent of the aircraft. In the AGIE study, however, the pilots preferred the shared-separation conditions and felt they were safer, even though they reported their workload as somewhat higher.

For the AGIE study, the nature of the separation management task was different between the pilots and controllers. The flight crew managed a single conflict between themselves and one other aircraft, while monitoring the CDTI-AL for potential developing conflicts for their aircraft, and attending to other cockpit duties. Within the realm of conventional ATC (e.g., CO and CO:CDTI conditions), the controllers were able to operate in the strategic and tactical modes, since they were actively controlling all of the aircraft within their sectors. From the controller's perspective, appropriate control meant resolving conflicts such that all the aircraft being worked were adequately attended to, and safety and traffic flow efficiency were maintained throughout the entire sector.

Under the shared-separation conditions of the AGIE study, the controllers were monitoring many aircraft, and attended to conflicts to see if the flight crews resolved them satisfactorily. The controllers were therefore operating under a context that supported the scrambled or opportunistic mode, since they were unable to determine at what point intervention may have been required and what the intervention technique should have been. The controllers also needed to insure a time budget for communications and maintain a high level of vigilance should they have needed to intervene in separation management.

Thus, in the shared-separation conditions, the nature of the controller's task changed from active control to monitoring and sometimes intervention, however the controller's training and information support did not change. Monitoring tasks or passive control can potentially move the controller to a lower planning mode. The automation support provided to the controller (i.e., URET) was intended to aid in the former task of tactical separation rather than the scenario-induced task of conformance monitoring. It is thus not surprising that the controllers reported higher workload in SS:L1 than in the two conditions in which they were solely responsible for separation, even though the traffic density was the same. Apparently, monitoring traffic to insure conflicts were resolved resulted in higher workload than when the controllers were actively controlling the traffic. Referring to the Hollnagel model, the system became less predictable, and the controllers would have been forced into a more reactive mode if the pilots had requested intervention. Conversely, the tools provided to the flight crews served to enhance the predictability of their aircraft's position relative to other aircraft and should have increased their awareness of conflicts and the means to resolve them.

The pilots from the AGIE investigation experienced little difficulty with the shared-separation concepts used in the study. From the flight crews' perspective, appropriate control meant solving their conflict optimally; too early, and they may have made an unnecessary or inefficient maneuver, too late, and an abrupt or large maneuver may have been required to maintain separation. It is probable that "appropriate" control for pilots meant a closer approach to the separation minimum than controllers were comfortable with under the same traffic conditions. However, the expected improvement in flight efficiency from transferring separation authority to the flight deck is the main justification for research in shared-separation. The pilots did report a slightly higher workload in SS:L1, but there were no differences between conditions for the pilots' ratings of situation awareness. In Hollnagel's terms, the shared-separation conditions supported a strategic/ tactical control mode for the pilots by giving them more flexibility in conflict resolutions. Although the controllers may have found that shared-separation led to less predictability and thus decreased or no strategic control, the pilots likely experienced the opposite effect. They had more direct control over conflict detection and resolution in the shared-separation environment. However, the pilots' increase in the strategic control relates to their own aircraft, not to the broader control of a particular airspace.

Thus, Hollnagel's model helps to explain the controllers' discomfort and pilots' preference for shared-separation operations. However, in order to make shared-separation a viable concept, the controllers' mode of control needs to move from completely reactive, and hence scrambled, to tactical. Providing more active control to controllers would increase their involvement in detecting and resolving conflicts. This could be achieved by allowing them to determine the bounds that pilots could use in conflict resolution. Such bounds, in the possible form of altitude blocks, time constraints, or heading

or speed ranges, would increase the predictability for controllers while keeping the conflict detection and resolution responsibility still with the pilots.
Hoffman, Zeghal, Cloerec, Grimaaud, and Nicolaon (2000) propose such an approach that involves limited delegation of separation responsibility to the flight deck, a concept being investigated under the Evolutionary Air-Ground Co-operative Air Traffic Management Concepts program. With this approach, the task of separation is divided into three sub-tasks; identification of the problem, selection of a solution, and implementation of the solution. Three levels of delegation are identified corresponding to which sub-tasks are delegated to the flight deck. Under limited delegation, identification of the problem and the solution remain with the controller, and implementation of the solution is delegated to the flight deck by the controller. Under extended delegation, the controller identifies the problem, and delegates both the choice of solution and its implementation to the flight deck. Under full delegation, the complete separation task is the responsibility of the flight deck, essentially autonomous free flight.

As Hoffman et al. (2000) point out, the level of delegation will significantly affect the controller's ability to predict the aircraft's trajectory and thus his/her workload in maintaining an adequate mental model of the situation. The more the controller can delegate, the less effort he/she needs to expend on separation tasks, but the more workload he/she has in maintaining situation awareness and conformance monitoring. At some point, the reduction in workload from delegating tasks could be more than offset by the increase in workload resulting from decreased situation awareness and increased conformance monitoring.

In general, the delegation of separation tasks and responsibilities should be structured so that the controller can remain in appropriate control. Hoffman et al. (2000) suggests that if the controller can delegate a separation task such that the aircraft's allowed options remain within suitable bounds that are selected for the particular situation, then the controller is in appropriate control. For example, a time constraint may be provided to the crew, but the crew may have flexibility in how that time constraint is met. Having delegated the task, the controller has no interest in how the aircraft accomplishes the task, so long as it stays within the bounds. The controller needs only to know when the delegated task is completed. Conformance monitoring of the bounds should be a less workload intensive task than conformance monitoring in the absence of being able to predict the aircraft's behavior. Appropriate automation aiding could reduce workload further by assisting the controller in monitoring the limits of the delegated separation authorization and alerting should the bounds be exceeded. Relative to the Hollnagel model, providing bounds to the flight crew may move the controller closer to a strategic/tactical mode (rather than opportunistic) when compared to the shared-separation concept in the AGIE research. However, providing bounds may also create a less strategic mode for the pilots as it puts more constraints on them, rather than allowing them to resolve conflicts without bounds.

CONCLUSIONS

Clearly there are many issues that need to be addressed in the consideration of the delegation of separation authority. Delegation of specific separation bounds to flight crews by controllers as proposed by Hoffman et al. (2000) may be preferable to the shared-separation concept investigated by the AGIE study. Previous research indicates the need for intent in a shared-separation environment; it is unclear, however, whether bounds provided to flight crews would offer the additional intent that may be required. More research is needed to define optimal roles for flight crews and controllers in separation assurance. Continued research in shared-separation is also needed to identify and resolve issues such as mixed equipage environments, and the transition from aircraft self-separation to positive control.

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