Feasibility of Mixed Equipage Operations in the Same Airspace

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This study used a human-in-the-loop simulation to examine the feasibility of mixed equipage operations in an automated separation assurance environment under higher traffic densities. The study involved two aircraft equipage alternatives – with and without data link – and four traffic conditions. In all traffic conditions the unequipped traffic count was increased linearly throughout the scenario from approximately 5 to 20 aircraft. Condition One consisted solely of this unequipped traffic, while the remaining three conditions also included a constant number of equipped aircraft operating within the same airspace: 15 equipped aircraft in condition two, 30 in condition three, and 45 in condition four. If traffic load became excessive during any run, participants were instructed to refuse sector entry to inbound unequipped aircraft until sector load became manageable. Results showed a progressively higher number of unequipped aircraft turned away under the second, third, and fourth scenario conditions. Controller workload also increased progressively. Participants rated the mixed operations concept as acceptable, with some qualifications about procedures and information displays. These results showed that mixed operations might be feasible in the same airspace, if unequipped aircraft count is held to a workable level. This level will decrease with increasing complexity. The results imply that integrated airspace configuration is feasible to a limit. The results also indicate that the conflict detection and resolution automation, equipage, and traffic density are important factors that will need to be considered for airspace configuration.

Introduction

As the concept for automated separation assurance evolves, the airspace requirements needed to support it must be established. One key design question is whether this future airspace should be segregated or integrated. Segregated (or 'exclusionary') airspace would only permit access to those aircraft that are supported by either ground-based or airborne separation management automation. Integrated (or 'non-exclusionary') airspace would also permit access to unequipped aircraft that require controller involvement in the separation assurance process.

The main advantage of segregated airspace is that it provides a more homogeneous operating environment (less variation in aircraft equipage, roles and responsibilities for human operators, potential differences in separation requirements, etc.). Simpler assumptions about the airspace should result in fewer complications during off-nominal events, and reduce controller workload and confusion during normal operations. Forest and Hansman suggest that, as a side benefit, efficient segregated airspace could also encourage users to invest in advanced equipage [Forest and Hansman, 2006].

However, segregated airspace could come at a significant cost in underutilized airspace capacity and in reduced user flexibility, because such partitioning by definition limits access to all users. This could be especially problematic during weather or other flow restricting events. Therefore, research into the feasibility of integrated airspace is warranted to determine whether aircraft with different levels of equipage can co-exist in the same airspace and under what conditions this may be possible (Kopardekar et al., 2008) [2]. Once the feasibility of an integrated airspace with mixed equipage and its upper/lower bounds of equipage mixture are established, future airspace designers can fully weigh the pros and cons of segregated vs. integrated airspace.

Prior literature on mixed equipage or mixed operations airspace (involving advanced separation concepts, different Required Navigation Performance (RNP) mixes, and different surveillance methods) has not been conclusive [Corker et al., 2000; Doble et al., 2005; Pina and Hansman, 2004; Forest and Hansman, 2006; Hoekstra et al., 2000; Kopardekar et al., 2008; and Lee et al., 2005]. Furthermore, the implications of mixed operations on airspace configuration were not addressed in these studies. The current study examines the implications of mixed equipage on airspace configuration requirements for advanced separation assurance operations, particularly under higher traffic densities.

Background

Forest and Hansman examined the impact of mixed equipage on oceanic operations by studying how different surveillance rates and separation minima (RNP capabilities of aircraft on oceanic routes) impacted controllers' reports of scenario difficulty and situation awareness. This study found the 50% equipage scenario had the most reports of difficulty and loss of situation awareness [Forest and Hansman, 2006]. Based on these results, the authors recommend further exploring airspace segregation as a means of reducing the complexity of the mixed equipage environment. This was also viewed as a means for providing an equipage incentive to airlines. In a follow-up study, Pina and Hansman found it was more difficult for controllers to correctly detect conflicts when equipage was lower than 50%, and that controllers incorrectly identified conflicts between equipages of 20% through 60% [Pina and Hansman, 2004]. The study was very low fidelity, and examined only 10 aircraft in the simulation scenarios.

The impact of mixed equipage on automated conflict detection and resolution was examined from the pilot's perspective in free-flight studies conducted by National Aerospace Laboratory of Netherlands (NLR). Hoekstra et al. conducted studies utilizing predictive Airborne Separation Assurance (ASAS) [Hoekstra et al., 2000]. Three concepts for airspace management were tested, one of which was fully mixed. In this condition, equipped and unequipped aircraft occupied the same airspace, with unequipped aircraft monitored by the ground. The same conflict detection and resolution (CD&R) algorithms were applied for the equipped and unequipped aircraft. Equipped aircraft did not have to maneuver around unequipped aircraft; a longer lead-time for CD&R was used for unequipped aircraft so they would avoid the ASAS (equipped) aircraft. Two different levels of equipage (25% and 75%) were examined, and the study examined high traffic density. The other two concepts that were tested had some form of segregation using an airspace structure similar to current day.

The NLR studies found the fully mixed condition most acceptable to the pilot subjects, with traffic density and equipage having little effect on acceptability. The fully mixed procedure also resulted in fewer conflict resolutions; this was attributed to the fact that unequipped aircraft were managed with a larger look-ahead time for conflict probing than the equipped aircraft. In all, the study found that the fully mixed concept was preferred over the airspace segregation concepts.

Corker, et al. conducted a study that included two mixed operations conditions that varied the percentage of free maneuvering aircraft [Corker et al., 2000]. Controllers maintained separation responsibility in all conditions, with the expectation that they would cancel free maneuvering if separation assurance became a concern. Scenarios progressively increased traffic count within each run, and measures of air-ground communications and self-reported controller workload were obtained throughout each run. Contrary to initial predictions, controller workload was highest in the condition with the greatest number of free maneuvering aircraft. The authors surmised that the operational concept led to these results, with controllers held responsible for separation of free-maneuvering aircraft. In the 80% free maneuvering condition, controllers were overwhelmed by trying to infer the intent of the free maneuvering aircraft, resulting in high overall workload.

In another study that explored a free-maneuvering aircraft concept, Doble et al. studied mixed operations by examining scripted en route conflicts that involved both Autonomous Flight Rules (AFR) (free maneuvering) and Instrument Flight Rules (IFR) (controller managed) aircraft [Doble et al., 2005]. In contrast to Corker, et al., the controllers were not responsible for the separation of AFR aircraft. In addition, the AFR aircraft were responsible for maneuvering around IFR aircraft in mixed equipage conflicts. Under these circumstances, the study found that controller performance was not significantly affected by high numbers of AFR aircraft. Taking a closer examination of the ground-side data, Lee et al. showed that the number of autonomous aircraft appeared to have little to no impact on controller workload, even when peak autonomous aircraft sector count more than tripled (from, e.g., 8 to 28) [Lee et al., 2005]. These results indicate strong potential for mixed operations to increase capacity. In summary, prior research involving mixed equipage operations indicated overall feasibility. Furthermore, free maneuvering concept simulations involving mixed equipage operations (i.e., aircraft that are capable of self-separating and aircraft that are controller-managed) indicated a very high potential to increase capacity.

In spite of the potential benefits of integrated airspace, the Joint Planning Development Office's (JPDO) Concept of Operations suggests segregated airspace for trajectory-based operations. Given the prior research, however, it is unclear if such segregation is warranted and, if so, at what level of mixed equipage it would be necessary. None of the prior studies specifically examined the implications of mixed equipage on airspace configuration or identified limits of feasibility for mixed equipage operations.

Therefore, the current study was conducted to examine if mixed equipage operations are feasible in the same airspace under varying levels of traffic densities and varying equipage levels. With conflict detection and resolution automation for equipped aircraft and conflict detection automation and resolution advisories for unequipped aircraft, it is hypothesized that mixed equipage operations could be feasible at high overall traffic density with a significant number of unequipped aircraft. The following sections describe the experimental method, results, and conclusions of the mixed equipage study.

Method

A. Experimental Design

The main objective of this study was to explore the feasibility and impact of mixed operations between equipped aircraft managed by automation and unequipped aircraft managed by air traffic controllers.

All aircraft were Automatic Dependent Surveillance-Broadcast (ADS-B) and flight management system (FMS) equipped, and had a required navigation performance (RNP) of RNP-1. Presence or absence of an FMS-integrated data link capability was the single equipage factor distinguishing equipped and unequipped aircraft. This integrated data link capability (similar to that supported by the Future Air Navigation System (FANS-1A) avionics package) enabled transmission of FMS-loadable trajectory clearances directly from the ground. On the groundside, integration of data link with an automated CD&R capability enabled ground automation to detect conflicts, construct trajectories to resolve those conflicts, and send them directly as clearances to the flight deck, all without involving the air traffic controller. Flight crews could load and review the uplinked trajectory, and if it was acceptable, engage the on-board automation to fly it. Furthermore, routine tasks, such as transfer of control and communication between sectors, were also entirely automated for equipped aircraft.

In contrast, unequipped aircraft had no data link capability, and were managed by the air traffic controller through radio voice communication.

The ground CD&R automation was responsible for detecting conflicts between *all* on-trajectory aircraft (both equipped and unequipped), and for resolving conflicts between equipped aircraft without involving the controller. Controller participants were responsible for resolving conflicts involving unequipped aircraft, and monitoring separation of unequipped off-trajectory aircraft. Controllers could access the conflict resolution automation to request conflict free routes or altitudes and issue these to the selected equipped or unequipped aircraft by data link or voice.

A general hypothesis of the study was that mixed equipage operations would be feasible with a low-to-moderate number of unequipped aircraft. It was also hypothesized that there would exist a certain critical airspace complexity threshold that, if exceeded, would make mixed operations infeasible. Conditions with a greater number of equipped aircraft were hypothesized to increase the overall traffic complexity and the number of mixed conflicts in the sector, increasing controller workload, and reducing the number of unequipped aircraft that could be safely managed. To investigate this hypothesis, the experiment design varied two traffic factors, the number of unequipped and the number of equipped aircraft, to examine when mixed operations become infeasible.

The experiment consisted of four conditions, incorporating a within-subjects design (Figure 1). The number of equipped aircraft was varied across the conditions. In the Baseline condition (0x), there were no equipped aircraft. In the Conditions 1x, 2x, and 3x, the number of equipped aircraft was held relatively constant at 15, 30, and 45 aircraft, respectively, across the 45-minute scenario. These were approximately 1, 2, and 3 times the maximum traffic count that a single controller could manage in the test sectors under current day operations.

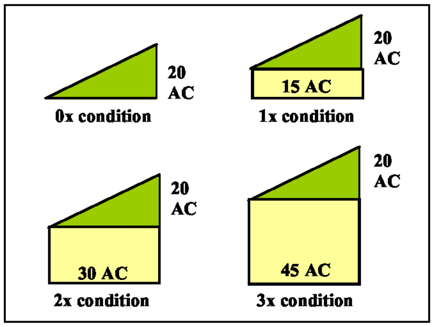

Figure 1. Experiment Design

In contrast, the number of unequipped aircraft was varied within each scenario, increasing linearly from around 5 to 20 aircraft, or until controller workload was subjectively assessed as at or above maximum. A confederate 'supervisor' assigned to each participant was asked to monitor controller workload and restrict unequipped aircraft entry into the sector as needed. This procedure was used during the simulation to establish a maximum unequipped aircraft count and 'turn away' count for each run.

i. Participants

Participants consisted of two certified professional air traffic controllers from Los Angeles Center (ZLA), and two operations supervisors from ZLA and Denver Center (ZDV). Their air traffic control (ATC) experience spanned from 11 to 25 years with an average of 20 years of ATC experience. In addition to the participants, there were four subject matter expert (SME) observers who provided additional data and feedback on operational feasibility.

Participants were divided into two groups of two and assigned to the first or second week of the study. Each controller participated in up to 12 data collection runs. Two sectors with different traffic characteristics were selected for the study, and controllers experienced each traffic condition in each sector at least once. Higher traffic conditions 3 and 4 were repeated when possible.

ii. Airspace

The simulation airspace consisted of Sector 90 in Kansas City Center (ZKC) and Sector 91 in Indianapolis Center (ZID). The traffic in ZKC-90 consisted mostly of en route aircraft in level flight (approximately 90% of all flights). Traffic flows in ZID-91 were a mix of over flights, arrivals, and departures with approximately 80% in level flight. For a given simulation run, each controller participant ran a single-sector problem, managing the traffic in either ZKC-90 or ZID-91. Retired controllers worked surrounding sectors to handle regular controller duties such as handoffs and transfer of communication (TOC) for all incoming and exiting traffic. All of the simulated aircraft were flown by pseudo-pilots.

iii. Operational Concept, Assumptions, and Separation Responsibilities

The concept was predicated on the assumption that the centralized groundside automation could detect and resolve conflicts involving properly equipped aircraft that were on 4D trajectories. The groundside automation was configured to resolve conflicts between equipped aircraft without controller involvement by issuing FMS-loadable data link clearances, thus maintaining common trajectory intent between air and ground. Given similar ADS-B-out and FMS equipage, the ground side automation could also detect conflicts for unequipped aircraft on known trajectories; thus it was important for the controller to keep unequipped aircraft on 4D trajectories whenever possible. This was a new responsibility for controllers, and somewhat different from current practice.

While data-link equipped aircraft were managed by the automation, controllers managed unequipped aircraft using manually created or automation-generated resolution maneuvers. Lateral or vertical solutions could be developed using advanced path planning tools. For a vertical path or altitude change, the controller issued the clearance and monitored the aircraft for safety and conformance during the transition. For lateral route changes, ground tools provided the controller with an initial heading, time-to-turn back, and the waypoint that returned the aircraft to its original path. The controller issued the initial heading change, monitored the aircraft until it reached the turn back point, then cleared it direct to the next waypoint. Because of the imprecision inherent in timing the heading change and turn back maneuvers, aircraft were likely to deviate somewhat from the automation generated trajectory until they resumed lateral navigation to the next waypoint.

Whenever unequipped aircraft were not on their trajectories, controllers were responsible for keeping them safely separated from other traffic. Controllers were also expected to monitor unequipped transitioning aircraft due to greater uncertainty in the trajectory predictions during climbs and descents and the resulting degradation of automated conflict detection performance. In order to enable controllers to monitor aircraft during off-trajectory and transitioning states, the data block or aircraft symbol needed to provide a clear, unambiguous indication where separation responsibility resided.

As an additional operator's incentive, the concept assumed that priority was given to data link equipped aircraft whenever a mixed conflict occurred between equipped and unequipped aircraft. In this situation the controller was responsible for resolving the conflict and was instructed to move the unequipped aircraft whenever possible. Assuming that the aircraft in conflict were on their trajectories, a conflict between equipped and unequipped or between two or more unequipped aircraft was detected by the automation and solved by the controller. Although priority was given to equipped aircraft when possible, the automation could provide a resolution for either aircraft, and controllers could move either aircraft at their discretion.

B. Controller Workstations

The controller's display was modified to support the redefined roles and responsibilities described above. Because trajectory monitoring, transfer of control and communication, and conflict detection and resolution would be handled by the automation for equipped aircraft, the controller did not need to maintain detailed awareness of each individual flight. Therefore the controller workstation was drastically re-designed.

The goal of this redesign was to provide the controllers appropriate and adequate awareness of the automation-managed (equipped) aircraft while maintaining focus on the unequipped aircraft that were their primary responsibility. Given the high levels of traffic this concept could support, equipped aircraft were represented by a limited data block (which could be expanded on demand) to reduce display complexity. Figure 2 shows the prototype display with 3x traffic (approximately 50 aircraft).

Controllers accessed the new CD&R tools through fields in the data tag, including a trial plan portal, the altitude, and a number that signified minutes-to-conflict whenever the CD&R algorithm detected a conflict. Current day data tags were used for unequipped aircraft, whereas equipped aircraft were depicted with low-lighted directional symbols and altitudes to provide a general picture of traffic clusters.

Figure 2. Controller Display for Sector 90

When conflicts between unequipped and equipped aircraft occurred, the conflicts were highlighted in magenta. For both mixed and unequipped only conflicts, the data tag color turned from green to yellow when the time-to-conflict was between two and five minutes, and then to red when the time-to-conflict was less than two minutes. These changes in the data tag colors for aircraft in conflict was intended to elevate the controller's situation awareness of these aircraft.

Results

C. Aircraft Count

The average number of unequipped and equipped aircraft was recorded throughout each simulation run. Figure 3 shows the average equipped and unequipped aircraft count over time for sector 91. A visual comparison of Figures 1 and 3 shows the actual number of aircraft in the study matching the original design. The aircraft count for sector 90 showed similar patterns.

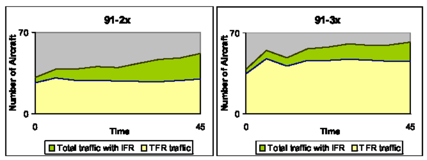

Figure 3. Average Aircraft Count, Sector 91 – number of unequipped (green) and equipped (beige) aircraft observed during 0x, 1x, 2x, and 3x traffic conditions

As designed, the unequipped aircraft count ramped up linearly over time, peaking at around 20 aircraft by the end of the run. Due to controller manipulation and the dynamic nature of air traffic, no two runs were exactly alike. In sector 91, unequipped aircraft count in the 3x condition was noticeably lower than the other traffic conditions in the final 15 minutes of the scenario. The observed peaks in total traffic were: 90-0x = 27, 90-1x = 39, 90-2x = 50, 90-3x = 64, 91-0x = 23, 91-1x = 39, 91-2x = 52, and 91-3x = 62. Equipped aircraft count was based on the number of aircraft in the physical sector. Unequipped aircraft count was the number of aircraft inside the physical sector plus the number of aircraft that the controller controlled outside the physical sector. This combination was chosen because it closely represents the true load of aircraft the controllers managed.

D. Controller Workload

Workload ratings were obtained during data collection runs by prompting controllers every five minutes to assess their instantaneous workload on a scale of 1 (very low) to 7 (very high), and then click on the corresponding button on the display. Figure 4 shows the average workload ratings for sector 90 over time. Subjective workload increased over time as aircraft count increased. Unlike the more linear increase in aircraft count, however, workload ratings show a slight inflection about 30 minutes into the scenario, followed by a rapid increase until the sector became "unworkable." For sector 91, which had more transitioning aircraft, a similar but more linear trend was observed. Workload for sector 91 was rated higher earlier in the scenario, presumably due to higher traffic complexity, and it too became "unworkable" in the final third of the run.

Controller workload was measured for both test sectors (90, 91) at different traffic levels (0x, 1x, 2x, 3x). The data was analyzed using repeated measures Two-Way Analysis of Variance (ANOVA). The level of equipped aircraft significantly affected workload ratings ($p < 0.005$), but there were no significant effects on workload ratings between the two test sectors ($p > 0.20$) or the interaction effects of sector and traffic level ($p < 0.20$). A One-Way ANOVA was then calculated to determine which of the traffic level conditions (0x, 1x, 2x, 3x) significantly affected workload ratings. Of the six possible combinations, 0x vs. 2x ($p < 0.05$), 0x vs. 3x ($p < 0.025$), and 1x vs. 3x ($p < 0.005$) were significant.

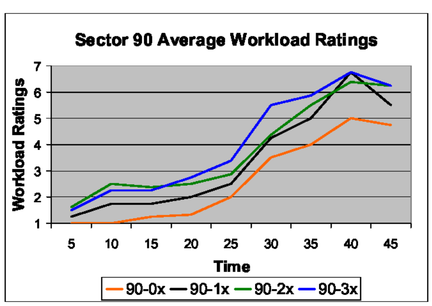

Figure 4. Average Workload Ratings for Sector 90 in 5-minute intervals

The results support the over-the-shoulder observations and participant feedback that 0x and 1x conditions exhibit similar levels of traffic complexity. Both were "controllable" traffic with acceptable level of workload and no loss of separation. In contrast, the 2x and 3x conditions exhibited higher traffic complexity due to increased overall traffic and a substantial increase in mixed conflict frequencies, resulting in traffic that was "less controllable" with excessive workload and possible loss of separation.

E. Number of Aircraft Turned Away

Total aircraft turned is the number of unequipped aircraft "turned away" when the participant sector load approached maximum. Confederate supervisors were assigned to each participant to monitor his/her workload and to limit aircraft entering the sector as needed. The number of aircraft turned away indicated when subjective controller workload reached its peak.

First, a Two-Way ANOVA was computed to test for significance. Again, sector (90, 91) and traffic level (0x, 1x, 2x, 3x) were the independent variables. Traffic level significantly affected the total number of aircraft turned ($p < 0.001$), whereas the sector ($p > 0.20$) and traffic level interaction ($p > 0.20$) did not.

Second, One-Way ANOVAs were used to test traffic level and total aircraft turned significance. Significance was found in four of six conditions: 0x vs. 2x ($p < 0.025$), 0x vs. 3x ($p < 0.025$), 1x vs. 2x ($p < 0.05$), 1x vs. 3x ($p < 0.025$). Similar to workload ratings, the results support a general grouping of 0x/1x vs. 2x/3x traffic levels in terms of overall difficulty in controlling the traffic.

Figure 5 shows the average number of aircraft turned away per traffic level condition for sectors 90 and 91. In the 0x condition, no aircraft were turned, suggesting that the peak unequipped aircraft count was challenging but manageable. In the 1x condition, the results were skewed by an anomaly of one participant turning away eleven aircraft, which accounted for all aircraft turned in sector 90.

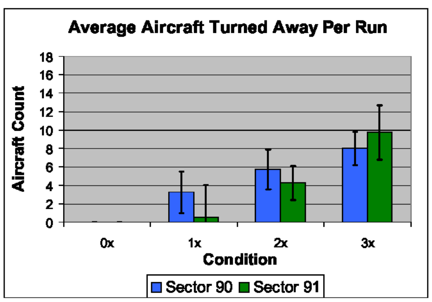

Figure 5. Average Number Aircraft Turned Away for Sector 90 (blue) and Sector 91 (green)

All participants contributed to the average in the 2x and 3x traffic level conditions. At the 2x traffic level, several aircraft were turned for each sector, though sector 90 had two more aircraft turned on average. Sector 91 was believed to be more difficult during higher levels of traffic, due to transitioning aircraft. This is supported by an average of 9.75 aircraft turned during the 3x condition.

An examination of when the controller turned the first aircraft shows a similar pattern of results. The traffic level significantly affected when the first aircraft was turned ($p < 0.001$). The sector and traffic level interaction were not significant.

In Figure 6, 0x had no aircraft turned, hence all 45 minutes passed with no first turn. The 1x condition had aircraft turned relatively late in the scenario (minute 42), suggesting the controllers were not overworked until a few minutes before that time. As the complexity increased over the conditions, controllers turned aircraft much sooner (some as early as 22 minutes in the 3x condition). Sector 91's average first turn was 28 minutes compared to sector 90's 35 minutes. This supports the overall results that sector 91 was more difficult to control due to greater traffic complexity.

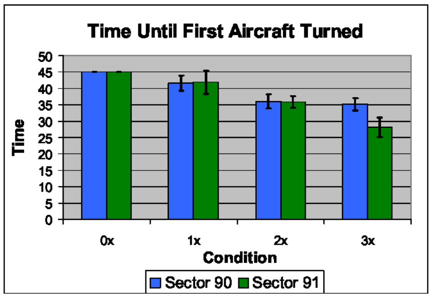

Figure 6. Time until First Aircraft Turned Away during 45-minute Simulation Run

F. Traffic Complexity Metrics

The relationship between subjective workload ratings and objective complexity metrics was examined using the step-wise multiple linear regression method. Fifty-three traffic complexity metrics (sometimes called "dynamic density" metrics) have been gathered from literature and their importance has been examined in prior studies by Kopardekar and Magyarits [Koardekar and Magyarits, 2003]. For this study, 53 complexity variables were analyzed separately for equipped, unequipped, and total aircraft.

The regression of the full complexity variable set resulted in coefficient of variation (R2 = 0.864, R = 0.746). In order to reduce the number of correlated variables, only variables with a variance inflation factor of 10 or less were identified. The following complexity variables were found to be significant based on that criterion:

- Horizontal proximity of all aircraft
- Number of unequipped aircraft
- Horizontal proximity of unequipped aircraft
- Aircraft density of unequipped aircraft
- Separation criticality index of unequipped aircraft
- Percentage of unequipped aircraft that are either climbing or descending
- Number of aircraft predicted to be in a mixed equipage conflict
- Aircraft density of equipped aircraft

It is interesting to note that the horizontal proximity of all aircraft and the unequipped aircraft count were significant variables. A possible reason is that the higher the horizontal proximity of the aircraft, the closer they are to each other, reducing the options available to resolve a conflict. The reduced number of resolution options resulted in increased complexity for controllers. The number of unequipped aircraft and their density (number of aircraft divided by the volume they occupy) were also related to their proximity and their impact on reducing the number of available options in conflict resolution. The equipped aircraft density also reduced the available options for unequipped aircraft, particularly for conflict resolution, which resulted in increased complexity.

The separation criticality index refers to how close the aircraft are with respect to their separation minima. This index often correlates with traffic density because higher density in the same airspace results in closer proximity between aircraft.

The percentage of climbing and descending unequipped aircraft increased complexity for controllers because climb and descend profiles involve uncertainties and must be monitored closely. Aircraft predicted to be in mixed equipage conflicts also added to complexity. The controller was instructed to give priority to equipped aircraft, moving unequipped aircraft using voice clearances. At their discretion however, (e.g., due to traffic and/or time constraints), controllers could choose to move the equipped aircraft via data link. In either case, resolving mixed conflicts involved added complexity.

As predicted, the greatest contributing factors to controller workload related to unequipped aircraft. The equipped aircraft contributed to the overall workload by the sheer increase in traffic density, resulting in greater proximity between aircraft and higher frequency of mixed equipage conflicts, reducing the number of maneuver options.

Comment [AB1]: SZ change

G. Conflict Analyses

Table 1 presents a side-by-side comparison of each test sector's distribution of the average number of conflicts according to the equipage mix of the conflict pairs. The number of conflicts between unequipped aircraft remains relatively constant across conditions because the traffic count and patterns of unequipped aircraft does not vary significantly between experimental conditions. In contrast, the number of mixed equipage conflicts increase along with traffic levels.

Table 1. Distribution of average number of conflicts per test sector according to equipage of conflict pair

	Sector 90		Sector 91	
Scenario	Mixed conflict	Unequipped conflict	Mixed conflict	Unequipped conflict
0x	0	11	0	7
1x	14	10	14	7
2x	22	11	26	7
3x	31	10	45	7

Although sector 91 has a lower number of unequipped conflicts than sector 90, the ratio between mixed and unequipped conflicts is larger and grows more quickly with traffic levels – the final ratio between the two types of conflicts being nearly 7:1- as opposed to 3:1 in sector 90. The rapid growth of mixed conflicts in sector 91 is likely due to sector geometry, more complex route structures, and higher numbers of transitioning aircraft, resulting in greater traffic complexity.

Conflict resolution strategies in the mixed operations were also examined. This analysis included the type of maneuver that was used for the resolution (lateral or vertical) as well as which type of aircraft was selected as the maneuvering aircraft in conflicts involving an equipped and unequipped aircraft pair.

Of the types of maneuvers participants used for resolving conflicts, there was a strong preference for using altitude rather than lateral maneuvers. However, a noticeable trend emerged where the percentage of lateral resolution maneuvers increased with increased traffic. This is most noticeable in sector 91 where lateral maneuvers at 0x traffic level were limited to 7% of the overall number of resolutions, compared to 3x, where lateral maneuvers made up 27% of the maneuvers. Increased use of lateral maneuvers in higher traffic levels was likely due to the fact that with greater numbers of aircraft occupying the sector, fewer conflict-free altitude maneuvers were available to the participant, especially in sector 91, which had a significant portion of the airspace occupied by transitioning aircraft.

Although controllers were asked to solve the mixed conflicts by moving the unequipped aircraft, they were given the authority and the tools to move the equipped aircraft if the traffic situation warranted it. Data on usage of the auto-resolution function was analyzed to examine whether the equipped or unequipped aircraft were maneuvered to resolve mixed conflicts. However, during 1x runs, controllers frequently resolved conflicts based on their own strategies and used the auto-resolution function primarily to solve conflicts that were more difficult to resolve. In these difficult situations, they maneuvered the equipped aircraft about one third of the time (31% in sector 90 and 43% in sector 91). In 2x and 3x runs controllers used the auto-resolution function frequently for all conflicts and followed its built-in preference to maneuver the unequipped aircraft whenever possible. For sector 90, the percentages were 7% of equipped aircraft maneuvered at 2x and 19% at 3x. Sector 91 showed a similar trend with equipped aircraft maneuvered in 2% of the conflicts at 2x and 5% of the conflicts at 3x.

H. Separation Violations

Separation violations were reported when aircraft came within a distance of 5 nm laterally and 1000 ft vertically, and at least one of the aircraft was unequipped. At the 0x level of traffic, no mixed or unequipped separation violations occurred in either sector. In the 1x condition, sector 90 experienced a mean number of 0.75 violations, with none recorded in sector 91. Both sectors experienced violations in the 2x condition, with more in sector 90 (M=0.75) than sector 91 (M=0.25). A violation increase in both sectors was again observed at 3x, with sector 91 reporting a mean of 2.0 and sector 90 a mean of 1.0 violations.

These numbers are relatively low, given the high traffic density and workload. As expected, the number of separation violations increases for the 3x condition, suggesting that a substantial increase in safety risk occurs between 2x and 3x traffic.

I. Participant Feedback

In the post-simulation questionnaire, participants and confederate supervisors were asked how many unequipped aircraft they felt could be safely managed in sectors 90 and 91 for each condition. Average responses for sector 90, were 17, 16, 13, and 10 aircraft in the 0x, 1x, 2x, and 3x traffic conditions, respectively, and 17, 15, 11, and 9 aircraft for sector 91. Comparing these aircraft counts to the subjective workload data recorded during the simulation found them corresponding to a workload rating of between 2 and 3 (on a 1 – 7 scale) for each condition.

During the debriefing discussions, participants expressed a different criterion for safe management. If they were responsible for monitoring separation when the aircraft were free track, climbing or descending, they suggested that they could safely manage a maximum of three aircraft in these states.

Participants, observers, and confederate supervisors were asked whether the traffic density of the equipped aircraft significantly affected the workload. They responded that workload was increased, because 1) there were more transitioning aircraft, which increased complexity; 2) there were more mixed conflicts; and 3) there were fewer resolution options. They also commented that as the traffic density of the equipped aircraft increased, the participants resorted to more automated conflict resolutions due to fewer resolution options and not enough time to manually search for the optimum resolution.

Questions about mixed operations acceptability addressed how acceptable it was to: 1) rely on the automation for conflict detection and resolution; 2) have aircraft in one's sector but not under one's control; and 3) manage unequipped aircraft in the mixed environment. Responses resulted in average ratings of 5 and above (1=completely unacceptable; 7=completely acceptable) for all questions.

Questions related to difficulty monitoring aircraft in different states in a mixed airspace environment suggested changes to decision support tools that would improve situation awareness. Better display information for separation status of off-trajectory aircraft, and an ability to monitor the turn back point in the voice-initiated lateral route change could lessen the overall monitoring workload and increase safety.

Discussion

The results of this study give relevant insights into the feasibility of air traffic controllers managing unequipped aircraft within the same airspace in which equipped aircraft are managed by ground automation. Complimentary research is being conducted to investigate the appropriate level of automation for safely managing equipped aircraft [Prevot et al., 2008].

Controller workload depends on various complexity factors. Higher traffic density of equipped aircraft has a generally small and predictable impact on controller workload, whereas factors related to the unequipped aircraft have a much more significant impact. For example 45 equipped aircraft managed by automation may still allow a controller to safely handle twelve unequipped aircraft as long as they are on their trajectories and the automation provides reliable conflict detection support. However, if three of these twelve aircraft are on vectors or transitioning, the situation may become uncontrollable and too complex.

Therefore, the main complexity factors need to be properly managed when allowing unequipped aircraft to enter integrated airspace that includes a high number of equipped aircraft. All aircraft should always be kept on trajectories to retain conflict detection integrity. When 1x traffic density is clearly exceeded, controllers can no longer monitor aircraft for potential losses of separation. In order to maneuver unequipped aircraft, procedures need to be in place to allow for a closed trajectory solution to be transmitted to the aircraft and entered into the ground system. The process of issuing a heading and a turn back in two separate steps is inappropriate for maneuvering multiple unequipped aircraft at high traffic densities.

The 0x condition showed that simply adding advanced ground automation (including CD&R) to an otherwise unchanged air traffic control environment does not provide major capacity benefits. In line with previous research, controllers may be able to handle a few more aircraft per sector, but the basic workload of conducting routine tasks and clearance based operations limits the scalability of the traffic to little more than the current day monitor alert parameters.

Overall, this study indicates that static and strict airspace segregation is not needed and could unnecessarily limit capacity. In the author's opinion, airspace can be integrated and unequipped aircraft can get access as long as an examination of the primary complexity factors does not exceed certain thresholds. Primary factors would have to include the number of unequipped aircraft already in the airspace, the overall traffic density and the number of current and expected off-trajectory operations. As more aircraft become equipped, fewer aircraft would likely get access to the integrated airspace. The results indicate that it is feasible for a controller, with the help from automation for conflict detection and resolution, to manage unequipped aircraft within the same airspace as equipped aircraft. Therefore, the study results suggest that the integrated airspace operations are feasible, to a limit, with support from automation for conflict detection and resolution. This finding has clear implications on the airspace configuration as a result of equipage and density.

Conclusion

The main results of this study indicate that the mixed equipage operations are feasible, to a limit, within the same airspace. The higher the traffic density of equipped aircraft, the lower the number of unequipped aircraft that can be managed within the same airspace. This is logical, because higher traffic density in the same volume reduces the degrees of freedom or maneuver options for conflict resolution. Under such conditions, the controller workload also increases. The statistically significant complexity factors also suggest aircraft density of equipped and unequipped aircraft impact the complexity. Interestingly, the controllers accepted all aircraft under all unequipped aircraft traffic condition with current level of traffic. Under mixed equipage traffic conditions, the higher the density of traffic, the earlier the controllers stopped accepting the unequipped aircraft in the sector. The simulation showed that mixed equipage operations are feasible in the same airspace, even under higher traffic density conditions such as 3x. However, there is a limit to which the controllers can manage the mixed equipage. In summary, it appears that integrated airspace operations are feasible to a limit. The traffic density, automation levels for conflict detection and resolution, and equipage will be key factors in the design and adjustments of the airspace configuration.

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List of Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast	JPDO	Joint Planning and Development Office
AFR	Autonomous Flight Rules	NLR	National Aerospace Laboratory of Netherlands
ANOVA	Analysis of Variance	RNP	Required Navigation Performance
ASAS	Airborne Separation Assurance	SME	Subject Matter Expert
ATC	Air Traffic Control	TOC	Transfer of Communication
CD&R	Conflict Detection and Resolution	ZDV	Denver Center
FMS	Flight Management System	ZID	Indianapolis Center
FANS	Future Air Navigation System	ZKC	Kansas City Center
IFR	Instrument Flight Rules	ZLA	Los Angeles Center

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