Feasibility of Integrating Automated Separation Assurance with Controller-Managed Aircraft 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 5–20 aircraft. The first condition consisted solely of this unequipped traffic, while the remaining three conditions included a constant number of equipped aircraft operating within the same airspace: 15 equipped aircraft in the second condition, 30 in the third condition, and 45 in the fourth condition. 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 self-reported workload also increased progressively with the increasing level of

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equipped aircraft. 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 an 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 must be considered in 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 permit access only to those aircraft that are supported by or equipped with ground-based or airborne separation management automation. In the segregated case, unequipped aircraft would operate in the airspace that is not reserved for equipped aircraft. Integrated (or "non-exclusionary") airspace would 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 1) aircraft with different levels of equipage can co-exist in the same airspace, and 2) under what conditions this may be possible [Kopardekar et al., 2008]. 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 conclusively addressed the issue at hand: the feasibility of integrating automated separation assurance with controller managed aircraft operations in the same airspace. [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, these studies did not address the implications of mixed operations on airspace configuration. 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 (based on RNP capabilities of aircraft on oceanic routes) impacted controllers' reports of scenario difficulty and situation awareness. Equipped aircraft in the study were outfitted with the Future Air Navigation System (FANS-1A) avionics package and datalink. The 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. Further, they suggest that airspace segregation could be viewed as a means for providing an equipage incentive to airlines. In a follow-up study, Pina and Hansman found that 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]. However, the study was very low fidelity, and examined 11 scenarios with different levels of mixed equipage where flights eligible for reduced separation standards coexisted with flights limited to standard separation minima. The experiment was designed with one independent variable: the level of mixed equipage represented by the percentage of aircraft eligible for reduced separation standards (i.e., equipped with direct pilot controller communication, ADS-C, and RNP-4). It varied between 0% and 100% with increments of 10% for each scenario.

The impact of mixed equipage on automated conflict detection and resolution (CD&R) was examined from the pilot's perspective in free-flight studies conducted by National Aerospace Laboratory of The Netherlands (NLR). Hoekstra et al. conducted studies utilizing Predictive Airborne Separation Assistance (PASAS) [Hoekstra et al., 2000]. Three air traffic management operational scenarios with free flight elements were defined, implemented and tested: 1) flight level,

2) protected airways, and 3) fully mixed. In the fully mixed scenario, equipped and unequipped aircraft occupied the same airspace and unequipped aircraft were monitored by the ground. The same CD&R algorithms were applied for 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 that they would avoid the aircraft equipped with the Airborne Separation Assistance System (ASAS). The study examined two different levels of equipage (25% and 75%) as well as high traffic density. The flight level and protected airways scenarios 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]. The experiment concentrated on the performance of the air traffic controller working the radar and communication position in the OCALA sector of the Jacksonville Center. The experiment measured controller performance in scenarios containing aircraft under their control and aircraft that were self separating in a "free flight" operation. Four scenarios were presented: 1) traditional ground-based control, 2) traditional control with all aircraft flying direct, 3) all aircraft flying direct with 20% self separating, and 4) all aircraft flying direct with 80% self separating. 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]. Laboratories at NASA Ames and NASA Langley were linked via a dedicated internet connection, allowing Automatic Dependent Surveillance-Broadcast (ADS-B), data link, and radio communications to be modeled in the experiment. In contrast to Corker, et al., the controllers were not responsible for the separation of AFR aircraft. (The study did not explore how the workload of pilots of AFR aircraft was affected.) 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. conducted a joint simulation to test the En Route Free Maneuvering concept element of Distributed Air-Ground Traffic Management (DAG-TM), which integrated advanced air and ground decision support tools with data link. In this concept, controller managed aircraft flying under IFR were mixed with self separating autonomous aircraft flying under AFR. The study 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 (e.g., from 8 to 28) [Lee et al., 2005]. These results indicate strong potential for mixed operations to increase capacity.

A mixed equipage operation is one area where human and automation roles must be carefully considered. Issues associated with workload and the functional allocation of roles and responsibilities are critical [Sheridan, 2000]. McNally and Gong [2007] reported analysis of the manage-by-exception concept where the controller is aided by conflict detection and is responsible for generating changes to trajectories that are identified to be in conflict. They discovered that a single controller maintained legal separation (5 nmi horizontal or 1000 ft vertical) and improved the flying time efficiency by 1.9% while working the combined traffic in five Fort Worth Center high altitude sectors at traffic levels nearly equivalent to that of today's traffic. The controller performed separation assurance functions in the experiment that typically are performed by 4–10 people under today's operations. The lessons learned from the manage-by-exception study influenced the functional allocation of the human-automation roles and responsibilities that were decided for the experiment reported in this paper.

In summary, prior research involving mixed equipage operations indicated overall feasibility. Furthermore, simulations of free maneuvering concepts 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

Version 2.0 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.

To address these questions, the current study was conducted to examine whether mixed equipage operations are feasible in the same airspace under varying levels of traffic densities and varying equipage levels. The study hypothesized that with CD&R automation for equipped aircraft and conflict detection automation and resolution advisories for unequipped aircraft, mixed equipage operations could be feasible at high overall traffic density that includes unequipped aircraft.

The following sections describe the experimental method, results, and conclusions of the mixed equipage study.

METHOD

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 providing advisories.

Equipage

All simulated aircraft were equipped with ADS-B OUT[1] and flight management systems (FMS) and had a required navigation performance of RNP-1. As shown in Table 1, the presence or absence of an FMS-integrated data link capability was the single equipage factor distinguishing equipped and unequipped aircraft in the study. The integrated data link capability (similar to that supported by the FANS-1A avionics package) enabled transmission of FMS-loadable

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[1] Automatic Dependent Surveillance-Broadcast OUT (ADS-B OUT) is a function on an aircraft or a surface vehicle that periodically broadcasts its state vector (horizontal and vertical position, horizontal and vertical velocity) and other information. Under ADS-B OUT, a vehicle periodically broadcasts its own position without knowing what other vehicles or entities might be receiving it. ADS-B OUT is automatic in the sense that no pilot or controller action is required for the information to be transmitted. It is dependent surveillance in the sense that the surveillance information depends on the navigation and broadcast capability of the source vehicle. ADS-B OUT is used by ATC for surveillance in a manner similar to the use of conventional radar. A complementary technology is called ADS-B IN, whereby ADS-B information is received, processed and displayed in the cockpit to provide an enhanced 'see and avoid' surveillance that is superior to TCAS. ADS-B IN also enables a number of advanced applications that can enhance safety, capacity and efficiency. Aircraft can be equipped with ADS-B OUT without having ADS-B IN capability.

Table 1. Characteristics of Equipped and Unequipped Aircraft

Equipped	Unequipped
FMS with LNAV and VNAV	FMS with LNAV and VNAV
RNP1	RNP2
RTA not required	RTA not required
Datacom with FMS-integrated route-uplink capability (FANS-like) and capability to receive transfer of communication and altitude uplink	Voice communication only
ADS-B OUT with position and velocity data	ADS-B OUT desired but not required

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.

Experimental Design

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 a certain critical airspace complexity threshold would exist, which, if exceeded, would make mixed operations infeasible. It was further hypothesized that conditions with a greater number of equipped aircraft would increase the overall traffic complexity and the number of mixed conflicts in the sector, thereby increasing controller workload and reducing the number of unequipped aircraft that could be safely managed. To investigate these hypotheses and examine when mixed operations would become infeasible, the experiment design varied two traffic factors: the number of unequipped aircraft and the number of equipped aircraft.

The experiment consisted of four conditions, incorporating a within-subjects design, as shown in Table 2. The number of equipped aircraft 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 remained relatively constant at 15, 30, and 45 aircraft, respectively, across the 45-minute scenario. These

Table 2. Experiment Design: Four Conditions (0x, 1x, 2x, and 3x) Across 45-Minute Scenario with Number of Equipped Aircraft Remaining Constant and Number of Unequipped Aircraft Increasing Until Controller Workload Reaches or Exceeds Maximum

Condition	Equipped Aircraft	Unequipped Aircraft
0x	0	From 0 to 20
1x	15	From 0 to 20
2x	30	From 0 to 20
3x	45	From 0 to 20

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.

In contrast, the number of unequipped aircraft was varied within each scenario, increasing linearly from approximately 5–20 aircraft, or until controller workload was subjectively assessed as reaching, or exceeding, the maximum. A confederate "supervisor" assigned to each participant monitored controller workload and restricted the entry of unequipped aircraft 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.

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 11–25 years, with an average of 20 years of ATC experience. Four subject matter experts (SME) observed the experiment and 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.

Airspace. The simulation airspace consisted of Sector 90 in Kansas City Center (ZKC) and Sector 91 in Indianapolis Center (ZID). ZKC-90 covered an area of 7943 nmi^2 and ZID-91 covered and area of 7561 nmi^2. The altitude range for both sectors during the simulation was FL240 and above, which was achieved by combining the medium high altitude and the high altitude sectors in that airspace. 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 comprised of 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. Pseudo-pilots flew all of the simulated aircraft.

Operational Concept, Assumptions, and Separation Responsibilities. The concept assumed that the centralized, groundside automation could detect and resolve conflicts involving properly equipped aircraft that were on four-dimensional (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. Figure 1 illustrates the operational concept.

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 were developed as needed 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

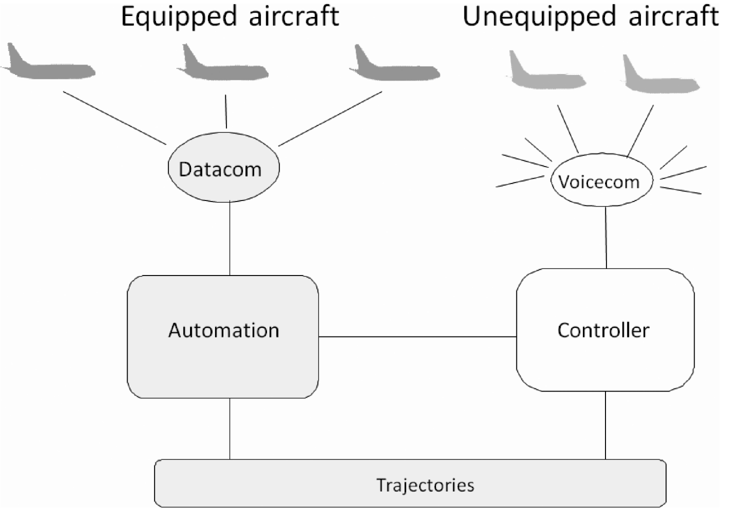

Figure 1. Operational concept. The presence or absence of an FMS-integrated data link capability was the single equipage factor distinguishing equipped and unequipped aircraft. Unequipped aircraft had no data link and were managed by air traffic control via radio voice communication.

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, and 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.

As shown in Figure 2 and Figure 3, 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.

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. Further, in order to help controllers monitoring aircraft during off-trajectory and transitioning states, a data block or aircraft symbol was needed to provide a clear, unambiguous indication where separation responsibility resided.

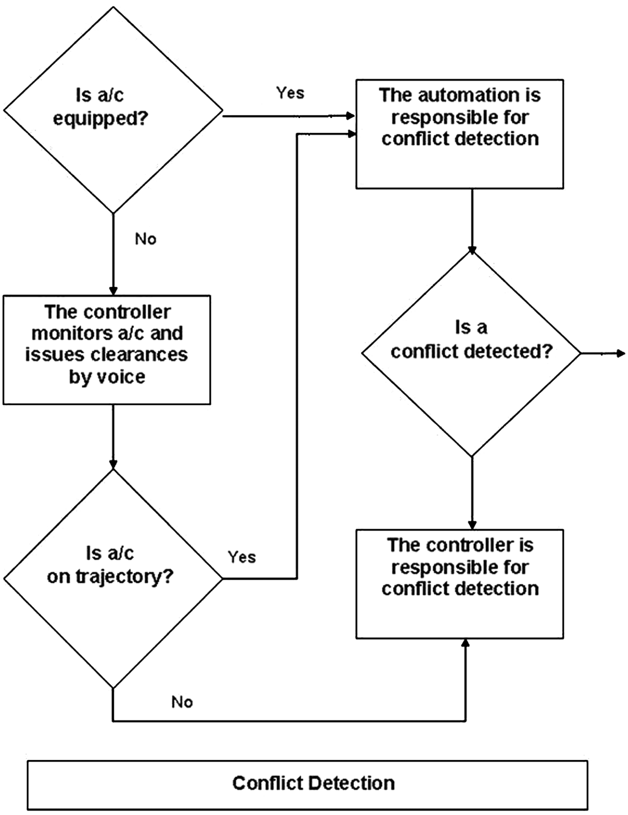

Figure 2. Conflict detection process.

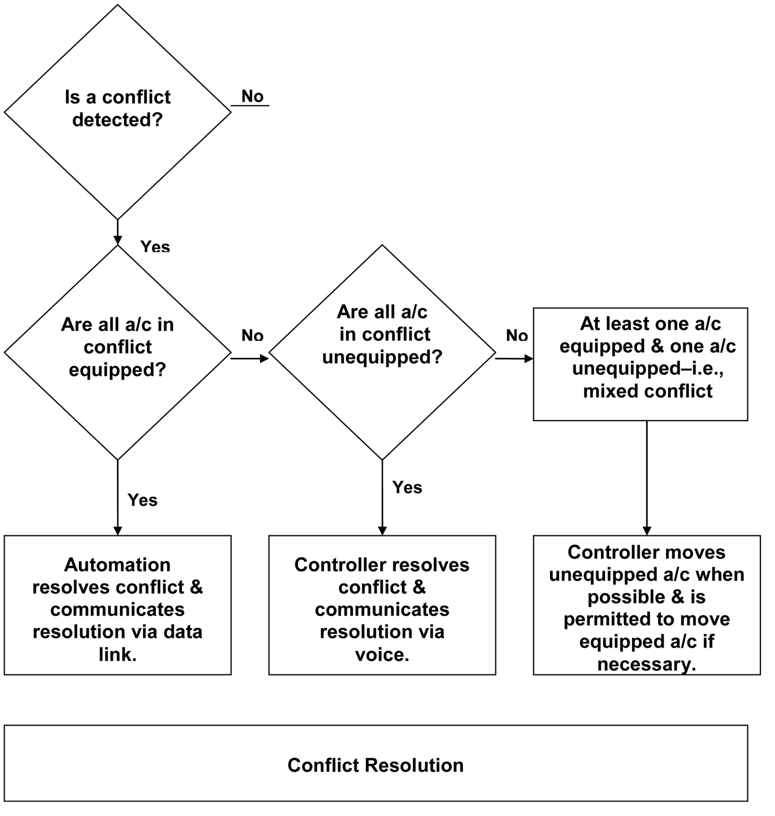

Figure 3. Conflict resolution process.

The concept utilized in this experiment 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.

Controller Workstations

The controller's display was modified to support the redefined roles and responsibilities described previously in this paper. 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 re-designed.

The goal of the redesign was to provide the controllers with appropriate and adequate awareness of the automation-managed (equipped) aircraft while maintaining their focus on the unequipped aircraft for which they were primarily responsible. 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 4 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.

When conflicts occurred between unequipped and equipped aircraft, the controller display highlighted the conflict in magenta. The display was designed in such a way as to highlight only those aircraft that the controller needed to monitor and control. Background

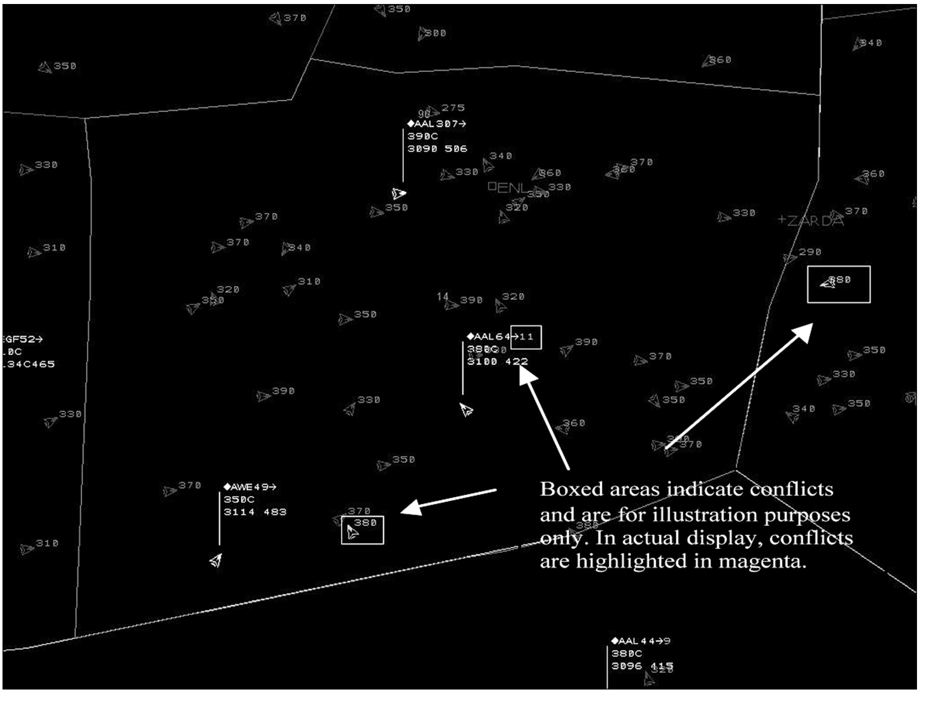

Figure 4. Prototype controller display with 3x traffic (approximately 50 aircraft). The display was designed to highlight only the aircraft that the controller needed to monitor and control; background aircraft controlled by the automation were visible but intentionally low-lighted.

aircraft controlled by the automation were visible but intentionally low-lighted. Consequently, although there were three times as many aircraft inside the sector and on the display as in a current-day environment, the controller was free to concentrate on the aircraft needing urgent attention because the automation managed the low-lighted aircraft in the background. The controller could get a sense of the overall density but did not need to know any specifics. The fact that the aircraft in the background were somewhat less visible was intentional and useful.

Throughout the experiment, for both mixed and unequipped-only conflicts, a data tag color turned from green to yellow when the time-to-conflict was between two and five minutes; when the time-to-conflict was less than two minutes, the data tag turned red. These changes in the data tag colors for aircraft in conflict was intended to elevate the controller's situation awareness of these aircraft.

RESULTS

Aircraft Count

The average number of unequipped and equipped aircraft was recorded throughout each simulation run. Figure 5 shows the average equipped and unequipped aircraft count over time for sector 91. A visual comparison of Figure 5 with Table 2 shows that the actual number of aircraft in the study corresponds with the original

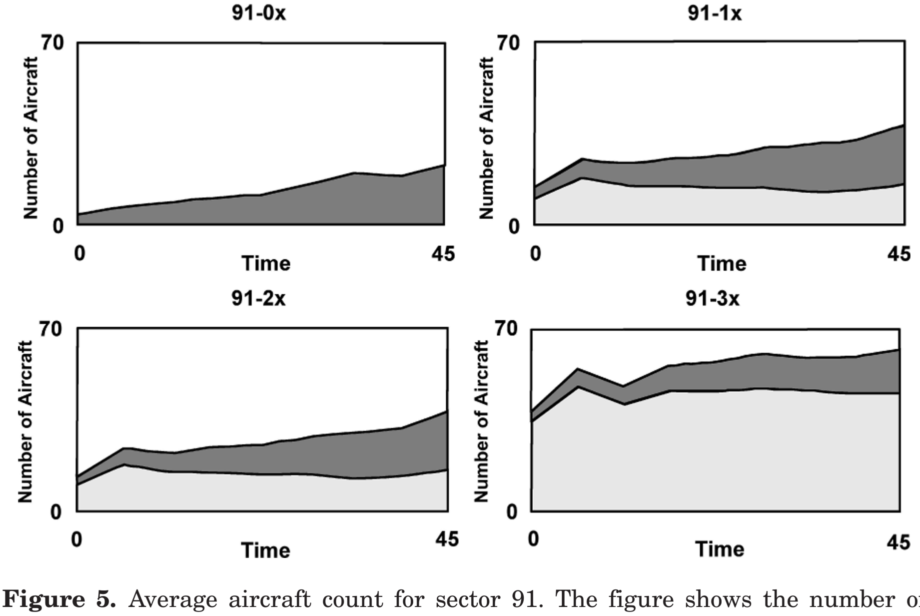

Figure 5. Average aircraft count for sector 91. The figure shows the number of unequipped aircraft (dark gray) and equipped aircraft (light gray) observed during 0x, 1x, 2x, and 3x traffic conditions.

experiment design. The aircraft count for sector 90 showed similar patterns.

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 for sector 90 and sector 91 are presented in Table 3.

Equipped aircraft count was based on the number of aircraft in the physical sector (since they were not handed off). The unequipped aircraft count was derived from the number of aircraft inside the physical sector plus the number of aircraft that the controller controlled outside the physical sector. This combination resulted in higher unequipped aircraft counts than would have resulted from counting the aircraft inside the sector, but it was chosen because it closely represents the true load of aircraft for which the controllers were responsible.

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 record the assessment by clicking on the corresponding button on the display. Controller workload was measured for both test sectors 90 and 91 at different traffic levels (0x, 1x, 2x, 3x). Figure 6 shows the average workload ratings for sector 90 over time. Subjective workload increased over time as aircraft count increased. Unlike aircraft count, which followed a more linear increase, workload ratings showed a slight inflection about 30 minutes into the scenario, followed by a rapid increase until the sector became unmanageable.

Figure 7 shows the average workload ratings for sector 91 over time. Sector 91 had more transitioning aircraft, and workload increased in a more linear trend. Workload was rated higher earlier in

Table 3. Observed Peaks in Total Traffic by Sector and Condition

Sector 90 and Condition	Peak Traffic	Sector 91 and Condition	Peak Traffic
90-0x	27	91-0x	23
90-1x	39	91-1x	39
90-2x	50	91-2x	52
90-3x	64	91-3x	62

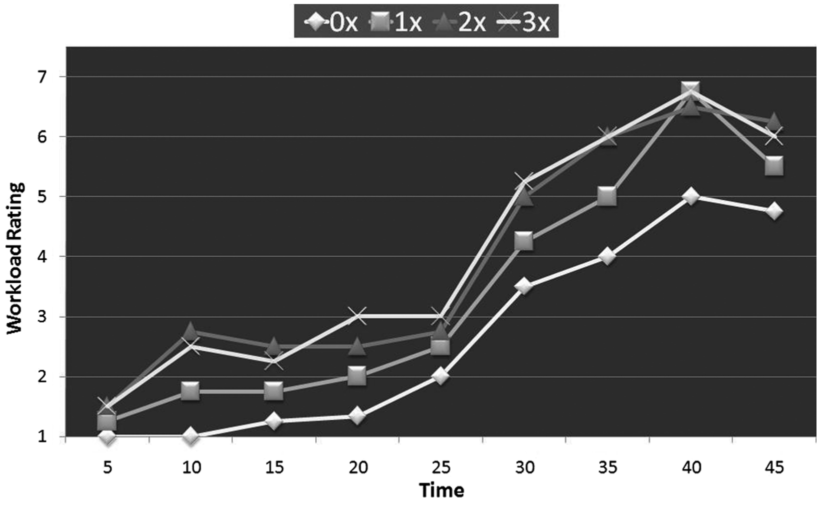

Figure 6. Average workload ratings for sector 90 in 5-minute intervals.

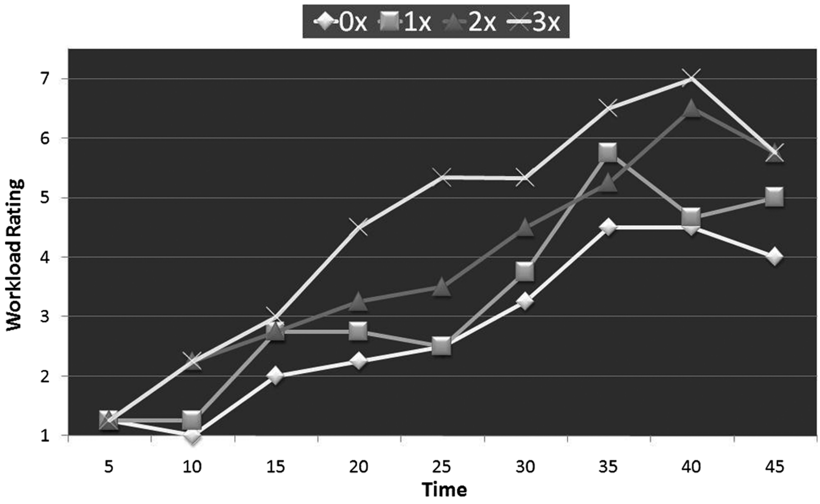

Figure 7. Average workload ratings for sector 91 in 5-minute intervals.

the scenario, presumably due to higher traffic complexity. Like sector 90, sector 91 became unmanageable in the final third of the run.

The controller workload data was analyzed using repeated Two-Way Analysis of Variance (ANOVA) measures. The level of equipped aircraft significantly affected workload ratings ($p < 0.001$) but the sectors and interaction between sectors and traffic levels did not significantly affect workload. A Post-Hoc Tukey test 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 ($p < 0.005$), 0x vs. 3x ($p < 0.001$), and 1x vs. 3x ($p < 0.05$) showed significantly different ratings.

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 levels 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.

Number of Aircraft Turned Away

Data was collected on the number of unequipped aircraft “turned away” when the participant sector load approached maximum. Confederate supervisors were assigned to each participant to monitor controller workload and to limit the number of 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 away ($p < 0.001$), whereas the sector ($p > 0.50$) and interaction ($p > 0.50$) did not affect workload.

Second, a Post-Hoc Tukey test was used to test traffic level and total-aircraft-turned significance. Significance was found in three of six conditions: 0x vs. 2x ($p < 0.05$), 0x vs. 3x ($p < 0.001$), 1x vs. 3x ($p < 0.005$). Similar to workload ratings, the results in terms of overall difficulty in controlling the traffic support a general grouping of 0x/1x vs. 2x/3x traffic levels.

Figure 8 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.

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.

Figure 9 shows the time until the first aircraft turned away during a 45-minute simulation run. The figure shows that for the 0x

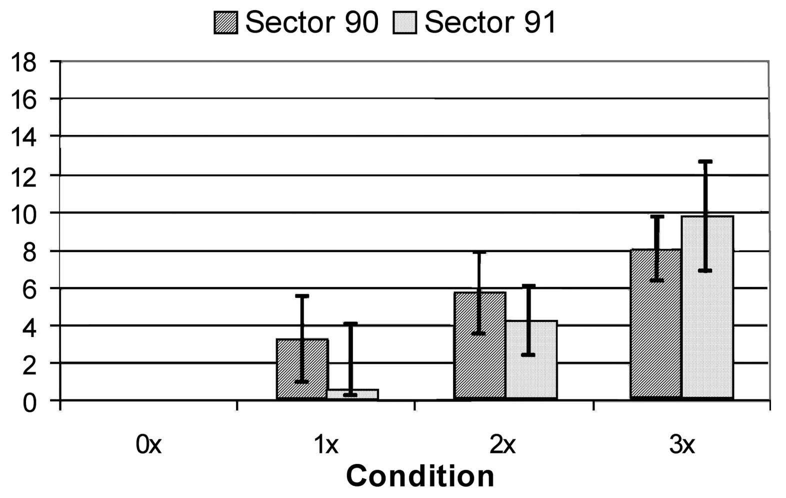

Figure 8. Average number aircraft turned away per traffic level condition, by sector.

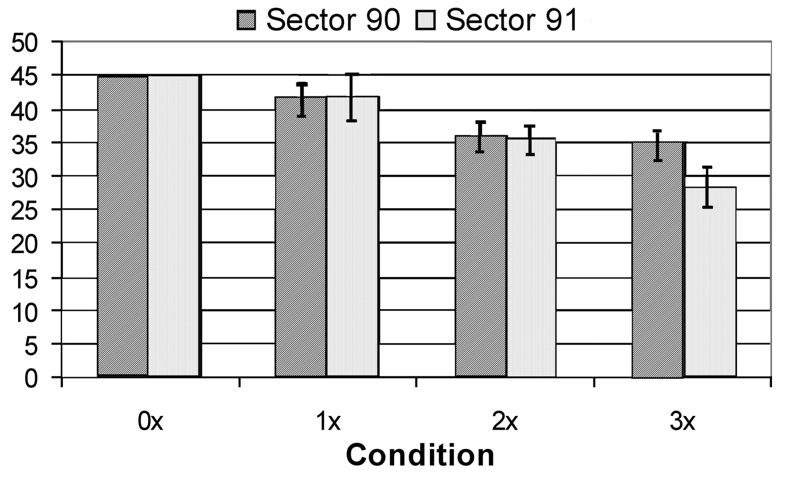

Figure 9. Average time until first aircraft turned away during 45-minute simulation run, by sector.

condition, no aircraft turned; hence, all 45 minutes passed with no first turn. In the 1x condition, aircraft turned relatively late in the scenario (minute 42), suggesting the controllers were not overworked until a few minutes prior to that the time the first aircraft was turned. As the complexity increased over the conditions, controllers turned aircraft much earlier (some as early as 22 minutes in the 3x condition). At 3x, the first aircraft were turned away when the number of unequipped aircraft in the sector was only 12-15, as opposed to 20-22 unequipped aircraft it took at 1x. Additionally, sector 91's average first turn at 3x was 28 minutes compared with sector 90's

35 minutes. This supports the overall results that sector 91 was more difficult to control due to greater traffic complexity.

Traffic Complexity Metrics

The relationship between subjective workload ratings and objective complexity metrics was examined using the step-wise multiple linear regression method. Prior studies by Kopardekar and Magyarits [Kopardekar and Magyarits, 2003] gathered 53 traffic complexity metrics (sometimes called “dynamic density” metrics) from literature and examined their importance. For the present study, 53 complexity variables were analyzed separately for equipped, unequipped, and total aircraft.

The regression of the full complexity variable set resulted in a coefficient of variation ($R^2 = 0.746$, $R = 0.864$). 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 explanation 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.

Conflict Analyses

Table 4 presents a side-by-side comparison of the distribution of the average number of conflicts for sector 90 and sector 91 according to the equipage mix of the conflict pairs. The number of conflicts between unequipped aircraft remained 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 increased along with traffic levels.

Although sector 91 had a lower number of unequipped conflicts than sector 90, the ratio between mixed and unequipped conflicts was larger and grew more quickly with traffic levels. At 3x, the ratio between the two types of conflicts was nearly 7:1 in sector 91 as opposed to 3:1 in sector 90. The rapid growth of mixed conflicts in sector 91 was likely due to sector geometry, more complex route structures, and higher numbers of transitioning aircraft, which resulted 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.

Table 4. Distribution of Average Number of Conflicts, by 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

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 was most noticeable in sector 91 where lateral maneuvers at 0x traffic level were limited to 7% of the overall number of resolutions, compared with 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. 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 31% of the time in sector 90 and 43% of the time 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.

Separation Violations

Separation violations were reported when aircraft came within a distance of 5 nmi laterally and 1000 ft vertically and at least one of the aircraft was unequipped. At the 0x level of traffic, there was no loss of separation. 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 were 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 increased in safety risk occurs between 2x and 3x traffic.

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. A comparison of these aircraft counts to the subjective workload data recorded during the simulation showed that they corresponded to a workload rating of 2–3 (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 aircraft were off-trajectory (i.e., vectoring), or climbing or descending, they could safely manage a maximum of 3 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 because the controller may have had to modify the trajectory of equipped and/or unequipped aircraft; and 3) there were fewer resolution options. They also said that as the traffic density of the equipped aircraft increased, the participants resorted to more automated conflict resolutions due to fewer resolution options and insufficient 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. Complementary 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 the aircraft 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 may have difficulty monitoring aircraft for potential losses of separation. In order to maneuver unequipped aircraft, procedures must be in place to allow 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. In the opinion of the authors, airspace can be integrated, and unequipped aircraft can get access to it as long as an examination of 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 are likely to get access to the integrated airspace. The results also indicate that it is feasible for a controller to manage unequipped aircraft within the same airspace as equipped aircraft when the controller is aided by CD&R automation. Therefore, the study results suggest that integrated airspace operations are feasible, to a limit, with support from CD&R automation. This finding has clear implications for airspace configuration as a result of equipage and density.

CONCLUSION

The main results of this study indicate that mixed equipage operations are feasible, to a limit, within the same airspace, assuming controllers keep unequipped aircraft on 4D trajectories whenever possible. In this study, controllers turned aircraft away when their workload became unmanageable under mixed equipage conditions and did not turn aircraft away under unequipped conditions. 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, controller workload also increases.

The statistically significant complexity factors also suggest that the aircraft density of equipped and unequipped aircraft impacts the complexity. Interestingly, the controllers accepted all aircraft under all unequipped aircraft traffic conditions with current levels of traffic. Under mixed equipage traffic conditions, the higher the density of traffic, the earlier the controllers stopped accepting the unequipped aircraft into the sector. The aircraft that were off trajectories were harder for controllers to manage. 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 the same airspace.

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ACRONYMS

A/C	Aircraft
ADS-B	Automatic Dependent Surveillance-Broadcast
AFR	Autonomous Flight Rules
ANOVA	Analysis of variance
ASAS	Airborne Separation Assistance System
ATC	Air traffic control
CD&R	Conflict detection and resolution
FMS	Flight management system
FANS	Future Air Navigation System
IFR	Instrument Flight Rules
LNAV	Lateral navigation
JPDO	Joint Planning and Development Office
NLR	National Aerospace Laboratory of The Netherlands

RNP	Required navigation performance
RTA	Required Time of Arrival
SME	Subject matter expert
VNAV	Vertical navigation
ZID	Indianapolis Center
ZKC	Kansas City Center
ZLA	Los Angeles Center

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