Design and Evaluation of a Corridors-in-the-sky Concept: The Benefits and Feasibility of Adding Highly Structured Routes to a Mixed Equipage Environment

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A human-in-the-loop simulation of a Corridors-in-the-sky concept was conducted that focused on investigating the potential benefits and feasibility of the concept with human operators in a realistic environment. In this simulation, the definition of "corridors" was changed from meaning *separate corridor airspace with dedicated corridor controllers* to *highly structured routes with potentially common speeds and avionics equipage*. The change in definition allowed the concept to be realizable within the mid-term Next Generation Air Transportation System (NextGen) timeframe and mitigated many of the feasibility issues that were identified in earlier research. Feasibility and benefits were tested through the variance of traffic levels within the test airspace (High and Max). In the High Traffic condition, the radar (R-side) and supporting data (D-side) controllers managed a high level of traffic without aircraft being rerouted out of the congested sectors. In the Max Traffic condition, a traffic flow manager and area supervisors worked together to reroute aircraft out of the congested sectors. Four different procedures were tested with different corridor structures: (1) no specific corridors (No Corridors), (2) only equipped aircraft within corridors (Equipped in Corridors), (3) only unequipped aircraft within corridors (Unequipped in Corridors), and (4) a mix of both equipped and unequipped aircraft within corridors (Mixed in Corridors). Surrounding non-corridor traffic consisted of a 50/50 mix of Data Comm and non-Data Comm equipped aircraft in all conditions. The results of the study indicate that the Equipped in Corridors condition showed the greatest benefits with the highest levels of throughput and the lowest reported workload relative to the other conditions. In contrast, the Unequipped in Corridors condition showed little throughput or workload benefits relative to the No Corridors condition. The results for the Mixed in Corridors condition fell in between the values observed for Equipped in Corridors and No Corridors. Feedback from the participants revealed that the observed reduction in benefits when unequipped aircraft were in the corridors was a result of the workload associated with the communications and monitoring required for the unequipped corridor aircraft as well as the display clutter of their data blocks. In addition, the study showed that the concept was feasible and was well received by the participants. Service for equipage was also shown to be feasible with fewer Data Comm equipped aircraft rerouted than non-Data Comm equipped aircraft.

Nomenclature

ADS-B	=	automatic dependent surveillance-broadcast
AOL	=	airspace operations laboratory

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DAC = dynamic airspace configuration
FL = flight level
FMS = flight management system
HITL = human-in-the-loop
LOS = loss of separation
MACS = multi aircraft control system
NAS = national airspace system
RNAV = area navigation
TMC = traffic management coordinator
ZOB = cleveland air route traffic control center

I. Introduction

THE transition from today's National Airspace System (NAS) to the Next Generation Air Transportation System (NextGen) will require changes to the current model of air traffic control and management in order to accommodate greater demand on the airspace as well as a more varied mixture of aircraft and equipage. While previous human-in-the-loop (HITL) simulations have shown that mixed equipage operations in non-segregated airspace are feasible,[1,2] the current control paradigm limits sector throughput and creates traffic bottlenecks. In recognition of this fact, a number of concepts have been developed to address and mitigate these challenges.

The Corridors-in-the-sky concept (referred to as the Corridors concept hereafter) was developed as a means of providing greater capacity and efficiency through the introduction of specialized airspace structures. These structures have taken many different forms across various research efforts ranging from intricate networks of tubes linking airport clusters or enveloping particular traffic flows, to parallel multi-track airways, and specialized airspace structures that overlay existing jet routes.[3-6] Regardless of the design, the common thread between the different approaches is that they are intended to accommodate high levels of traffic consisting of highly equipped aircraft (e.g., data communications (Data Comm), self-separation capability, etc.). To allow for heightened levels of traffic density within these corridor structures, they have often been conceptualized as being segregated or exclusive airspace with their own set of requirements for occupancy and associated procedures.

To date, research into the Corridors concept has been conducted almost exclusively through fast-time modeling to assess the potential benefits and feasibility of introducing such airspace structures into the NAS. However, the results have been mixed.[7-9] While potential benefits in efficiency and throughput have been shown as a result of structuring traffic flows within corridors, they were often negated by the inefficiencies associated with the procedures and requirements for entering and exiting the corridor structures. There were also feasibility issues related to the interactions between the corridor and surrounding non-corridor airspace. The results suggested that the need to route non-corridor aircraft around corridor airspace would result in greater complexity and difficulty for the controllers, and inefficiencies for the rerouted aircraft.

II. Objective

While fast-time modeling is a useful and powerful research tool, its capabilities can be limited in scope and cannot account for the complexity inherent in an environment in which air traffic controllers are tasked with operating in the presence of corridor structures and surrounding traffic. Additionally, based on the mixed findings of the larger body of prior research, an alternative definition of a corridor was formulated to simply mean a highly structured route with potentially common speeds, altitudes, and avionics equipage rather than the prevailing notion of separate corridor airspace with dedicated corridor controllers. The elimination of the constraints associated with segregated, exclusive corridor airspace was intended to mitigate many of the feasibility issues identified previously. In order to test this approach to the Corridors concept in an operationally relevant environment, a human-in-the-loop simulation was conducted in the Airspace Operations Laboratory (AOL)[10] at the NASA Ames Research Center from July 11th to 22nd, 2011. This paper describes the simulation and presents results related to the benefits and feasibility of introducing corridor structures into a dynamic and complex environment.

The questions that guided this research effort were threefold and were meant to address the feasibility and benefits of the Corridors concept while incorporating the additional issue of mixed equipage operations within the same en route airspace. These research questions are as follows:

1. Can corridors be used to add more aircraft to busy sectors?
2. What is the best procedure for a given mixture of aircraft equipage?

3. What is the impact of each procedure on sector throughput and flight efficiency inside and outside the corridors?

III. Method

The following sections describe how the simulation was designed and executed in response to the research questions. This is followed by a presentation and discussion of the results.

A. Participants

Thirteen recently retired air traffic controllers from Oakland Center participated in this simulation. Of those, one staffed a Traffic Management Coordinator (TMC) position, two staffed Area Supervisor positions, five staffed R-side positions, three staffed on-demand D-side positions, and the remaining two staffed supporting confederate controller positions. Seven simulation pilot stations were staffed by general aviation students and pilots.

B. Experimental Design

This simulation was a within-subjects design that examined two variables: Traffic Levels and Corridors (Figure 1). The *Traffic Levels* variable consisted of two primary levels (*High* and *Max*). The *High Traffic* level was designed to allow for a comparison of the relative workload associated with each of the Corridors conditions. The traffic included peak loads that were slightly above the level that controllers could handle without active corridors. This level of traffic was established through evaluations in the laboratory prior to the simulation. The *Max Traffic* level included peak traffic loads that were well beyond the limits of operability without active corridors. By including such high levels of traffic, relative peak throughput was able to be determined across the Corridors conditions

The *Corridors* variable consisted of four levels (*No Corridors, Unequipped in Corridors*, *Mixed in Corridors*, and *Equipped in Corridors*). The *No Corridors* level served as a baseline condition in which active corridors were not in place and the traffic was structured more closely to what is observed today. The *Unequipped in Corridors* level included active corridors that accommodated non-Data Comm equipped aircraft exclusively. The *Mixed in Corridors* level included active corridors with a mix of approximately 50% equipped and unequipped aircraft on corridors. The *Equipped in Corridors* level included active corridors occupied by Data Comm equipped aircraft exclusively. Varying the composition of corridor traffic across the conditions with active corridors provided the means in which to investigate the interactions between equipage and airspace structure and how it impacts workload and throughput as a result.

In the *High Traffic* level, the overall equipage mix within the test airspace was approximately 50% Data Comm equipped and 50% unequipped, regardless of the Corridors condition. In the *Max Traffic* level, the equipage mix of non-corridor traffic at this level was 50/50, but the overall mixture ratio shifted according to the associated Corridors condition (e.g., greater number of equipped aircraft in the Equipped in Corridors condition, greater number of unequipped aircraft in the Unequipped in Corridors condition, etc.).

A Max Extended Traffic condition was added as an extension to the main study as a follow-up “mini-study”. The objective of this mini-study study was to control for potential confounds related to corridors and equipage that could have resulted from different equipage ratios in the Max condition. Specifically, the Equipped in Corridors condition at the Max Traffic levels resulted in an equipage mix of 70% Data Comm vs. 30% non-Data Comm equipped aircraft, compared to the No Corridors condition that had a 50/50 equipage mix. Therefore it was unclear whether the results observed in the Equipped in Corridors condition were due to the higher overall equipage ratio (i.e., greater number of equipped aircraft) or due to the presence of corridors. The Max Extended traffic level held the overall ratio of equipped and unequipped aircraft constant at 70% and 30% respectively for both No Corridors and Equipped in Corridors conditions. The No Corridors and Equipped in Corridors conditions were then run with this equipage ratio to isolate the effect of the presence of corridors from that of equipage.

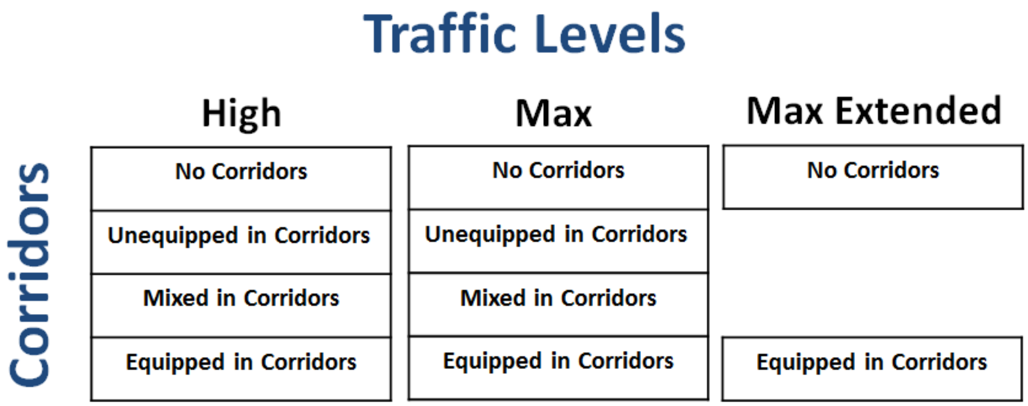


Figure 1. Experimental design consisting of the Traffic Levels and Corridors variables.

C. Airspace

The Cleveland Air Route Traffic Control Center (ZOB) was selected as the test airspace for this simulation due to the known complexity of traffic in the region and the relevance of such an environment to the Corridors concept. Five adjacent sectors were selected from ZOB to serve as test positions, and were further assigned to two areas of specialization (Figure 2). The North Area consisted of sectors 26, 38, and 79. The South Area consisted of sectors 49 and 59. The floor of the test airspace was set at flight level (FL) 330 and above. All areas outside of the test sectors at FL 330 and above were assigned to a confederate "ghost" high position, and the airspace below FL 330 was assigned to a confederate "ghost" low position. The ghost positions handled the aircraft that were entering or exiting the test sectors.

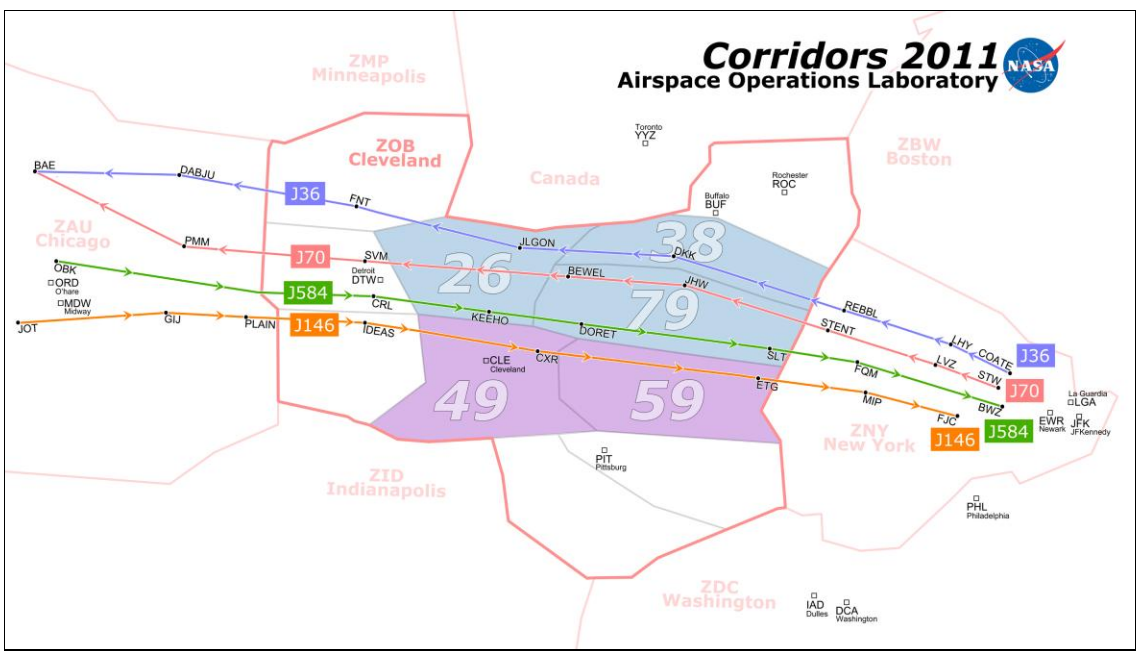


Figure 2. Test airspace and surrounding areas. Note the North (ZOB 26, 38, and 79) and South (ZOB 49 and 59) Areas overlaid with the four corridors.

D. Corridor Structure

Four corridors were selected in this simulation that leveraged existing jet routes in the NAS (see Figure 2). Each corridor was assigned a unique set of speed, altitude, and/or destination requirements. The corridors each accommodated two streams of traffic stacked vertically with 4000 feet of separation. On the J36 corridor, westbound traffic at FL 360 was assigned a speed of Mach (M) 0.75, while those at FL 400 were assigned a speed of M 0.77. Westbound traffic on the J70 corridor flew at FL 360 with an assigned speed of M 0.79, or at FL 400 with an assigned speed of M 0.82. To the South, eastbound traffic on the J584 corridor destined for JFK or EWR flew at FL 350 with an assigned speed of M 0.77. The remaining J584 corridor traffic flew at FL 390 with an assigned speed of M 0.82. Eastbound traffic on the J146 corridor destined for LGA or PHL flew at FL 350 with an assigned speed of M 0.77, and the remaining J146 traffic was at FL 390 with an assigned speed of M 0.77. These speeds were selected through a sampling of typical aircraft speeds at these altitudes and with subject matter expert input.

E. Apparatus

As shown in Figure 3, the North and South Areas were assigned to separate rooms, which required any communications between the two to be conducted via voice or data communications. The apparatus for the North Area consisted of three R-side stations, each flanked by a D-side station. The R- and D-side workstations were set up nearly identically, and were synced with each other such that certain actions on one station (e.g., moving a data block) were reflected in real-time on the other. The Area Supervisor stations included a tool suite used for traffic assessment and flow management. In each area, traffic load predictions for each sector, in addition to an expanded Traffic Situation Display, were projected onto the wall for greater situation awareness and informed decision-making. The TMC station was positioned outside of both areas. This position included a tool suite similar to the Area Supervisors', but was tailored to display and assess a larger portion of the overall airspace.[11,12] Seven pilot stations were used with each one mapped to a test or confederate sector position. Each station provided the pilot with a list of aircraft assigned to the sector of ownership and associated flight decks for each aircraft. The simulation software used was the Multi Aircraft Control System (MACS).[13] MACS is a Java program that was developed by the AOL and is used for all its real-time simulation and rapid prototyping activities. All of the stations used in the simulation were Windows PCs and were networked together to share real time, common data references.

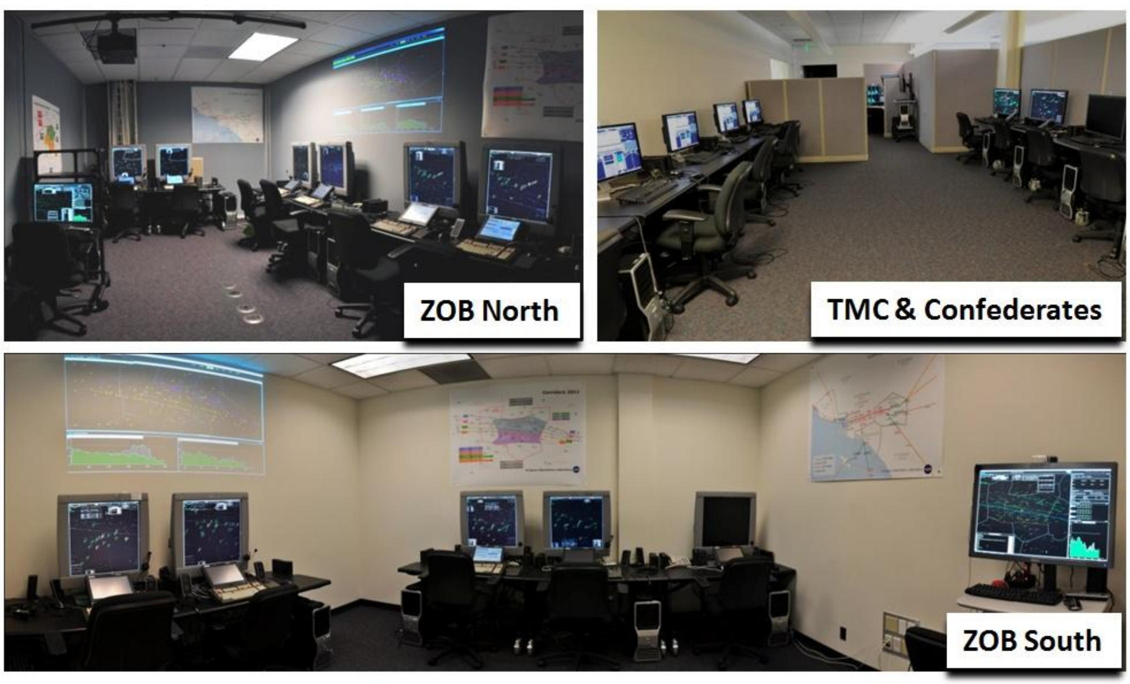


Figure 3. Laboratory setup for each test and confederate area.

F. Operational Environment

All aircraft in the simulation were equipped with Flight Management Systems (FMS), Automatic Dependent Surveillance-Broadcast (ADS-B), and were Area Navigation (RNAV) capable. At the sector level, voice communications were available at all times between controllers and pilots. Conflict detection automation was active and resolution support was available. For Data Comm equipped aircraft, clearances were sent either via data communications and auto-loaded into the FMS, or via voice in which the pilot manually performed the required changes. Handoffs and transfers of communication for Data Comm equipped aircraft were automated and did not require controller involvement. For unequipped aircraft, clearances were only sent via voice and were typically followed by controller actions to update the system accordingly. Handoff initiations were automated, but acceptance and transfer of communications were performed manually by the controller.

The aircraft targets and data blocks were displayed differently based on their equipage and their status as corridors vs. non-corridors traffic. Non-corridor traffic within the test sectors were displayed with full data blocks and were collapsible only after being handed off and exiting the sector. Equipped aircraft were displayed in green while unequipped aircraft were displayed in yellow (see Figure 4). For aircraft in the corridors, data blocks regardless of equipage were collapsible at any time. By default, equipped aircraft in the corridors were displayed with minimized data blocks. The data blocks of unequipped aircraft in the corridors popped up when in hand off status. The colors used for corridors traffic were muted variants of the green and yellow used to denote the equipage of non-corridor traffic. Additional information was also included in the data blocks of corridor traffic that indicated time to entry or exit of corridors, and the assigned corridor for entering traffic.

Area Supervisors and the TMC stations were equipped with interactive traffic load graphs and tables for traffic assessment and Flow Based Trajectory Management tools for trial planning and rerouting traffic. Trajectory change proposals were communicated via ground-ground data communications and typically accompanied by voice communications.

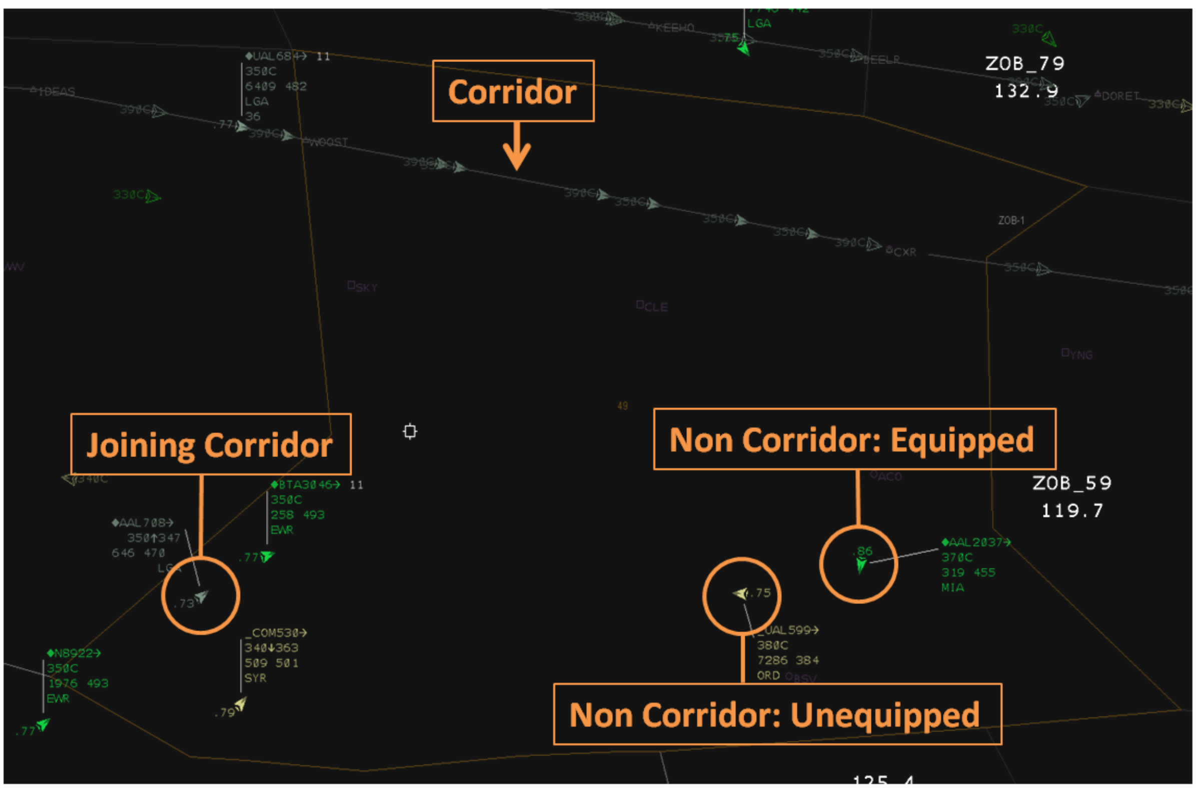


Figure 4. Controller display with active corridors and surrounding mixed equipage traffic.

G. Procedure

Beginning in April and leading up to the simulation in June, weekly shakedowns and discussions with controller participants were conducted. These trials helped shape and inform the final design of the simulation. A subject matter expert from ZOB also participated in preparations and provided valuable input as to the requirements and procedures for the tested areas.

Prior to the onset of the simulation, the participants underwent 1.5 days of formal training to ensure their familiarity with the concept, tools, and procedures. Following this initial training period, the formal data collection runs commenced. A total of 36, one-hour runs were conducted over the course of two weeks. The first 32 consisted of alternating High and Max Traffic runs with the four Corridors conditions counterbalanced throughout to avoid potential confounds. The final four runs were devoted to the Max Extended runs of the follow-up mini-study, in which relative equipage mixtures were held constant for both No Corridors and Equipped in Corridors conditions across the Max Traffic level.

Upon commencement of the High Traffic runs, only the five R-sides and two Area Supervisor positions were staffed. The traffic scenarios were designed to place maximum stress on the test airspace without exceeding the threshold of operability. Accordingly, traffic reroutes to alleviate sector loads were not allowed and the TMC position was not staffed. The Area Supervisors were able to provide support to the R-sides by selectively introducing the D-sides prior to and during periods of heightened traffic and/or complexity. For the ZOB North area, there was one D-side available for the three R-side positions. This individual typically cycled through the positions at different times to assist with the tasks defined by the R-sides. The ZOB South area had two D-sides available for the two R-side positions. When not on position, the D-sides awaited their assignments in a nearby common area that was easily accessible from both areas.

For the Max Traffic runs, the scenarios were designed to exceed the limits of R- and D-side workability, particularly in the No Corridors condition. While staffing assignments in the areas were identical to the High Traffic runs, the notable difference was that the TMC was on position. Due to the fact that the traffic was designed to be so challenging, the two Area Supervisors and the TMC planned reroutes of traffic to reduce sector loads and complexity. These actions were coordinated via voice and ground-ground Data Comm. The supervisors were advised to only reroute aircraft after putting the D-sides on position or accounting for the D-sides' contributions to workload reduction. The procedures for the Max Extended runs were identical to those of the Max Traffic runs.

Participants were asked to give priority to traffic in the corridors (in relevant conditions) and also to provide service for equipage (i.e., preference for equipped aircraft to maintain their user-preferred trajectory) workload and safety permitting. This also applied to the rerouting of traffic in cases where the Supervisors and TMC were asked to consider rerouting unequipped aircraft first, followed by equipped and corridors traffic when able. Departures from area airports were given temporary altitudes of FL 320 (just below the FL 330 floor of the test airspace), and the participants were advised to approve their climbs through the corridors if and when able. For arrivals to area airports, the southern sectors attempted to descend arrivals to the northern airports (e.g., Montreal, Buffalo, and Syracuse) prior to their entry into the northern sectors. This was done to reduce the added complexity of aircraft transitioning through corridor structures in Corridor conditions, or to avoid the need for tactical maneuvers in accommodating their descents upstream. Similarly, eastern sectors attempted to descend area arrivals to the west (e.g., Cleveland and Detroit) prior to their entry to the western test sectors.

Throughout each run, aural and visual workload prompts were presented at each station's display at three-minute intervals. This, along with aircraft trajectory and controller/pilot event data, was recorded through MACS' data collection processes. Screen and voice recordings were also collected for each run at each station. Following each run, the participants were presented with an online questionnaire to fill out. A final, more comprehensive questionnaire was presented to the participants following the conclusion of the final data collection run. This was followed by a debrief discussion between the participants and researchers.

IV. Results

One of the primary objectives of this study was to assess the benefits and feasibility of implementing corridor structures and operations as part of the Corridors concept. The following results will pertain to the benefits and feasibility as observed in each of the conditions tested. Results for the High and Max Traffic levels will be presented first followed by those for the Max Extended runs.

A. Benefits

For the assessment of benefits provided by the Corridors concept and associated operations, capacity was analyzed in terms of aircraft count, reroutes performed, and service for equipage. The results for this section only relate to the Max Traffic level runs due to the fact that reroutes were not permitted in the High Traffic runs, and therefore the throughput was identical across Corridors conditions. The hypothesis leading into the simulation and resulting analyses was that corridors operations would serve to increase throughput with higher numbers of aircraft in the test area and fewer reroutes required relative to operations without corridors.

1. Aircraft Count

The first capacity metric analyzed was aircraft count where the number of unique aircraft that entered each test sector per run was summed and averaged across conditions. As shown in Figure 5, according to this metric, the greatest numbers of aircraft allowed into the test airspace were in the Equipped in Corridors (EIC) condition (*M*= 111.40, *SD*= 16.42) followed by the Mixed in Corridors (MIC) condition (*M*= 110.10, *SD*= 16.42), Unequipped in Corridors (UIC) condition (*M*= 104.10, *SD*= 16.17), and the No Corridors (NC) condition with the lowest relative aircraft count (*M*= 102.30, *SD*= 15.50). A one way, repeated measures ANOVA revealed that the differences between conditions was significant ($F(3, 9)= 62.00$, $p< .0001$). Post-hoc contrasts showed that the Equipped and Mixed in Corridors conditions accommodated significantly more aircraft than the No Corridors and Unequipped in Corridors conditions, but did not differ significantly from each other.

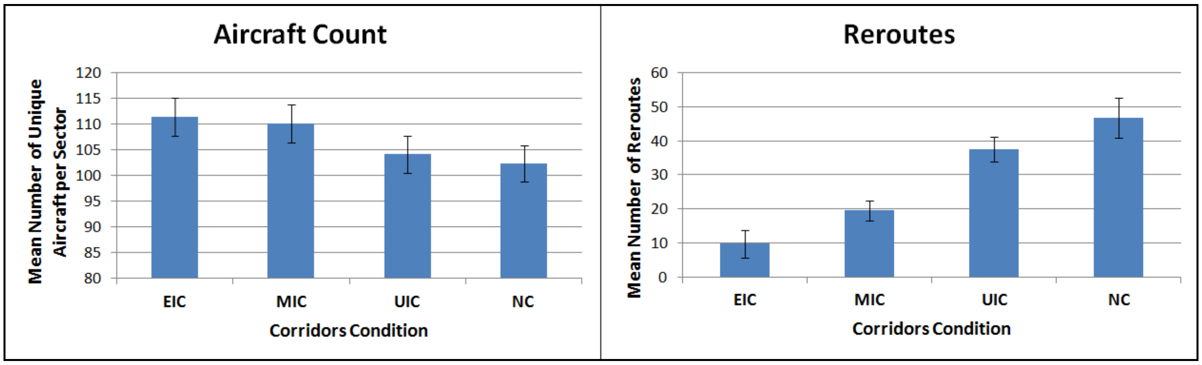


Figure 5. Throughput results in terms of the number of aircraft that transited the test airspace and the number of reroutes performed in the Max Traffic conditions.

2. Reroutes

The number of reroutes to avoid the test airspace by the Area Supervisors and TMC was analyzed in order to understand to what extent each of the conditions required capacity reductions. As shown in Figure 5, these results confirm those for aircraft count in that the fewest reroutes were performed in the Equipped in Corridors condition (*M*= 9.75, *SD*= 7.93), followed by the Mixed in Corridors condition (*M*= 19.50, *SD*= 5.80), Unequipped in Corridors (*M*= 37.50, *SD*= 7.05), and the No Corridors condition with the greatest number of reroutes performed (*M*= 46.75, *SD*= 11.50). A chi-square test of goodness-of-fit confirmed that the number of reroutes performed were not equal between the Corridors conditions ($X^2(3, N = 16)= 119.34$, $p< .001$).

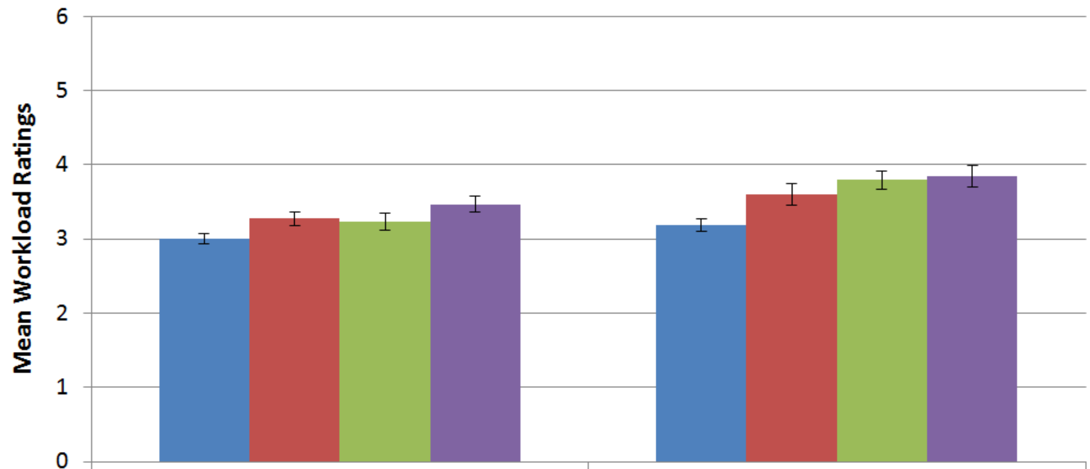
With regard to the ability to provide service-for-equipage in the performance of reroutes, of the total 455 reroutes performed by the Area Supervisors and TMC in the Max Traffic runs, 350 were for unequipped aircraft and 105 were for equipped aircraft. From these results, it is clear that reroutes could be performed selectively to not only provide maximum throughput while minimizing workload, but to also provide greatest access to the airspace for equipped aircraft.

B. Feasibility

To address the feasibility of the Corridors concept in an operationally relevant environment, the metrics of workload and safety were selected. Workload was selected as a means of evaluating the impact of corridors operations on the ability of controllers to manage their sectors within acceptable limits and the role that aircraft equipage played. Safety was selected as a means to examine whether operations as part of the Corridors concept had an adverse impact on the ability of controllers to maintain the safe separation of aircraft.

1. Workload

Throughout the course of each run, workload prompts were presented to the participants at three-minute intervals through an integrated workload assessment keypad. The scale ranged from one to six, and the participants were instructed to rate their workload as “Low”, “Medium”, and “High” across the scale as 1-2, 3-4, and 5-6, respectively. Figure 6 presents the results of an analysis performed on the R-side workload data. A repeated measures Analysis of Variance (ANOVA) was performed across the Corridors conditions and the Traffic Levels where results showed that the Corridors conditions and Traffic Levels were significantly different from each other ($F(3,57) = 13.42$, $p < 0.001$ for Corridors; $F(1,19) = 27.86$, $p< 0.001$ for Traffic Levels). For the High Traffic level runs, planned contrasts showed that the Equipped in Corridors condition resulted in significantly lower workload when compared to the Mixed in Corridors (Bonferroni $t(19) = 3.11$, $p < 0.006$, $p_{crit} = 0.00833$) and No Corridors conditions (Bonferroni $t(19) = 4.20$, $p < 0.001$, $p_{crit} = 0.00833$). For the Max Traffic level runs, planned contrasts showed that the Equipped in Corridors condition resulted in significantly lower workload when compared with all other Corridors conditions (Equipped vs. Mixed: Bonferroni $t(19) = 3.91$, $p < 0.001$, $p_{crit} = 0.00833$; Equipped vs. Unequipped: Bonferroni $t(19) = 6.37$, $p < 0.001$; Equipped vs. No Corridor: Bonferroni $t(19) = 5.48$, $p < 0.001$). Neither Mixed nor Unequipped in Corridors resulted in significantly lower workload when compared to No Corridors or to each other.



	High Traffic	Max Traffic
EIC	3.01 *(0.31)*	3.19 *(0.38)*
MIC	3.28 *(0.41)*	3.60 *(0.63)*
UIC	3.23 *(0.49)*	3.79 *(0.58)*
NC	3.47 *(0.50)*	3.84 *(0.64)*

Figure 6. Mean R-side workload ratings in the High and Max Traffic conditions. Standard deviation is presented in parentheses.

2. Safety

An examination was performed of the loss of separation (LOS) events that were recorded during the simulation. An event was categorized as a LOS under the following criteria: 1) the event lasted longer than 12 consecutive seconds (equal to the duration of one update cycle of today's en route radar display); 2) it occurred following the first five minutes of the simulation start time; 3) ghost controller or pilot errors did not unfairly precipitate the event; and 4) the involved aircraft were both under ownership of one or more test participants at the initial LOS. According to these criteria, a total of two LOS events (one in the No Corridors and one in the Unequipped in Corridors condition) occurred across the 32 runs. The results of this examination showed that the levels of safety were not compromised at the expense of operations in this complex environment.

V. Follow-on Results (Max Extended)

Potential confounds in the initial design of the experiment related to the different equipage ratios in the Max Traffic condition were addressed in a follow-up study. The composition of traffic was such that the Equipped in Corridors condition had a greater overall number of equipped aircraft in the test airspace relative to any of the other conditions. This raised the question of whether the observed results from the Equipped in Corridors condition were due to the higher numbers of equipped aircraft or if they were attributable to the presence of corridors. To address this concern, a Max Extended condition was designed to compare the No Corridors condition to the Equipped in Corridors condition. The overall equipage ratios of the equipped and unequipped aircraft were held constant at 70% and 30% respectively across both conditions.

A total of four runs were conducted, two per No Corridors and Equipped in Corridors conditions. Figure 7 shows the mean aircraft counts during the Max Extended runs broken down by equipage contributions for each of the conditions. Although the absolute numbers are different due to reroutes, it can be seen that the equipage ratios remained true to the 70/30 target. This removes the uncertainty related to uneven equipage ratios between conditions and thus allows for a more equivalent comparison. The following results focus on the benefits and feasibility of the Corridors for the Max Extended runs.

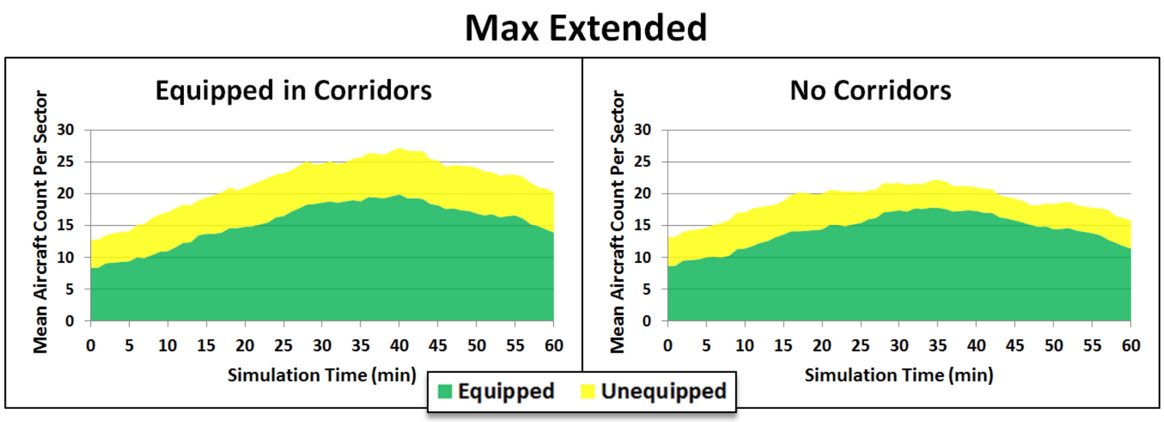


Figure 7. Mean aircraft counts per sector with equipage contributions in the Max Extended conditions.

A. Benefits

1. Aircraft Count

The total number of aircraft that entered each test sector during the Max Extended runs was averaged for each Corridors condition. The left panel of Figure 8 shows that the Equipped in Corridors (EIC) condition had a greater mean number of aircraft transiting the test sectors (M= 121.30, SD= 16.77) than the No Corridors (NC) condition (M= 105.80, SD= 15.75). A pair-wise comparison showed a significant difference between the means ($t(9)$= 7.72, p< .001), indicating that the Equipped in Corridors condition enabled higher throughput than the No Corridors condition.

2. Reroutes

The right panel of Figure 8 presents the mean number of reroutes performed in each condition of the Max Extended runs. Results from this analysis showed that fewer reroutes were performed in the Equipped in Corridors condition (M= 24.0, SD= 7.07) than in the No Corridors condition (M= 67.0, SD= 4.24). A chi-square test of goodness-of-fit confirmed that the number of reroutes performed were not equal between the Corridors conditions ($X^2(1, N = 4)$= 40.64, p< .001), suggesting again that operations with corridors enabled higher levels of throughput than operations without corridors.

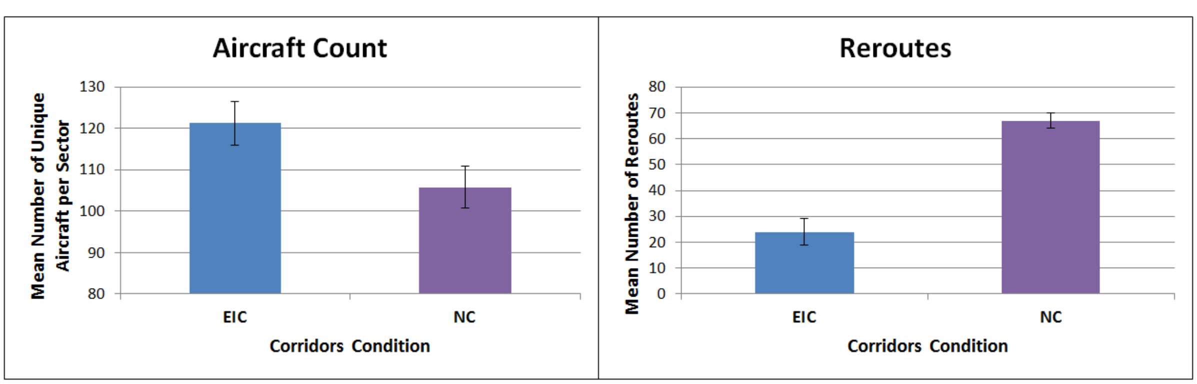


Figure 8. Throughput results for the Max Extended runs in terms of mean aircraft count per test sector (left panel) and mean number of reroutes issued (right panel).

B. Feasibility

1. Workload

The workload ratings for the Max Extended runs were averaged across each condition per test sector. Figure 9 shows the mean workload ratings for the Equipped in Corridors (EIC) (M= 3.36, SD= 0.50) and No Corridors (NC) conditions (M= 3.39, SD= 0.22) where the differences were very small. A pairwise comparison of the means confirmed a null difference ($t(9) = 0.18$, $p > 0.8$).

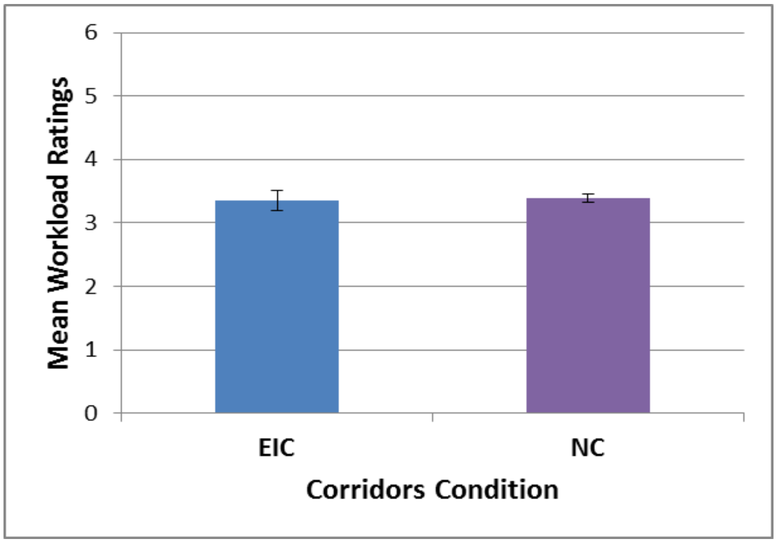


Figure 9. Mean R-side workload ratings in the Max Extended conditions.

2. Safety

The Max Extended runs revealed one case that was classified as a LOS, occurring in the Equipped in Corridors condition. In the post-run questionnaire, the involved participant commented on the events leading up to the LOS as follows: "too many [aircraft] were trying to enter the corridor," and that the controllers were "busy making sure [the corridor aircraft's] speeds were working and seeing why their data blocks were popping up (which was largely due to conflicts involving corridor aircraft). This caused data block overload." The situation preceding and during the LOS resulted in high and maximum workload ratings from the participant suggesting that they had exceeded their level of operational control. It is also worth pointing out that the participant owned approximately 20 aircraft at the time of LOS. Although it is difficult to fully attribute this event to the corridor structure and related operations, it does highlight the importance of being able to balance structure, capacity, and flexibility.

C. Participant Feedback

Subjective feedback from the participants was obtained through post-run and post-simulation questionnaires as well as a simulation debrief discussion. These opportunities allowed the researchers to gain insight to the feasibility and benefits of the Corridors concept from the controllers' perspective. With regard to feasibility, perhaps one participants' response summed up the overall view with the statement, "I think it is very feasible." However, there were some qualifications and suggestions for improvement. Some participants felt that the corridors essentially shrunk the available airspace, which increased the overall sector complexity. Some participants suggested increasing the lateral separation between the corridors as well as the sector boundaries in order to provide greater maneuvering space and reduce some of the complexity related to crossing traffic.

In terms of benefits, participants unanimously reported an overall system benefit from corridors, which "greatly enhanced the throughput" and allowed them to "handle the non-corridor traffic more effectively." However, as with the objective throughput results, a central theme emerged regarding the relationship between corridor aircraft equipage and the potential benefits. Controllers almost unanimously stated that equipped aircraft in the corridors reduced complexity and workload because they did not need to perform handoffs as they did with the unequipped aircraft, and they felt comfortable in keeping the data blocks of equipped aircraft collapsed as a result. By removing the need to communicate with the equipped corridor traffic and having them "procedurally separated," display clutter and taskload was reduced, which allowed greater throughput. The introduction of unequipped aircraft in the corridors in the Mixed and Unequipped in Corridor conditions incrementally degraded the perceived benefit of corridor operations as a result of the increased workload that resulted from the required communications and display clutter as well as the increased demands of vectoring via voice in support of separation and corridor merging efforts.

Perhaps one participant's comments best summarized the feasibility and benefit discussion of the Corridors concept with the following: The "advantages [of corridors] are that you can increase throughput and the ability to reduce data blocks if equipped aircraft are in the corridors…" The "disadvantages are that there is less distance for [non-corridor] aircraft to maneuver in, and that the addition of corridors results in a more structured and less flexible airspace."

VI. Discussion

Through the results presented here, it is apparent that the Corridors concept as it was tested in this simulation was feasible and provided benefits. With respect to feasibility, workload was found to be manageable and consistently lower in operations with active corridors than in those without. Corridors operations also did not compromise safety. In terms of benefits, operations with corridors enabled higher rates of throughput and required fewer numbers of aircraft to be rerouted. Service for equipage was also shown to be possible in this environment.

The results from the Max Extended runs served to remove the uncertainty regarding whether the observed benefits of corridors, particularly in the Equipped in Corridors condition, were simply due to more equipped aircraft in the test airspace, or if the corridors and associated operational environment were the enabling factors. While holding the equipage ratios constant between the Equipped in Corridors and No Corridors conditions, the Corridors concept appeared feasible with equivalent workload to the No Corridors environment. The benefits in terms of significantly higher levels of throughput and fewer required reroutes were again observed as with the preceding results.

When the different corridors conditions were compared to each other, clear and consistent benefits occurred when Data Comm equipage was combined with the corridors structure. There was a strong relationship between the number of equipped aircraft in the corridors and the capacity and workload benefits that were realized. Workload was lowest and throughput was highest for the Equipped in Corridors condition with benefits diminishing as a function of the reduction in number of equipped aircraft in the corridors. While the Mixed in Corridors condition did provide similar levels of throughput, the unequipped aircraft sharing the corridors resulted in higher levels of workload. Finally, the Unequipped in Corridors condition resulted in lower levels of throughput and higher workload than the other corridor conditions.

Feedback from the participants provided valuable insight and corroborated the results regarding the interaction between aircraft equipage and the benefits of corridors. The Equipped in Corridor condition significantly reduced workload by requiring minimal attention for the Data Comm equipped corridor traffic. The reduced workload thus freed the controllers to concentrate on the surrounding traffic and increased the total number of aircraft that they could handle. The introduction of unequipped aircraft to the corridors reduced the observed benefits in Mixed and Unequipped in Corridor conditions because unequipped aircraft required manual handoffs and transfer of communications, which meant that controllers needed to pay more attention to these aircraft. In other words, the task load of making manual handoffs served as a disruption to the workflow of the controller that did not exist with only equipped aircraft in the corridors.

VII. Conclusion

This simulation investigated an approach to the Corridors concept through human-in-the-loop testing in an operationally relevant setting. The results show that this version of the concept can provide increased throughput in a mixed equipage environment if predominantly Data Comm equipped aircraft use the corridors. However, if the concept is to move forward, further investigation is needed to more fully understand the usefulness of corridors operations under different airspace types, traffic conditions, and weather-related congestion.

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