# A Human-in-the Loop Exploration of the Dynamic Airspace Configuration Concept

Jeffrey Homola[1], Paul U. Lee[2], Thomas Prevôt [3],
Hwasoo Lee[1], Angela Kessell[2], and Connie Brasil[1]
*San Jose State University, San Jose, CA, 95192*

Nancy Smith[4]
*NASA Ames Research Center, Moffett Field, CA, 94035*

**An exploratory human-in-the-loop study was conducted to better understand the implications of the Dynamic Airspace Configuration (DAC) concept. Three progressively more aggressive algorithmic approaches to airspace sectorization were selected to test and quantify the range of impact on the controller and sector operations. Results show that traffic count was more equitably distributed between the four test sectors and the duration of excessive aircraft counts was progressively lower as the aggressiveness of sectorization increased. However, taskload and workload were also shown to increase with the increase in aggressiveness while the acceptability of the boundary changes decreased. Overall, simulated operations of the DAC concept did not appear to compromise safety. Feedback from the participants highlighted the importance of limiting some aspects of boundary changes such as amount of volume gained or lost and the extent of change relative to the initial airspace design.**

## Nomenclature

| | | |
|---|---|---|
| *ATC* | = | Air traffic control |
| *DAC* | = | Dynamic Airspace Configuration |
| *DAU* | = | Dynamic Airspace Unit |
| *DFPA* | = | Dynamic Fix Posting Area |
| *DSR* | = | Display System Replacement |
| *FAA* | = | Federal Aviation Administration |
| *FPA* | = | Fix Posting Area |
| *JPDO* | = | Joint Planning and Development Office |
| *MACS* | = | Multi-Aircraft Control System |
| *MIP* | = | Mixed Integer Programming |
| *NAS* | = | National Airspace System |
| *NASA* | = | National Aeronautics and Space Administration |
| *NextGen* | = | Next Generation Air Transportation System |
| *RNAV* | = | Area navigation |
| *RNP* | = | Required Navigation Performance |
| *TMU* | = | Traffic Management Unit |

[1] Research Associate.
[2] Senior Research Associate.
[3] Senior Research Engineer.
[4] Senior Research Psychologist, Human-Systems Integration Division, NASA ARC, MS 262-4.

## I. Introduction

In the current National Airspace System (NAS), one of the primary goals and functions of air traffic management resides in allocating and maintaining the balance between air traffic demand and the current and predicted airspace capacity. This is done through a collaborative process involving the various operators among the air traffic organizations (e.g., Command Center, Traffic Management Units (TMU), En route, Terminal Radar Approach Control, and Tower facilities). If the current or forecast demand is expected to exceed capacity due to situations such as convective weather, special events, or controller workload, then a variety of methods are available for use in addressing the demand-capacity imbalance. Some of these methods include enacting traffic management initiatives that involve placing certain aircraft in miles-in-trail or on playbook routes, rerouting aircraft outside of particular sectors or areas, and implementing a ground stop or ground delay programs. While necessary, one common criticism of these traffic management methods is that they are often overarching in their scope and consequently introduce unnecessary and excessive inefficiencies into the system. This problem will likely be compounded if the current Federal Aviation Administration (FAA) predictions for a threefold increase in traffic in the near future hold true.[1]

To address these issues and develop viable alternatives, a number of research efforts and concept developments have been aimed at finding ways of reducing controller workload while being able to provide greater efficiency within the system. One area of research referred to as the Multi Sector Planner (MSP) examines the functionality necessary to allow for the planning and operating on a level that is more tactical than the TMU while simultaneously working more strategically than the Area Supervisor and the floor.[2-4] The potential benefit for such functionality could be more responsive and dynamic traffic management that would allow for greater efficiencies relative to current management methods as well as reduced impact to system users and a better distribution of workload and resources at the sector level. However, the actions of such a position still require aircraft and flows to be moved in response to demand-capacity imbalances.

An alternative to this approach is instead to look at ways of designing the airspace such that capacity can be reallocated to meet demand. This relatively recent area of research is referred to as Dynamic Airspace Configuration (DAC), which encompasses three focus areas: restructuring airspace, generic airspace, and adaptable airspace.[5]

This paper will focus on the adaptable airspace area of DAC research listed above. Adaptable airspace relates to the ability to dynamically change airspace sectorization in response to a demand-capacity imbalance without the need for altering aircraft trajectories. Dynamic sectorization would change the geometry of affected sectors to adapt to a given traffic situation and would serve to more equitably distribute the demand placed on a given airspace as well as the workload that would accompany that demand without the need for impacting the airspace users.

Traditional sector geometry has been designed to take into account the relationship between traffic pattern characteristics and their effect on workload for the controller assigned to that airspace. In current day operations, sectors can be split or combined to resolve the demand-capacity imbalances depending on the needs of the situation. However, these responses typically have a limited set of options from which to choose from.[6] In the Next Generation Air Transportation System (NextGen), the adaptable airspace concept would allow for more strategic planning for the best sector geometries available based on real-time predictions and analyses.

To that end, the formulation of optimal sectorizations has been an area of concerted effort through the development and testing of the algorithms. A number of algorithms are in development and refinement, each with a differing approach to dynamic sectorization using different input metrics and goals to inform the calculations. A good overview and comparison of some of these algorithms can be found in Zelinski's, "A Comparison of Algorithm Generated Sectorizations."[7] Over the years, airspace sectorization algorithms have been tested extensively through an iterative fast-time modeling process. However, the thrust of this research has largely been limited in scope and has not been integrated with humans to understand and how they would perform in an adaptable airspace environment.

The questions that guided this next phase of research into DAC came about through collaboration and consultation with fellow researchers and stakeholders. One of the central questions related to dynamic airspace reconfiguration as it relates to human-system integration is the necessary and appropriate operational procedures and guidelines to most effectively handle the transition from one configuration to another. A better understanding of the human abilities to handle such transitions and the impact that they would have on controllers is needed. Some of the fundamental questions related to airspace changes and their impact are as follows:

1. Which airspace-related factors (e.g., airspace volume, number of aircraft affected by the boundary change, changes in the traffic flow, etc.) significantly impact the controllers during the boundary change?
2. How long does it take for the airspace transition process to complete?
3. How often can airspace be changed?

4. What factors determine when airspace change is feasible?
5. Are new automation tools required to facilitate an airspace change?
6. How much notice do controllers require prior to the boundary change?
7. What are the procedures for changing from one configuration to the next?
8. What conditions (e.g., changes in flow or complexity, increase/decrease in traffic volume, duration of peak traffic, etc.) are needed to justify a boundary change?

## II. Simulation

To take a first step toward answering these questions, a human-in-the-loop (HITL) study was conducted in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center from May 12-21, 2009. The intent of this study was to gain a greater understanding of the impact that dynamic airspace boundary changes have on air traffic controllers as well as to answer some basic questions regarding the feasibility and operational procedures necessary for this aspect of the DAC concept to proceed. To accomplish these goals, previous work on algorithm development was leveraged in order to provide realistic and appropriate dynamic sectorizations to the participants. Three separate algorithms were selected based upon their different approaches to sectorization and their aggressiveness related to the magnitude of change: Low, Medium, and High. The decision to choose these algorithms according to a categorization based in part on change magnitude stemmed from the exploratory nature of this study and the desire to test the limits of change and more fully quantify their effects.

### A. **Algorithm Descriptions**

For the Low magnitude change sectorizations, an approach was preferred that involved sector geometry changes that, to a certain extent, respected the composition of the current sector and would theoretically have less of an impact on the controller during a transition. This type of approach was embodied by an algorithm that formulated sectorizations based on Dynamic Fixed Posting Areas (DFPA), which has since shifted its basis to Dynamic Airspace Units (DAU).[8] As with most algorithms developed for DAC, the end state goal is reduced workload through the distribution of airspace. Because workload is an inherently subjective construct and dependent upon various factors, the algorithm must use as input estimates of workload referred to as Simplified Dynamic Density (SDD) metrics,[9] which are a subset of the larger body of metrics known as Dynamic Density.[10, 11]

As initial input for the DAU algorithm, the initial airspace is defined and provides the basis for subsequent changes in the sectors. From here the algorithm searches for shared boundary areas from which a line can be drawn that will connect the shared vertices of the two boundaries (see Fig. 1). Based on this “trend” line, the algorithm begins making slices moving away from the “trend” line toward the sector’s center at 1 nautical mile (NM) intervals. Once these slices have been apportioned they serve as the basis for a slicing series that incrementally allocates slices from one sector to another based on demand. The number of slices gained or lost by a sector depends on the calculated effect that the transfer has on reducing and distributing the SDD metrics among the sectors. Throughout the series of slices, continuity of shared areas and conformance to previous configurations is attempted such that transitions from one sectorization to the next are less extreme than they might be through a different algorithm.

For the Medium magnitude change sectorizations, a slightly more aggressive approach was used that differed from the Low magnitude change algorithm in its input parameters and formulation. These sectorizations were done using a clustering algorithm that generated sectorizations based on the grouping of flights.[7, 12] The key difference is that it takes into account flow information in the design and generation of sectorizations. This results in more drastic changes to sector geometries than the Low magnitude change algorithm because rather than focusing on boundary commonalities and how they can be configured, it analyzes traffic flow characteristics over time and determines how best to alter sector geometries to accommodate changes in those flows.

As an initial step, this algorithm calculates an independent measure of demand given the traffic for the area of concern. The flights are then clustered together according to defined clustering criteria and DD factors with an associated time dimension; changes in the clustering of flights over time result in changing sector geometries over time. This is done through computational geometry techniques and strives to most adequately encapsulate the identified clusters and reduce the contribution of DD factors to the complexity and workload of the controllers responsible for working the areas undergoing these transformations. Further refinements are made in an attempt to more effectively distribute DD among the sectors. An example of one proposed sectorization set based on the

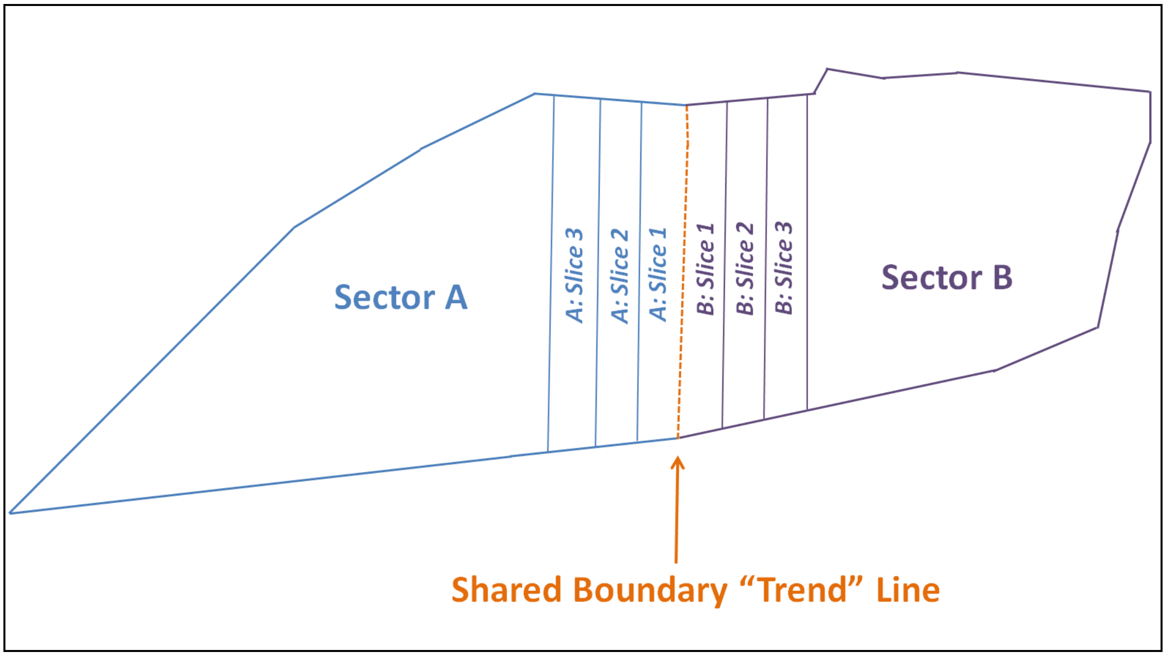


**Figure 1. Example of sector slicing and resulting airspace units that can be gained or lost between sectors based on demand distribution.**

parameters set forth for this study can be seen in Fig. 2. The left portion of the figure shows the static, current day sector geometries for four high altitude sectors in ZKC center. Using scenario traffic data as trajectory input, the four sectors were transformed to accommodate the flows of traffic seen in the right portion of the figure in grey, overlaid on the sector boundaries.

The High magnitude change algorithm selected for this study was one based on the Mixed Integer Programming (MIP) method.[7, 13, 14] This particular algorithm was selected as it was observed to provide more radical sectorizations and would provide a challenging environment in which to test controller impact. Unlike the Low and Medium change algorithms, this one did not use DD metrics to inform its sectorizations. Instead, it used a number of metrics (e.g., dwell time average of tracks, traffic count imbalance between sectors, boundary stability and convexity) that constituted a decidedly different approach with likewise different results.

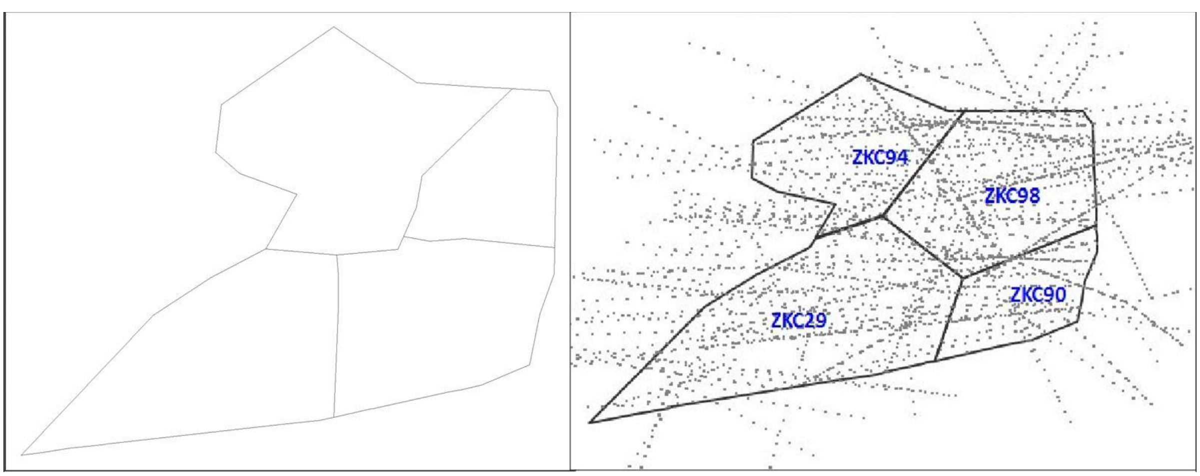


**Figure 2. Example sectorization based on the clustering algorithm used for the Medium magnitude change condition.**

Given a predefined number of sectors to configure, the first step in reconfiguring sectors using the MIP approach involves transforming the airspace of interest into a network of hexagonal cells. Trajectory data for traffic traversing the airspace/network of cells provide the basic input for how best the cells can be connected for the most effective sector configuration. The load of each cell and the connectivity to adjacent cells- defined by the traffic flow pattern from one cell to the next- are primary considerations for the final sectorizations. Basically, this approach does its best to respect flows of traffic without much regard to sector geometry. Due to the initial hexagonal partitioning of the airspace, resulting sector boundaries tend to be quite jagged. For this study, developers were asked to provide additional smoothing to increase the acceptability of the sectors for the controllers without detracting too much from the intent of the final sectorizations. The compromise between the smoothing and respecting of the original sectorizations resulted in less yet still somewhat jagged sectors as seen in Fig. 3.

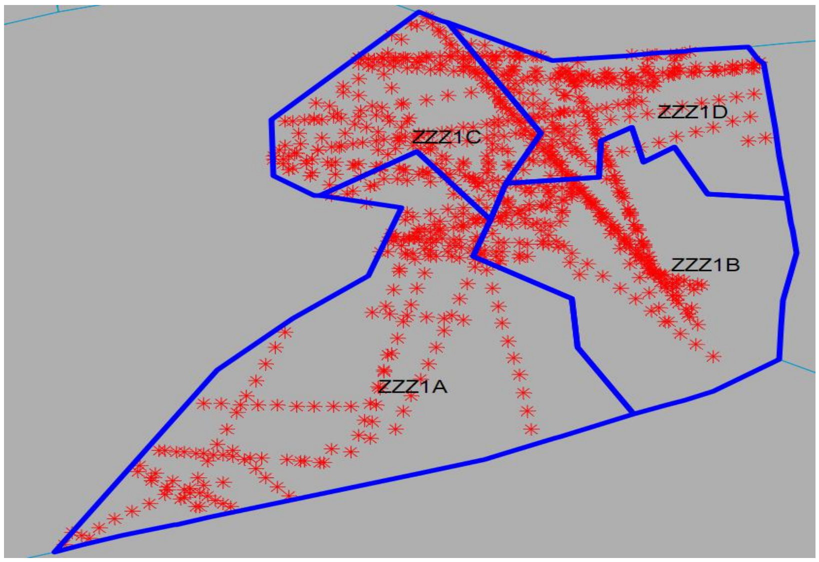


**Figure 3. Example sectorization based on the MIP approach used in the High magnitude change condition.**

B. **Implementation and Approach**

There were a number of research questions related to the impact of the sector change magnitude (i.e. Low, Medium, and High) on the controllers that were of interest in addressing. However, there were an insufficient number of simulation runs available to test the questions independently. Therefore, an approach was taken where a number of the questions put forth earlier were manipulated per boundary change within each scenario. The questions were transformed into specific metrics, and varied within and across the runs. Many of the metrics were confounded (i.e., highly correlated with each other) but without such an approach, the variables and subsequent conditions and runs necessary to address each one would quickly multiply to the point of becoming unwieldy and unrealistic to run let alone analyze.

As shown in Fig. 4, some of the factors that were chosen for manipulation at the scenario level were the frequency in sector boundary change (i.e., how often), the timing of the change relative to the imposed trigger event of traffic peaks that exceed the Monitor Alert Parameter (MAP) value, and the traffic patterns that had varying durations of sustained counts in excess of the MAP value. Other factors that were intended to be manipulated in a similar fashion were standardized for the study and will be explained in the following section along with the details of the final experiment design.

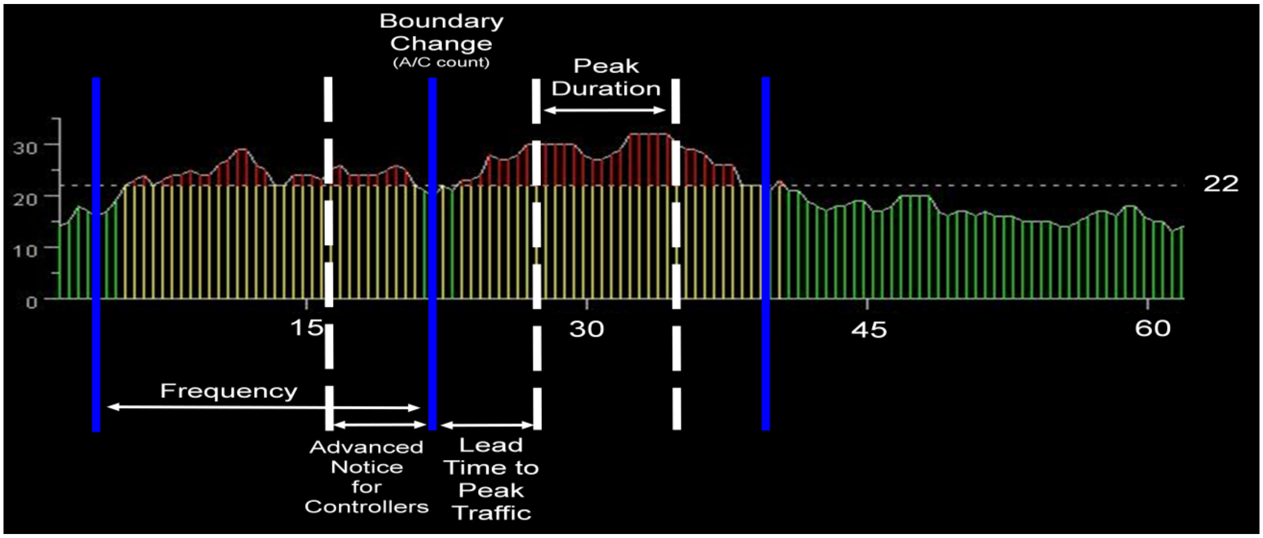


**Figure 4. Traffic load (y axis shows aircraft count) in a given sector over time (minutes) with potential boundary changes shown (blue lines).**

## III. Method

### A. Experiment Design

The design for this experiment included one independent variable (IV), Magnitude of Boundary Change, which consisted of four levels: Baseline, Low, Medium, and High Magnitude Changes. The Baseline level of the IV did not involve any boundary changes and required the participant team to manage traffic load imbalances without any involvement of airspace redesign. The Low, Medium, and High Magnitude Change levels of the IV refer to the aggressiveness of the boundary reconfigurations relative to the Baseline configuration. As discussed in the algorithm descriptions in the previous section, the Low Magnitude Change level involved boundaries that did not have drastic configuration changes and tended to respect the composition of the boundaries used in the Baseline condition. The Medium and High Magnitude Change levels of the IV presented to the participants progressively more aggressive changes to the boundary configurations that did not necessarily respect those used in the Baseline condition.

This was a within-subjects, repeated measures design with the four test participants being exposed to all four conditions. The dependent variables selected to measure the impact of the IV manipulations were aircraft counts on a per sector basis, subjective workload ratings, taskload, safety, and acceptability.

Factors varied within condition were the frequency of sector boundary changes, the timing of the boundary change, and the traffic pattern characteristics. Factors held constant were the number of boundary changes, the preview time given to the controllers prior to a boundary change, and the number of sectors within the test airspace. The number of boundary changes was held constant at three within each 60 minute run; three boundary changes were determined to be the maximum that could be performed in each run. The preview time given to the controllers prior to a boundary change was tested prior to the simulation and based on the results an optimal preview time of three minutes prior to a boundary change was selected. This timing appeared to be just enough to adequately prepare for the upcoming boundary change without being too far in advance as to not warrant any action. The number of sectors was limited to four and was a hard constraint imposed in the formulation of new sectorizations.

### B. Participants

There were a total of four test participants. Of those, three were operations supervisors from Washington Center (ZDC), Atlanta Center (ZTL), and Indianapolis Center (ZOA), and one a recently retired controller from Oakland Center (ZOA) who actively controlled traffic within the last 4 months prior to the start of the simulation. Their air traffic control (ATC) experience spanned from 20 to 25 years with an average of 22.5 years of ATC experience.

In addition to the test participants who worked as Radar Controllers, the duties of Area Supervisor, two Radar Associates (RAs), and "ghost" controllers responsible for all of the aircraft outside of the test airspace were performed by retired controllers from ZOA. The Area Supervisor and the two RAs played an integral role in the study. The RAs had recently retired within 2.5 and 2 years, respectively, and the Area Supervisor had retired within

6 years. All of the simulated aircraft were flown by pseudo-pilots, who were active commercial pilots and/or San Jose State University students from the aviation department.

C. **Apparatus**

For this simulation, the participant test area consisted of six radar controller stations (Fig. 5) each equipped with 28” Barco displays, Display System Replacement (DSR) keyboard and trackballs as input devices, and tablet PCs for Voice Communication System emulators for air-ground and ground-ground communications. In addition to these six stations, there was an Area Supervisor’s station with monitor, PC keyboard and mouse, and a Traffic Management station configured similarly to the controller stations but with extra displays for load analyses. Two side-by-side projectors were also in the test area that projected a Traffic Situation Display (TSD) with a real-time display of traffic as well as load graphs showing the current and predicted loads for each of the test sectors. The TSD also displayed upcoming boundary previews, which was used by the Area Supervisor for controller briefings. In a separate room were the two “Ghost” confederate stations. These were equipped with 30” monitors with PC keyboards and mice. Also in an adjacent room, there were six pseudo-pilot stations which were all standard PC setups.

**Figure 5. Test area of the AOL showing the six controller and Area Supervisor stations.**

The common simulation platform that threaded all of the positions together was the Multi-Aircraft Control System (MACS).[15] This is a JAVA based software package developed at the NASA Ames Research Center by Dr. Thomas Prevôt and his development team. MACS emulates many of today’s ATC capabilities and is also scalable to test future concepts and tools. Through the development of MACS and configurations to the test stations, an environment envisioned by NextGen and specific to the testing of this DAC concept was created.

D. **Airspace**

The test sectors used in this study were adapted from high altitude sectors in Kansas City Center (ZKC). The four sectors (ZKC sectors 94, 98, 29 and 90) are shown in green in Fig. 6. Surrounding the test airspace were two “ghost” sectors, divided along East-West lines that were composed of all of the non-test airspace. Retired controllers worked the traffic in these “ghost” sectors and handled regular controller duties such as handoffs and transfer of communication (TOC) for all incoming and outgoing traffic. The flows in the test scenarios consisted of a mix of arrivals and departures to and from the local area airports as well as a number of over flights en-route to various outlying destinations. For this study there were a total of six airports with arrivals and departures transitioning in the test airspace. The minimum altitude of overflight aircraft was FL 290 with maximums being dependent upon aircraft performance characteristics. In general the East-West flows in these scenarios were slightly heavier than the flows running North-South.

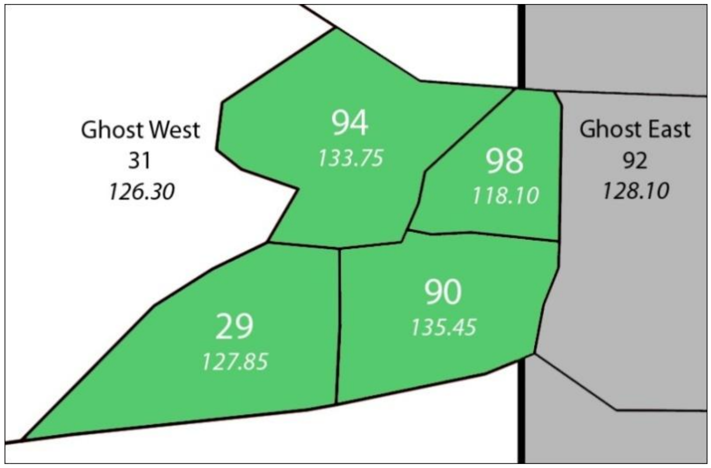


**Figure 6. High altitude test airspace used in the study. The airspace was adapted from ZKC center.**

E. **Operational Environment**

The operational environment for this study incorporated components of what is explicitly envisioned as part of NextGen and included some technological assumptions in line with that vision. With respect to assumed aircraft equipage levels, all aircraft entering the test airspace were equipped with data communication (Data Comm) capabilities, Automatic Dependent Surveillance-Broadcast (ADS-B) reporting, and were capable of flying 4-D trajectories to a Required Navigation Performance (RNP) level of one. It was also assumed that the test airspace and all aircraft entering were conducting Trajectory Based Operations, which, for this study, meant that all aircraft flying their nominal trajectories were cleared to travel according to their known route provided they remained on trajectory. This also implied that aircraft that reached their top of descent or were in their departure/climb phase were cleared for their optimal transition.

In addition to the flight-deck, a number of technological assumptions were made for ground-based capabilities as well. In this environment, the responsibility for conflict detection was shifted from the controller to ground-based automation and conflicts that were detected were conveyed to the controller through conflict lists and datablocks of the involved aircraft. While the controllers always had the ability to communicate with aircraft via voice, they also had access to decision support tools that eased and expedited the process of resolving conflicts and altering trajectories. A trial planning tool integrated with the DSR display allowed the controller to dynamically drag an aircraft's lateral route, trial plan a different altitude, or a combination of the two. The trial plan tool provided real-time feedback on whether the proposed trajectory was conflict free. Another tool that aided conflict resolutions specifically was the auto resolver, which was the front end of an algorithm developed as part of the Advance Airspace Concept (AAC).[16] This tool provided controllers with the capability to call up, on demand, a suggested resolution for a given conflict that would be presented to the controller as a trial plan. The controller could then decide whether to accept the resolution, modify it through the trial plan, or reject it and solve the conflict without the auto resolver's support. Once a resolution was chosen, the new trajectory could be uplinked to the aircraft, loaded directly into the aircraft's FMS, and flown accordingly.

F. **Procedure**

For this study, the research team collaborated heavily with outside researchers who provided the three sets of sectorizations based on their algorithmic approach. The first step in this process required the development of two traffic scenarios that would serve as the trajectory input for these algorithms. Scenario development was done through the scenario editor function in MACS with resulting scenarios designed for a 90 minute run length with load imbalances between the four test sectors that would drive the resectorizations in each of the algorithms. Although the actual runs were 60 minutes in length, longer times of sector occupancy were necessary for the algorithms to be able to generate sectorizations based on future traffic loads. The load imbalances were constructed with differing load characteristics between the two scenarios in terms of timing and duration. The load imbalances were developed by building up traffic peaks in two of the four test sectors (ZKC 90 and ZKC 94) while keeping the loads in the other two sectors more in line with the established Monitor Alert Parameter (MAP) value based on the predicted aircraft count. A MAP value of 22 aircraft was selected for each of the sectors in the test airspace and the peaks were built to reach counts of up to approximately 28 aircraft in the two targeted sectors. In each of the two scenarios, two peaks were built in at different times and the duration of time that aircraft counts exceeded the MAP value also differed.

After completion of the two test scenarios, they were run in the AOL where trajectory data was collected and sent to the three algorithm development teams for testing and sector generation. The constraints placed on the sectorizations were that the initial sectors always start with the current day configuration, there would always be four sectors, the outer lateral boundaries of the test airspace remain constant, and the vertical dimension of the boundaries would remain constant. The Low magnitude change algorithm resulted in revised sector configurations at 15 minute intervals for the two traffic scenarios that covered the 90 minutes of trajectory data. This resulted in six sectorizations for each scenario. The Medium and High magnitude change algorithms generated sectorizations at five minute intervals based on a 30 minute look ahead of trajectory data. This resulted in 18 sectorizations per scenario from which to choose.

After the traffic scenarios and sectorizations were complete, final decisions were made on when the three boundary changes would occur in each run relative to traffic peaks. The original two traffic scenarios were replicated and varied slightly, so as to appear different to the participants yet preserve the original overall traffic patterns. This resulted in four test scenarios, allowing us to test four different boundary change timing conditions, each with the boundary changes occurring at different points in the run. For descriptive purposes, the first scenario and its variant will be referred to as scenario 1A and 1B respectively and the second set as scenario 2A and 2B. The first set of scenarios was constructed to include two traffic load peaks: one that occurred 10 minutes into the run and the other at 40 minutes, each lasting for approximately 10 to 15 minutes. The boundary change points for scenario 1A were placed at five, 30, and 50 minutes into the 60 minute run, and those for 1B were placed at 10, 25, and 55 minutes into the run. The selected schedule provided for boundary changes that occurred at different times relative to the peaks in order to test for differences in their impact. The second set of scenarios also had two traffic load peaks, the first at 15 minutes into the run lasting between 10 to 20 minutes, and the last peak at approximately 40 minutes into the run and lasting between 15 and 20 minutes. Based on this pattern, boundary change points for scenario 2A were placed at 10, 25, and 55 minutes into the run, and scenario 2B's boundary change points were placed at 5, 30, and 55 minutes into the run.

Having decided upon the boundary transition points, the next step was to match the different sectorizations to the times. Three sectorizations were mapped to each of the four boundary change conditions resulting in a total of 12 sector configurations per algorithm that would be used for the study. While the finalization of boundary configurations was taking place, trial runs were carried out with local retired controllers from ZOA center participating. Through these runs a number of procedures, boundary change, and display issues were identified and refined. One of the results of these trial runs was the preview time needed for the controllers prior to a boundary change. Feedback from the controllers was that three minutes was nominally enough time to handle the tasks associated with a boundary change. Another important piece of input from these trial runs was in response to the sectorizations provided for the Low magnitude change condition. This condition was intended to reflect a more human-centered approach to sector configuration and feedback was solicited from the retired controller subject matter experts regarding the sector designs. This feedback was obtained by presenting the participants with each of the Low magnitude change condition boundary configurations in a post-session questionnaire packet along with questions regarding some of the factors that impact the acceptability of the sector configurations. Following the completion of the trial runs, the feedback was used to make adjustments to the necessary boundary configurations. With the exception of the Low magnitude change, the final sectorizations were left untouched in order to test the full range of impact of the designs. This meant that sector characteristics such as jagged edges and extreme changes in the geometry and relative positions of sectors were allowed in the Medium and High conditions. This also benefited the algorithm developers by providing data for them to use in being able to identify additional considerations for their respective approaches. Figure 7 presents an example of the first boundary change from the Low, Medium, and High magnitude change conditions for one of the four final boundary change conditions. Note that the initial sector configuration, regardless of condition, was the current day sector configuration as presented in Fig. 6.

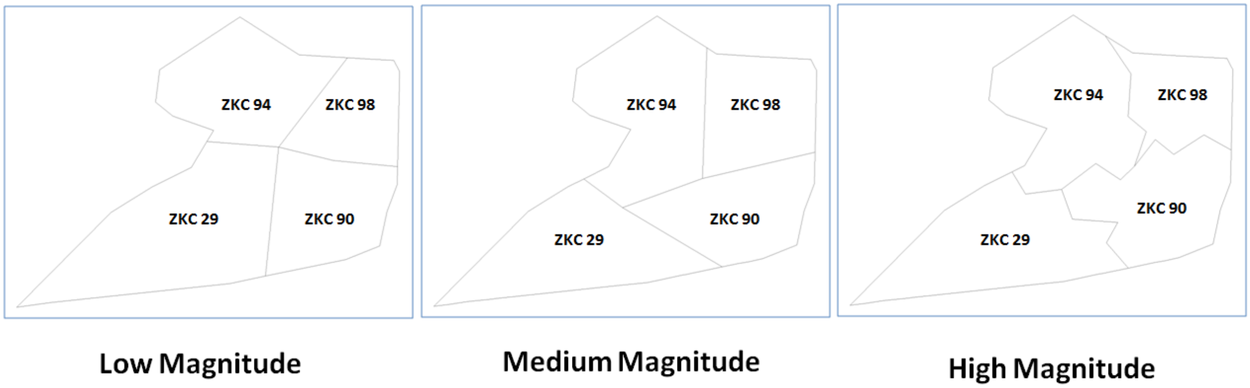


**Figure 7. Example of the first sector boundary change for each of the change conditions in Scenario 1A.**

Once the preparation was completed, the actual HITL study was conducted over the course of two weeks and involved the participation of four active operations supervisors as R-side controllers for the four test sectors, two recently retired confederate controllers as supporting Radar Associate (RA) controllers, and a recently retired confederate controller acting as an Area Supervisor. Two additional retired confederate controllers acted as "ghost" controllers that handled air traffic feeding into and exiting the test airspace. After the initial briefing and administrative duties were performed, training on the tools and environment was started in the AOL. The training was conducted over the course of three days and involved the use of training traffic scenarios that started with 50% of the eventual traffic levels that would be presented during the data collection runs, and progressed to 70% and eventually 100% of the traffic levels. The entire first day of training was devoted to tools and airspace familiarization with the first set of boundary changes not being presented until the second day. The sectorizations used in training were selected from each of the three different algorithms but did not include those actually used during data collection. Once proficiency with the tools and understanding of the airspace sectorizations was observed, the team was ready for the full test runs.

Data collection began on the fourth day after an initial briefing and discussion. The run order was counterbalanced in order to minimize the possibility of confounding data related to order and training effects. A total of 16 runs were conducted with each of the four boundary change conditions (Baseline, Low, Medium, and High magnitude change) being presented four times. Throughout each of the runs, real-time workload ratings were collected through an integrated workload assessment keypad in MACS on a scale from one to seven, with one being the lowest and seven the highest rating of perceived workload. Prompts were presented at different times according to the boundary change schedule in each of the four scenario types. Workload prompts were presented at three minutes and one minute prior to a boundary change, and likewise following the change. At other times, in between boundary changes, workload prompts were presented at five minute intervals. For Baseline runs, workload prompt sequences were identical to the ones used in each of the corresponding conditions involving boundary changes so that they were comparable to the corresponding workload in the boundary change conditions.

For each run, the four test participants were, similar to today, responsible for making and taking handoffs of aircraft entering and exiting their sector and maintaining safe separation distances in accordance with current separation minima. The Area Supervisor monitored the current and predicted traffic loads for the test sectors through interactive load tables and graphs, and assessed the workload of the controllers. For non-Baseline runs, the Area Supervisor also had access to a preview of each upcoming boundary change. Based on the supervisor's judgment of available resources and the work that would be required before and after a particular boundary change, RAs were assigned to assist one of the R-side controllers. Due to the layout of the lab in this study, there were two RA positions situated between an R-side pair on opposite sides of the room. Because of this layout, support from the RA controllers was limited to only one of the associated R-side pairs. The pairs were divided according to horizontal proximity of the initial sectors such that ZKC 29 and ZKC 90 was a pair assigned one RA controller and ZKC 94 and ZKC 98 were assigned the other. The RA position assisted one position at a time and had access to the same tools and functionality that the R-side position had. Prior to being assigned a position to support, the Area Supervisor met with the RAs for a quick briefing on the current or upcoming situation. Following this briefing and after the supervisor gave the final go-ahead, a lab team member activated the appropriate RA position.

For boundary change conditions, the controllers on station received a boundary preview three minutes prior to each change. Figure 8 presents how this preview looked on the controllers' displays. The displays had a small boundary preview window that gave a countdown until the boundary change and the upcoming boundary was overlaid on the current boundary. Additionally, the corresponding sector numbers were displayed with the preview to aid controller situational awareness of the new configuration. These sector numbers remained on the display for one minute following the boundary change to assist with handoffs and general situation awareness. Typically upon activation of the change preview, the R-sides and RA controllers began making handoffs and point outs to the appropriate sectors. Point outs were done through the DSR keyboard, but there were also some done verbally. When all steps proceeded ideally, all aircraft were transferred to and under track control of the appropriate sectors by the time of the actual boundary change. If a certain boundary change appeared particularly workload intensive, the supervisor would often assign an RA to assist with the initiation of handoffs and switch position assignments shortly after the change to assist the receiving sector in managing the new set of aircraft gained.

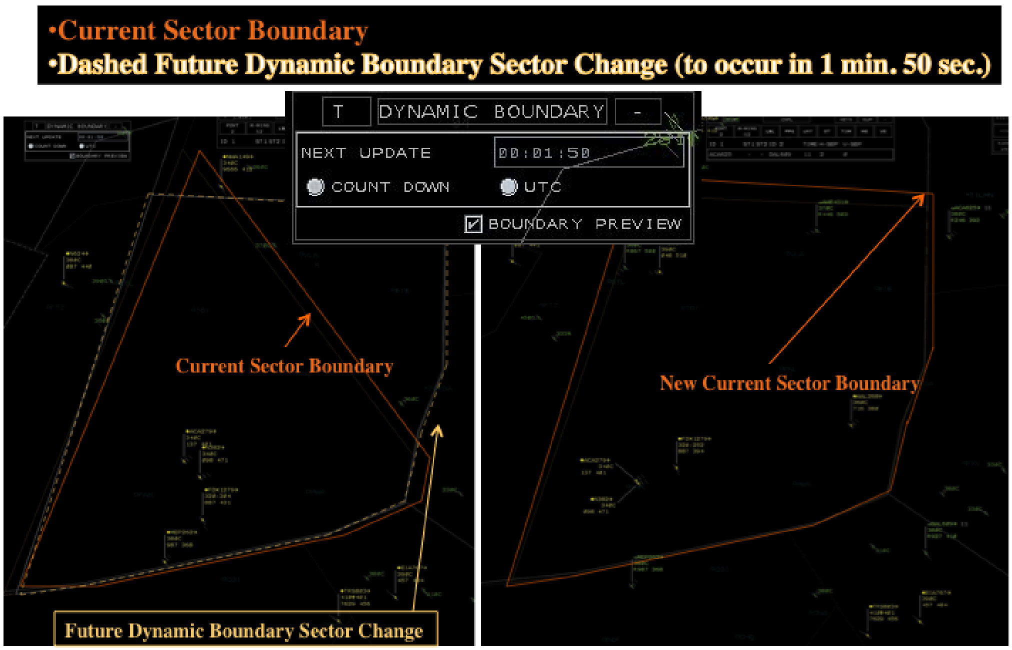


**Figure 8. Example of a sector boundary preview (left) and the actual change (right). A countdown was also provided indicating time left until next boundary change.**

Following each run, a post-run questionnaire was distributed to each participant. Questions covered the overall workload experienced during the previous run, and the acceptability of boundary changes when applicable, and solicited comments on what factors affected their acceptability ratings for the boundary changes in that run. In addition to these data, a wide variety of other data (e.g., workload, aircraft trajectories, system interaction, and safety) were recorded through the data collection system of MACS. Screen recordings of all stations were also made for each run for later reference during analyses. Another source of data came from observers that sat next to the controllers during the run taking note of communications and coordination between sectors and any special situations that arose throughout the course of the run. A post-simulation questionnaire was given following the final data collection run followed by a debrief discussion involving all participants where feedback regarding the concept, tools, automation, and a host of other topics were covered and discussed collaboratively.

## IV. Results

The results presented in this section compare a number of metrics across the four boundary change conditions- Baseline, Low, Medium, and High magnitude change. An investigation into the specific factors tested by the individual boundary changes that correlated with the IVs has been presented in a separate report.[17, 18] Results to be presented here will pertain to quantifying the change in airspace for each of the applicable boundary change conditions, traffic characteristics, taskload, workload, safety as it relates to conflicts and operational errors, and finally the acceptability of the different approaches to airspace configuration.

## A. Airspace

The first aspect of airspace to be evaluated is the percentage of airspace volume that was gained and lost through the boundary changes in each of the boundary change conditions. The percentage of volume gained refers to how much new airspace, in addition to the previous sector volume, was gained upon the reconfiguration. The percentage lost refers to the volume of airspace previously assigned the sector prior to the change that is no longer assigned after the change. The two separate measures, therefore, allow for a sector to both gain and lose airspace volume through a boundary change. Figure 9 shows the percentage of volume gained and lost for the Low, Medium, and High boundary change conditions.

If the categorization of Low, Medium and High magnitude changes were accurate, the percentage of airspace volume gained and lost would be expected to increase from Low to High conditions accordingly. The mean percentage of airspace volume gained was 9.56% (*SD* = 3.58) in the Low magnitude change conditions, 15.99% (*SD* = 10.35) in the Medium change condition, and 23.66% (*SD* = 7.12) in the High change condition. A comparison of the means was conducted with a one-way Analysis of Variance (ANOVA) where a significant main effect was found using an alpha of .05, $F(2,33) = 10.52$, $p < .01$. Tukey's Honestly Significant Difference (HSD) tests were conducted to further investigate the differences between the means, and showed significant differences between the percentage of volume gained between the Low and High magnitude change conditions ($p < .01$) as well as between the Medium and High change conditions ($p < .05$).

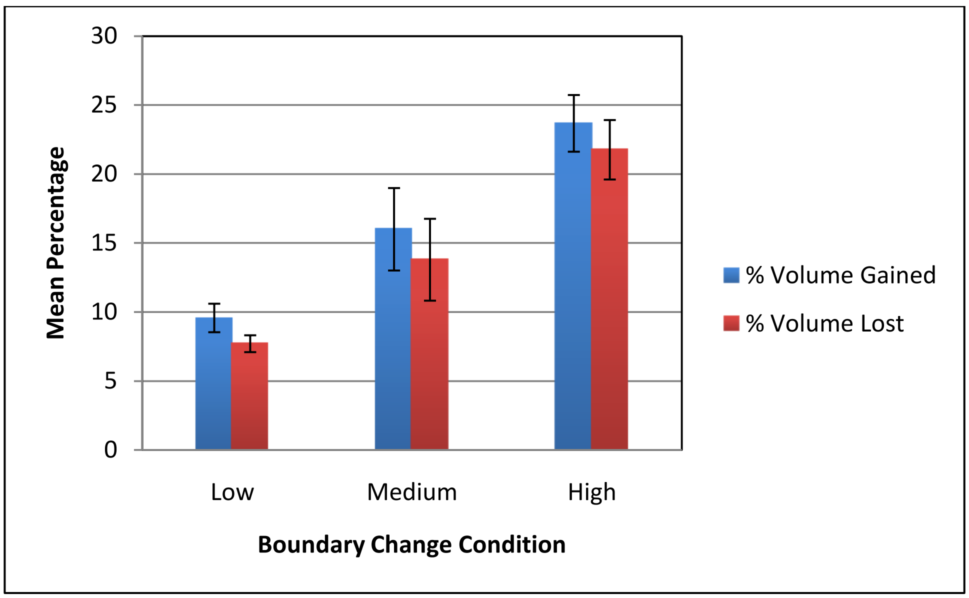


**Figure 9. Differences in airspace volume gained and lost between boundary change conditions.**

Results for airspace volume lost were similar to those observed for gain. The Low change condition had a mean percentage of volume lost of 7.69% (*SD* = 2.11), the Medium change condition had a higher mean percentage lost of 13.78% (*SD* = 10.28), and the High change condition had a mean loss of 21.75% (*SD* = 7.46). To investigate the differences between these means a one-way ANOVA was conducted and a significant main effect was found, $F(2, 33) = 10.79$, $p < .01$. Tukey's HSD tests were conducted to investigate the differences between the means and, just as with airspace gained, showed significant differences between the percentage of volume lost in the Low and High magnitude change conditions ($p < .01$) as well as the Medium and High change conditions ($p < .05$).

## B. Traffic Characteristics

### *1. Traffic Distribution*

One of the reasons why certain boundary change conditions created large airspace volume changes may be that they were more aggressive in distributing and managing the traffic loads across the sectors. The traffic distribution among sectors was examined as a difference of the standard deviations in the aircraft count. The standard deviations were plotted for the four test sectors over time for each of the boundary change conditions (Fig. 10). The aircraft counts for the test sectors were collapsed across the scenarios for each of the four boundary change conditions (Baseline, Low, Medium, and High). The overall results show lower standard deviation values for the higher boundary change conditions, suggesting a more even distribution of aircraft across the sectors because the differences in count between them were less. Figure 10 shows that the earlier time segment with the initial traffic peak has a tighter clustering between each of the conditions with the Low magnitude change condition having the lowest amount of deviation followed by the High magnitude change condition. However, in the latter half where there was a more sustained traffic peak, the boundary change conditions begin to differentiate a bit more. In particular, the Baseline and Low magnitude change condition show higher deviation among the sectors whereas the Medium and High magnitude change conditions showed lower deviation suggesting that the greater magnitude in change in these sectorizations resulted in a more even distribution of aircraft among the test sectors. Overall, the High magnitude change condition seemed to distribute the traffic count more equitably than the other change conditions.

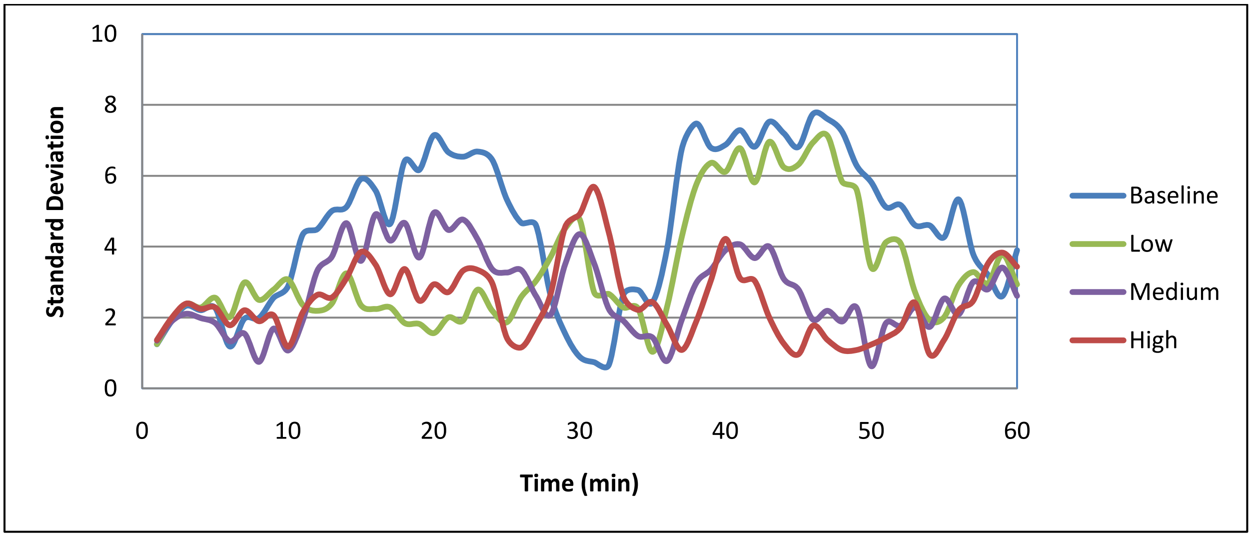


**Figure 10. Standard deviation of aircraft count among the four test sectors plotted over time for each boundary change condition.**

*2. MAP Value Management*

The amount of time in each sector that the aircraft count exceeded the MAP value of 22 aircraft was measured as another indication of how well each of the different approaches to sectorization performed the task of traffic distribution and airspace capacity management. For this analysis, the total number of minutes above MAP in all four test sectors was initially summed and averaged for each run with the final mean across the four scenario types being reported and compared here. Before this analysis was conducted, it was assumed that the Baseline condition, without any boundary changes, would show the greatest mean duration over MAP compared to any of the other conditions. This hypothesis was supported (see Fig. 11) in that the mean duration over MAP for Baseline was 14.63 minutes (*SD*= 0.75) per 60 minute traffic scenario. In contrast, the Low magnitude change condition had a mean duration of 11.25 minutes (*SD*= 3.40) over MAP, the Medium magnitude change condition a mean of 10.50 minutes (*SD*= 3.01) over MAP, and the High magnitude change condition had the least amount of time over MAP with a mean of 8.50 minutes (*SD*= 2.03). A comparison of the means was performed using a one-way ANOVA where a significant main effect was found, $F(3, 12)= 4.12$, $p< .05$. These results suggest that more aggressive changes in the boundaries resulted in less time in which the sectors were over the MAP threshold. Subsequent Tukey's HSD tests showed that the only comparison to have a significant difference was between the Baseline and High magnitude change conditions ($p<.05$). This meant that the High magnitude change condition was significantly better than Baseline in keeping counts below MAP whereas the other conditions were not.

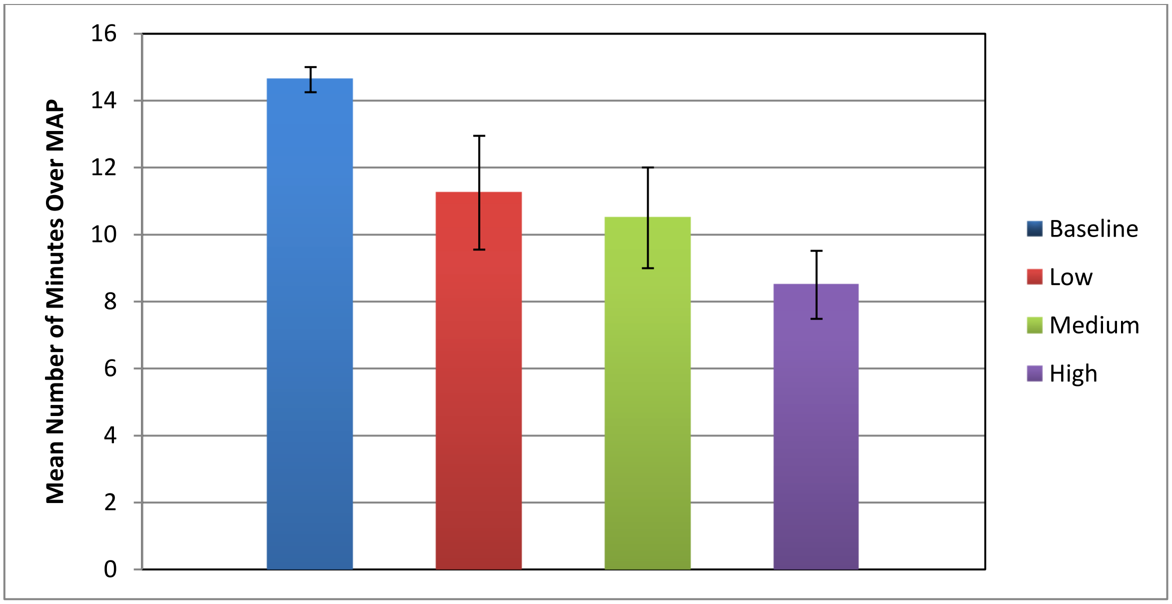


**Figure 11. Mean duration in excess of the MAP value across all four test sectors.**

*3. Aircraft Dwell Time*

Another measure of the impact that sectorizations might have on traffic and associated workload is aircraft dwell time, or the amount of time aircraft spend in a sector. The longer an aircraft spends in a sector, the more stable it is and the more time the controller has to incorporate that aircraft into his or her operational picture. To address this factor, the average time spent in a sector was examined for all four boundary change conditions. The descriptive statistics for this measure as well as Fig. 12 show that the Baseline condition had the greatest mean dwell time (*M*= 462.12 seconds, *SD*= 75.87) followed in decreasing order by the Low magnitude change condition (*M*= 439.14 seconds, *SD*= 61.18), the Medium magnitude change condition (*M*= 424.69 seconds, *SD*= 41.25), and finally the High magnitude change condition with the shortest mean dwell time of all conditions (*M*= 399.22 seconds, *SD*= 53.29). A one-way ANOVA revealed a significant difference between the means, $F(3, 60) = 3.167$, $p < .05$, and Tukey's HSD tests revealed the source of the difference in mean dwell times to be between the Baseline and High magnitude change conditions ($p < .05$). The sectorizations in the High magnitude change condition resulted in aircraft travelling through sectors for a significantly shorter duration of time, an indication of less stability and potentially greater difficulty in handling aircraft and maintaining a coherent picture of the traffic in this condition.

## C. Taskload

*1. Handoffs*

Taskload refers to controller actions, such as handoffs and point outs, which have physical action components that contribute to their mental workload. In this paper, taskload is analyzed by comparing the number of handoffs and point outs across the four boundary change conditions. These results will provide insight into the potential contributors to the controller workload imposed by the various sectorization approaches. The first measure of taskload to be analyzed is the number of handoffs that were required in each of the conditions. The handoff analysis was done by averaging the total number of handoffs performed in each of the boundary change conditions. Figure 13 shows that the Baseline condition had the fewest (*M*= 475.75 handoffs, *SD*= 8.69) with the next highest number of handoffs being the Low magnitude change condition (*M*= 500.25 handoffs, *SD*= 22.47). This trend continued with the Medium change condition having the next highest mean of 513.75 handoffs (*SD*= 21.75) and the High change condition requiring the highest number of handoffs to be performed (*M*= 522.25 handoffs, *SD*= 26.61). A one-way repeated measures ANOVA was performed on these means and a marginally significant difference was found, $F(3, 9) = 3.45$, $p = .06$. Despite this non-significant finding, the increasing trend in the number of handoffs by change magnitude is clear.

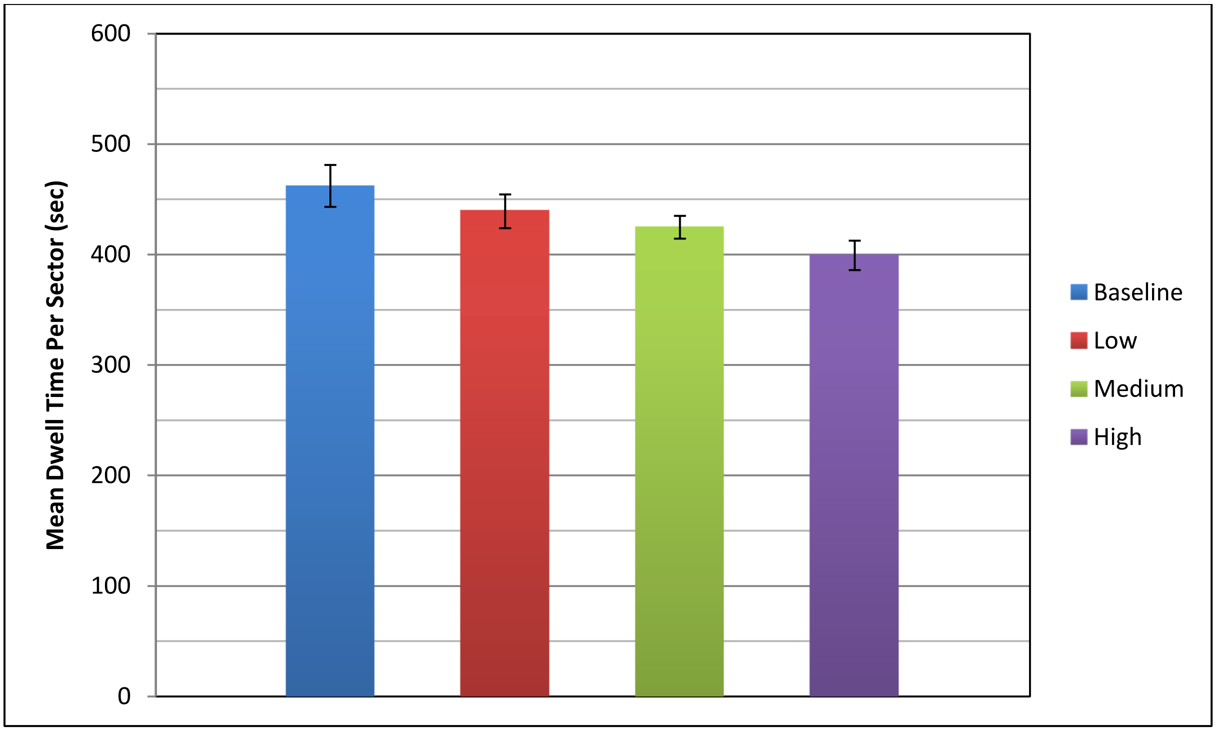


**Figure 12. Mean dwell time of aircraft in the four test sectors. A lower value is considered worse in terms of stability and situation awareness.**

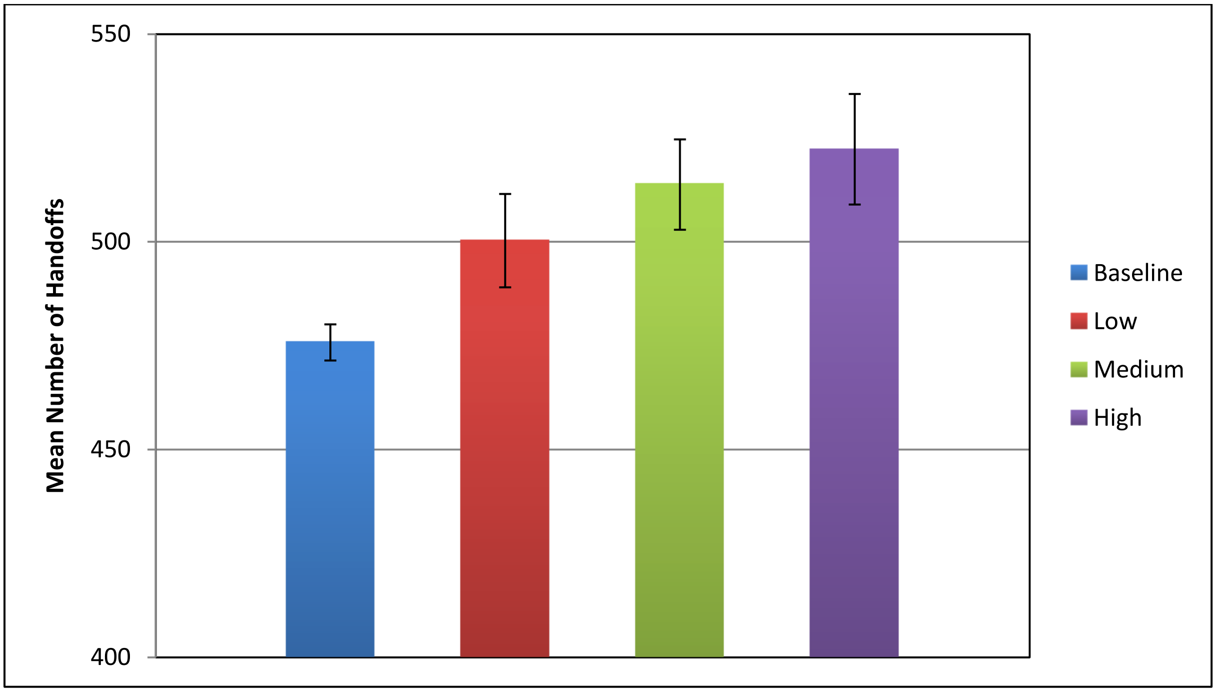


**Figure 13. Comparison of mean number of handoffs performed for each of the boundary conditions.**

*2. Point Outs*

Another measure of the taskload related to boundary changes is the number of point outs. This refers to cases where certain aircraft may not enter a proximal sector's airspace but come close and thus require notification and awareness. This task requires extra time and coordination and adds to the controllers' workload. It should be noted that the numbers presented here are a subset of all point outs performed due to the fact that while the participants made a great effort to perform point outs through DSR keyboard entries, a number were performed verbally and were therefore not recorded. These data should be used in support of the handoff results in highlighting the progressive difficulty imposed by the higher degree of airspace transition. Figure 14 presents the descriptive statistics on the available data, which shows that, similar to handoffs, the Baseline condition required the fewest number of point outs (*M*= 38.25, *SD*= 3.78), the Low magnitude change condition required the next highest number (*M*= 48.50 point outs, *SD*= 13.48), the Medium change condition had the next highest number of point outs (*M*= 56.25 point outs, *SD*= 21.42), and the High change condition required the highest number of point outs (*M*= 68.25 handoffs, *SD*= 15.31). A one-way repeated measures ANOVA was conducted to further examine the differences between these means, but was not significant, $F(3, 9)= 2.45$, $p> .05$. Despite this result, the increasing trend is clear and in line with the handoff results.

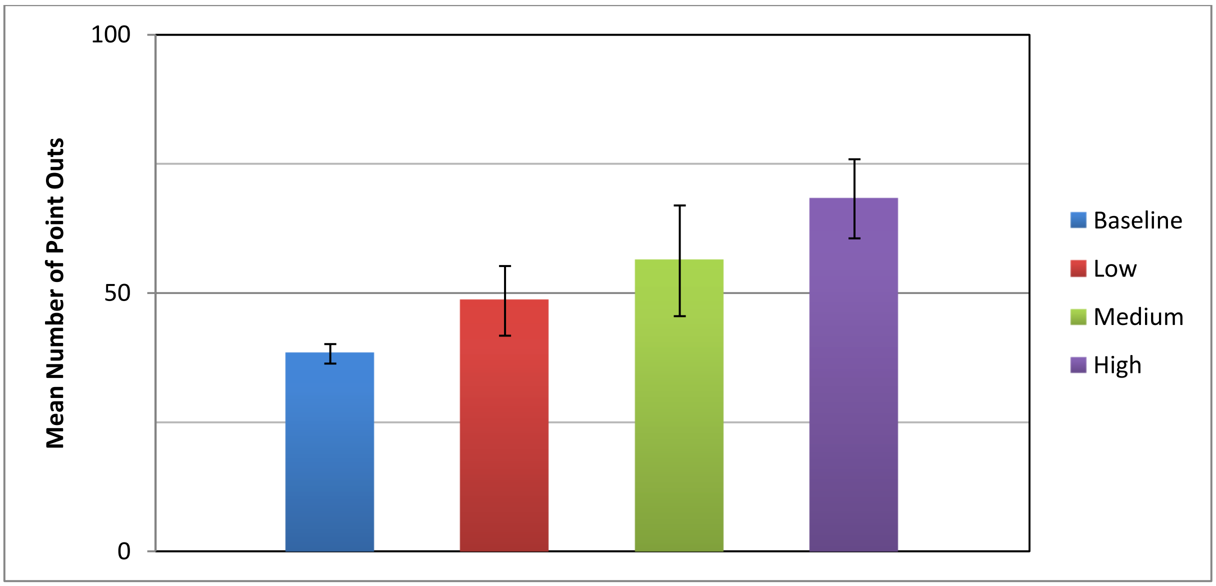


**Figure 14. Mean number of recorded point outs performed for each boundary change condition.**

D. **Workload**

Workload was obtained through prompts displayed on the DSR display in MACS throughout each run. Participants rated their perceived workload based on a 7-point rating scale with one being the lowest possible rating and 7 the highest. The sequences of prompts were at different times in each run according to the boundary change point. Prompts were presented at three minutes and one minute prior to and after the change and every five minutes during periods of 10 minutes or more without a boundary change. The workload results presented here relate to the average workload reported for each run as well as the average workload limited to the time segments surrounding the boundary changes only.

*1. Mean Workload Per Run*

The mean overall workload by condition takes a more general view of the workload that was experienced in each of the boundary change conditions taking into account the time in between boundary changes. Figure 15 shows a consistent upward trend in reported workload corresponding with the boundary change condition. The mean workload reported in the Baseline condition was the lowest at 4.41 (*SD*= 0.84). Results for the Low change condition were higher at 4.85 (*SD*= 0.83) followed by the Medium change condition at 5.02 (*SD*= 0.66) and the High change condition, with the highest mean workload rating of 5.45 (*SD*= 0.45). To look more closely at the differences in mean workload, a one-way repeated measures ANOVA was performed and a significant difference was found, $F(3, 9)= 12.60$, $p< .01$. Tukey's HSD post hoc tests revealed significant differences between the Baseline and Medium ($p<.05$), Baseline and High ($p<.01$), and Low and High ($p<.05$) magnitude change conditions.

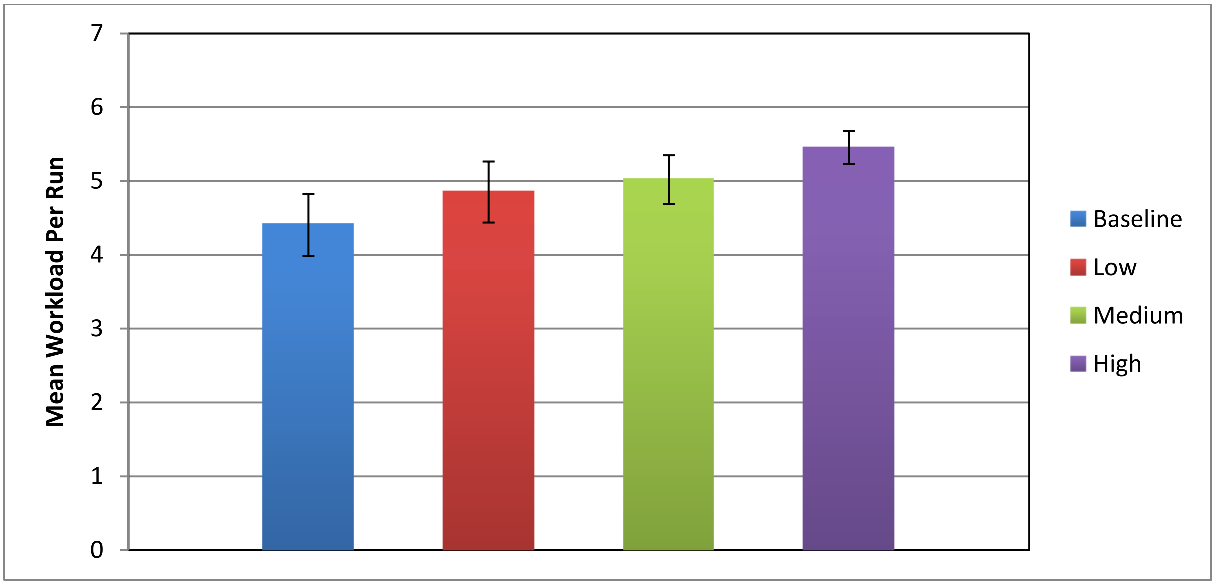


**Figure 15. Mean workload reported throughout the run.**

*2. Workload at the Boundary Change*

The workload used in this portion of the analysis was limited to the ratings observed at the three and one minute prompts on either side of the boundary change. It was thought that this would remove the extraneous factors unrelated to boundary changes and therefore provide a clearer picture of the workload as a function of the boundary change condition. The descriptive statistics for this metric show that, similar to overall workload, the Low magnitude change condition resulted in lower workload relative to the other change conditions with a mean of 4.78 (*SD*= 0.60). The Medium change condition resulted in a mean workload rating of 5.08 (*SD*= 0.93). The High change condition again resulted in the highest workload rating with a mean of 5.65 (*SD*= 0.54). To test the differences in mean workload at the boundary change, a one-way repeated measures ANOVA was performed, which revealed a significant difference, $F(2, 22)= 5.52$, $p< .05$. Tukey's HSD tests also showed a significant difference between the Low and High magnitude change conditions ($p<.01$).

E. **Safety**

The results for safety will cover three areas: number of conflicts, losses of separation, and airspace deviations. Each of these metrics has its own implications on safety with conflicts relating to airspace complexity and potential losses of separation, and airspace deviations and losses of separation falling within the category of operational errors.

*1. Number of Conflicts*

The number of conflicts refers to the number of unique instances of each pair of aircraft detected by the conflict probe within the test area. Excluding false alerts, each of these instances required an action by the controller so it is at once an indicator of safety as well as one for taskload and a contributor to workload as well. Since the goal of airspace sectorizations is not to move aircraft, the number of conflicts should not be significantly impacted by the boundary change conditions. Supporting this hypothesis, the results (Fig. 16) for this metric show that there was approximately the same mean number of conflicts per boundary condition with Baseline having a mean number of 70.00 conflicts (*SD*= 6.63), the Low change condition had a mean number of 64.25 conflicts (*SD*= 13.60), the Medium change condition had a mean number of 62.00 conflicts (*SD*= 7.87), and the High change condition had a mean number of 66.75 conflicts (*SD*= 12.23). Conducting a one-way repeated measures ANOVA on these means did not reveal a significant difference, $F(3, 9)= 1.66$, $p> .05$.

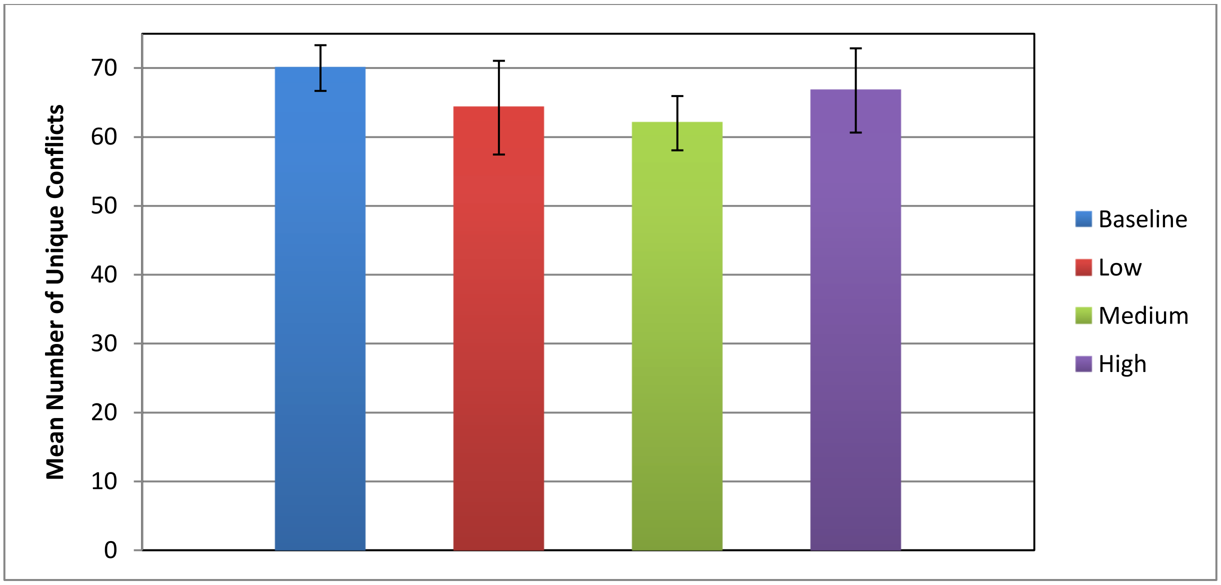


**Figure 16. Mean number of unique conflict occurrences per boundary change condition.**

*2. Losses of Separation*

This category is the most serious as it represents cases where two aircraft violated the separation minima defined by five NM of lateral separation and 1000 feet of vertical separation. Additional categorizations of these events involve Proximity Events where above 90% of the defined minima are maintained and Operational Errors, which represent a violation of the 90% threshold. Figure 17 presents the total counts for this breakdown. Of interest here is that the most consistently difficult boundary change condition-High magnitude change- was the only one to not experience any operational errors. The Medium change condition had by far the most. However, of all of the actual operational errors, an investigation into each revealed extenuating circumstances that either related to simulation artifacts or had greater implications for future concepts related to communications and trajectory based operations. None of the cases merited the drawing of any conclusions of safety based explicitly on any of the boundary change conditions or the DAC concepts as a whole.

| Boundary Change Condition | Proximity Events | Operational Error (LOS) |
|---|---|---|
| **Baseline** | 2 | 1 |
| **Low Magnitude** | 1 | 2 |
| **Medium Magnitude** | 0 | 5 |
| **High Magnitude** | 0 | 0 |

**Figure 17. Total counts of Proximity Events and Operational Errors.**

*3. Operational Deviations*

A less severe safety metric than the loss of separation is an operational deviation. This metric was broken down into three separate components, each representing a different case where an aircraft violated a particular sector's airspace, resulting in an operational deviation. The deviations occurred when the handoffs were initiated late (Late Initiate), where an aircraft is owned by one sector and has entered another sector's airspace without a handoff. Another case was a late handoff bypass (Late Bypass) where an aircraft is in another's sector without a handoff, and then is handed off to a sector further downstream that bypasses the sector that the aircraft is in. The final category of deviations involves the late acceptance of handoffs (Late Accept) (i.e. an aircraft has crossed the sector boundary with an initiated handoff but is not accepted until later). An important note here is that for this study the normal rules of "spinning" an aircraft if a handoff is not accepted were not in effect. Figure 18 presents the total counts across the four boundary change conditions broken down by type of airspace deviation.

For this analysis, the total number of all deviations in each of the scenario types was averaged according to each boundary change condition in order to make a comparison of the means. For the Baseline condition, a mean number of 103.50 deviations (*SD*= 17.02) occurred, with an increasing trend observed starting with the Low change condition (M= 152.00, *SD*= 56.49) continuing with the Medium change condition (M= 155.50, *SD*= 27.19) and the High change condition showing the largest increase in airspace deviations relative to the other change conditions (M= 220.00, *SD*= 16.59). A comparison of the means shows a significant difference through a one-way repeated measures ANOVA, F(3, 9)= 8.81, p< .01. Similar to other analyses, Tukey's HSD tests reveal a significant difference in airspace deviations between the Baseline and High change condition (p< .01).

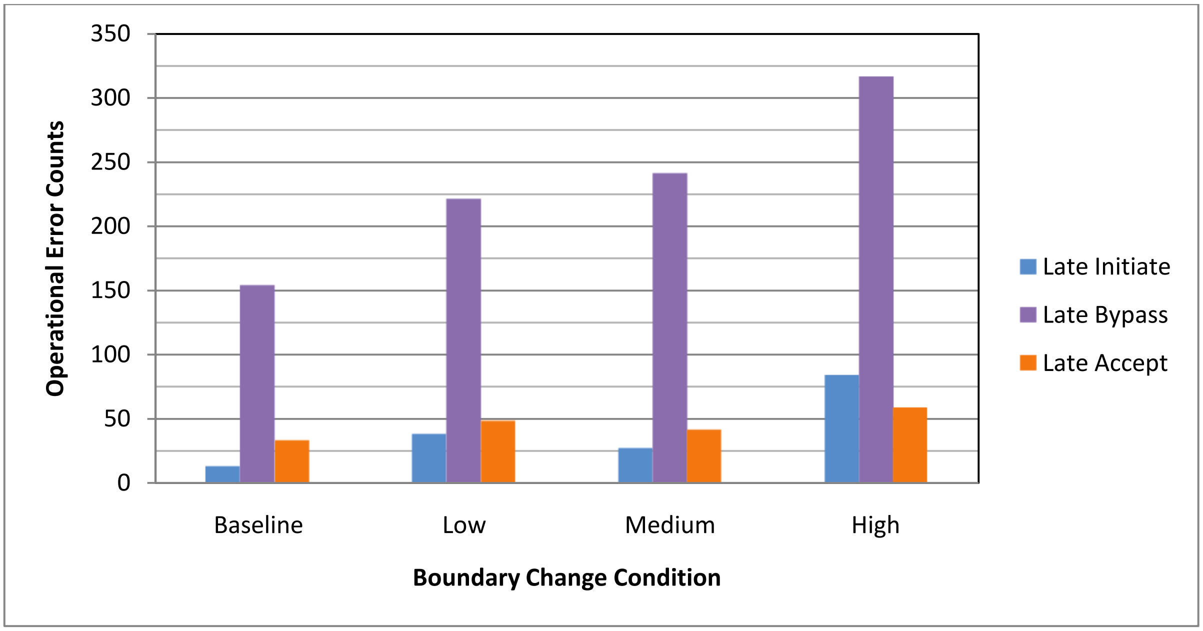


**Figure 18. Total counts of airspace deviations by type.**

## F. **Acceptability**

Following each run, participants were given a questionnaire created specifically for that run. A number of questions were presented in the questionnaire as well as an image of each boundary change as a reminder. One of the questions asked for an acceptability rating, on a scale of one to seven with seven being the most acceptable, for each boundary change. While each boundary change was different, the results presented here take an overall look at acceptability as it applies to the boundary change conditions rather than specific boundary configurations. The results as shown in Fig. 19 reveal a downward trend in acceptability as the magnitude of change increased. The Low magnitude change condition resulted in the highest mean acceptability rating with 6.65 (*SD*= 0.30) while the Medium change condition was slightly lower with a mean rating of 6.04 (*SD*= 0.92). The High magnitude change condition had a much lower acceptability rating for its boundary changes with a mean rating of 4.46 (*SD*= 1.25). A one-way repeated measures ANOVA was conducted to examine the differences in the reported mean acceptability ratings where a significant difference was found, F(2, 22)= 17.63, p< .01. Tukey's HSD tests revealed significant differences between the Low and High magnitude change conditions (p<.01) as well as the Medium and High change conditions (p<.01) meaning that the High magnitude change condition's boundary configurations were significantly less acceptable to the participants than either the Low or Medium change boundaries.

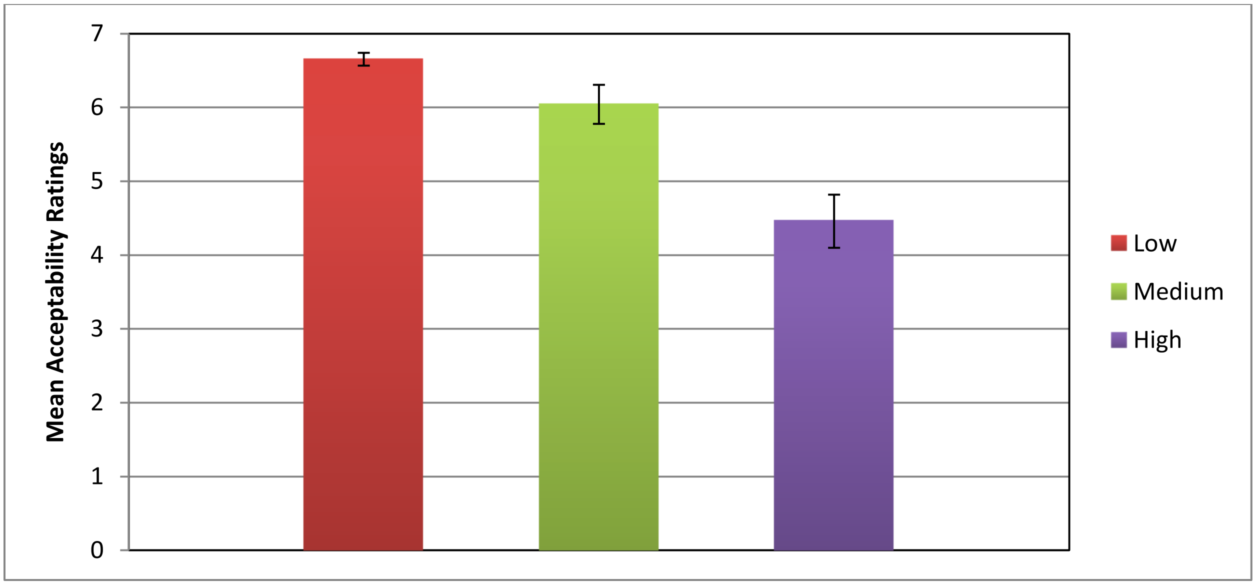


**Figure 19. Mean post-run acceptability ratings for boundary configurations experienced.**

## V. Discussion

This was the first in a planned series of human-in-the-loop simulations designed to examine components of the Dynamic Airspace Configuration concept. The answers sought through this study were to questions concerning some of the basic, fundamental issues surrounding the adaptable airspace concept and its potential impact on the airspace system. The results presented in this paper provide insight into the different forms of impact that some of the different algorithmic approaches had both on traffic and on the human operators.

Three different DAC algorithms were initially selected for their different approaches to the DAC concept as well as for their relative differences in terms of aggressiveness in the changes to sector geometry. The resulting sectorizations from the three algorithms were categorized for this study into Low, Medium, and High magnitude change. The first analyses conducted as part of the larger effort concerned the actual airspace changes that took place in the final sectorizations used in the study with an eye toward quantifying the differences between them. This was done through a comparison of the percentages of airspace gained and lost for each boundary change relative to the previous boundary. In support of the categorization of the sectorizations into the three levels, the results for airspace gained and lost showed significant differences between each of the three magnitude change conditions. Confirming these categorizations was a necessary first step in the analysis due to the fact that this would be the context through which the other results would be framed and was also an integral aspect of how the study was designed and conducted.

The next step in the analysis was to look at how each of the boundary change conditions, this time including the Baseline (no boundary change) condition, managed to effectively distribute traffic loads between sectors. This is, after all, one of the primary purposes of the DAC concept and is therefore important to see how the different approaches to the problem handled this task. Not surprisingly, Baseline showed the greatest amount of variability due to the fact that this was intentional through the construction of the traffic scenarios. Results at this juncture basically show that the Baseline condition was a decent representative example in support of the need for dynamic sectorizations to address demand-capacity imbalances and would serve as an adequate comparison point. The patterns for the three other boundary change conditions, however, were not as straightforward as the Baseline. Some approaches performed better than others depending on the various characteristics of the traffic peaks that they were in response to. The traffic scenarios had two peaks in the traffic pattern with the first exceeding and sustaining traffic counts above the MAP value before dipping back below. The duration of this first peak was not as sustained as that of the later peak, however, and it appears as though this made somewhat of a difference in how the load imbalance was handled. In Fig. 10, one can see that for the shorter peak, the Low magnitude change condition managed to better distribute the traffic followed by the High magnitude change condition and then the Medium change condition. However, as the scenarios progress to the longer peak, there is a reversal where the High magnitude change condition appears to more successfully manage the traffic distribution with the Medium change condition showing a similar behavior. This suggests a potential avenue for further investigation into the relationship between the different sectorizations and particular types of traffic patterns that they might handle. With respect to the handling of the load imbalances during the two scripted peaks, it appears as though the High magnitude change condition did the better job but, as the other results showed, it was at the expense of other factors.

Another indicator of effective traffic distribution was addressed through the analysis of duration of aircraft count over the established MAP value of 22. The trend observed through the analysis was downward, meaning that the Baseline condition sustained the greatest number of minutes that the test sectors had aircraft counts in excess of MAP with each successive increase in boundary change aggressiveness resulting in fewer numbers of minutes. This meant that in the end, the condition with the shortest duration of MAP excess was the High magnitude change condition.

Despite the results showing the effectiveness of the High magnitude change condition, there were other areas that pointed to potential problems. One example of this came in the analysis of aircraft dwell times, which refers to how long aircraft spent in a sector. For these results, shorter time durations can be interpreted as being less desirable because short transit times require a faster turnaround of handoff and point out tasks without the ability to incorporate aircraft into a more stable and coherent operational picture. The factors that can produce these short durations are sector characteristics such as narrow aspect ratios and boundary characteristics like jagged edges as observed in the High change sectorizations. In the end what was observed was that the High magnitude change condition had a significantly shorter duration for dwell time compared to that of the Baseline condition, which also means that an increased level of taskload and workload would likely accompany shorter dwell times due to the extra coordination that would be required in response.

The number of handoffs and point outs across the four boundary change conditions was examined as a partial reflection of taskload and, as just referenced, an inverse relationship between dwell time and taskload was observed. More specifically, for both the comparisons of handoffs and point outs, each progressive level of boundary change magnitude resulted in an increased number of both tasks such that the High magnitude condition had the greatest numbers of both. Analyses of each task showed strong yet non-significant differences in means for handoffs and point outs, but the increasing trends for both tasks are clear and consistent and seem to correlate with dwell time. One note about the results for point outs is that the numbers obtained were a subset and do not provide a full accounting of them. In busy and complex times, a number of point outs were made verbally and for groups of aircraft at a time when certain sector configurations affected many aircraft.

Just as the numbers of handoffs and point outs increased along with boundary change magnitude, so too did the reported workload both in terms of overall workload and the ratings that surrounded boundary changes only. While the tasks surely contributed to workload it is just as certain that there were other factors worth investigating that contributed to workload as well. The results presented in Fig. 15 show overall mean workload ratings that increased with boundary change condition. There was also another piece of data in this presentation that is worth noting, however, and that is the trend in the standard deviation. As the workload increased for each change condition, the standard deviation values decreased. This follows the earlier results for traffic distribution where counts were distributed more evenly among the sectors. As more traffic was evenly distributed, so too was the workload such that in the High magnitude change condition the participants were almost uniformly reporting the same level of high workload. These trends remained constant for workload reported at the boundary changes with a slight decrease in the Low change condition, a slight increase in the Medium change condition, and the greatest increase in the High change condition. One possible interpretation of these trends is that for the Medium and High change conditions, the times of lower workload tended to mask the increased levels of workload associated with the boundary changes.

While workload and taskload do have implications for safety, the results did not entirely follow the same trend nor suggest that any one type of boundary change condition or the DAC concept as a whole was any less safe than the Baseline. In terms of the number of conflicts, there was no significant difference in the number between any of the boundary change conditions. This speaks to one of the virtues of this concept due to the fact that the changing of aircraft trajectories is unnecessary to manage the airspace and demand-capacity imbalance. With more trajectory changes come greater complexity and the greater possibility of creating conflicts that could result in losses of separation. One aspect of safety that did follow the earlier trends was in the area of operational errors with respect to operational deviations. For the three components that were analyzed (late handoff, late handoff bypassing owned sector, and late acceptance of handoff), the number of deviations increased with change magnitude, with the High change condition having the greatest overall numbers for each of the components. A comparison of the means showed that the High change condition had significantly higher numbers of deviations which could have an impact on safety given the right conditions. However, a look at the number of proximity events and separation violations does not support this idea. Looking at the number of actual losses of separation shows that the High change condition actually had none whereas Baseline had one occurrence, the Low change condition had two, and the

Medium change condition had five. An examination of each of these occurrences with respect to the actual events that led to the violation did not reveal any consistencies that could be attributed to anything related to the DAC concept as a whole or any of the particular boundary change conditions.

The final metric that was analyzed was the acceptability of the boundary changes in each of the boundary change conditions (excluding Baseline). This was an important metric to include because the acceptability ratings share a relationship with feasibility in terms of the concept and the ability of the controllers to work in the type of environment envisioned in the concept. As seen in Fig. 19, there is a decreasing trend in the level of acceptability where the Low change condition had the highest acceptability rating followed by the Medium change condition with slightly less, and a more marked decline in acceptability for the boundaries presented in the High change condition.

## VI. Future Directions

The results presented in this paper provide some direction on avenues to take in subsequent research and development. In some ways the results were paradoxical in that as the magnitude of boundary change increased, the management and distribution of traffic became more effective. However, this came with the added cost of taskload and workload and ultimately had a negative impact on acceptability. This suggests that there is not a singular solution or way forward but that, at least with the approaches implemented in this study, there are benefits and useful components in each approach that are worth investigating and considering further. It is also likely that these different benefits are realized through different situations and traffic environments such that a more inclusive or patchwork approach may be the most effective way forward.

Feedback from the participants regarding factors that they felt negatively impacted their ability to control traffic and the acceptability of particular boundary changes provided further guidance on how to move forward both in terms of algorithm and concept development. The factors that they cited as important were large changes in airspace volume, large modifications to the shape of the boundary, large changes in the number or orientation of adjacent sectors and, similarly, changes in the sequence/position of upstream or downstream sectors, large changes in traffic flow, high frequency of boundary changes, and not having adequate preview time in which to handle the transition. Other feedback from the participants pointed to what they felt were key enabling technologies for the concept and environment presented to them in this study to be realized. These technologies were almost unanimously agreed upon, which were data link communications with automatic transfer of control, automated conflict probe, and automated conflict resolution support.

## VII. Conclusion

Taken together, the results and feedback from the study showed that DAC is a promising concept worth further development and refinement. The results also present researchers with a number of items and issues to consider and incorporate into future work in making DAC viable. It appears as though a number of tradeoffs are required if some middle ground is to be met between how the demand-capacity imbalance is most effectively addressed and how best to do that while keeping the human controller integrated and functioning meaningfully within the system. Based on the results from this study, further research can begin addressing these issues.


## Acknowledgments

This work was funded by NASA's Airspace Systems Program and NextGen-Airspace Project. The authors would like to thank the participants in this study and the algorithm developers for their hard work and unending patience. Thanks must also go to the MACS development team for making the study possible.


## References


[1]Federal Aviation Administration, "FAA Aerospace Forecast Fiscal Years 2009-2025," Washington, DC, 2009, p.31.

[2]Lee P., Corker K., Smith N., Prevôt T., Martin L., Mercer, J., Homola J., & Guneratne E., "A Human-in-the-loop Evaluation of Two Multi-Sector Planner Concepts: Multi-D and Area Flow Manager" *25th Digital Avionics Systems Conference (DASC)*, Portland, OR., 2006.

[3]Corker, K., Liang, D., Lee, P., & Prevôt T., "New Air Traffic Management Concepts Analysis Methodology: Application to Multi-Sector Planner in US Airspace," *Air Traffic Control Quarterly*. Vol. 15, no. 4, 2007, pp. 347-367.

[4]Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE), "En-route Multi Sector Planning Procedures," 1997, PHARE document DOC 97-70-15.

[5]Kopardekar, P., Bilimoria, K., & Sridhar, B., "Initial concepts for Dynamic Airspace Configuration," *7th Aviation*

*Technology, Integration and Operations (ATIO) Seminar*,AIAA, Belfast, Northern Ireland, 2007.
[6]Lee, P., Mercer, J., Gore, B., Smith, N., Lee, K., & Hoffman, R., "Examining Airspace Structural Components and Configruation Practices for Dynamic Airspace Configuration," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Honolulu, HI., 2008.
[7]Zelinski, S., "A Comparison of Algorithm Generated Sectorizations," *8th USA/Europe Air Traffic Management Research and Develpoment Seminar (ATM)*, Napa, CA., 2009.
[8]Klein, A., Rogers, M., and Kaing, H., "Dynamic FPAs: A New Method for Dynamic Airspace Configuration," *Integrated Communications Navigation and Surveillance (ICNS) Conference*, Bethesda, MD. 2008.
[9]Klein, A., Rogers, M., and Leiden, K., "Simplified Dynamic Density: A Metric for Dynamic Airspace Configuration and NEXTGEN Analysis," *27th Digital Avionics Systems Conference (DASC)*, St. Paul, MN., 2008.
[10]Kopardekar, P., & Magyarits, S., "Measurement and prediction of dynamic density," *5th USA/Europe Air Traffic Management R&D Seminar*, Budapest, Hungary, 2003.
[11]Kopardekar, P., Schwartz, A., Magyarits, S., & Rhodes, J., "Airspace complexity measurement: an air traffic control simulation analysis," *7th USA/Europe Air Traffic Management R&D Seminar*, Barcelona, Spain, 2007.
[12]Brinton, C. and Pledgie, S., "Airspace Partitioning using Flight Clustering and Computational Geometry," *27th Digital Avionics Systems Conference (DASC)*, St. Paul, MN., 2008.
[13]Drew, M., "Analysis of an Optimal Sector Design Method," *27th Digital Avionics Systems Conference (DASC)*, St. Paul, MN., 2008.
[14]Yousefi, A., Khorrami, B., Hoffman, R., and Hackney, B., "Enhanced Dynamic Airspace Configuration Algorithms and Concepts," Metron Aviation Inc., Technical Report No. 34N1207-001-R0., 2007.
[15]Prevôt, T., "Exploring the Many Perspectives of Distributed Air Traffic Management: The Multi-Aircraft Control System MACS," *International Conference on Human-Computer Interaction in Aeronautics (HCI-Aero)*, Cambridge, MA. 2002.
[16]Erzberger, H., "The Automated Airspace Concept," *4th USA/Europe ATM R&D Seminar*, Santa Fe, NM. (2001).
[17]Lee, P., Smith, N., Prevot, T., Homola, J., Lee, H., Kessell, A., & Brasil, C., "Impact of airspace reconfiguration on controller workload and traffic performance," 3rd *International Conference on Applied Human Factors and Ergonomics (AHFE)*, Miami, FL., 2010, (to be published).
[18]Jung, J., Lee, P., Kessell, A., Homola, J., and Zelinski, S., "Effect of Dynamic Sector Boundary Changes on Air Traffic Controllers," *AIAA Guidance, Navigation, and Control Conference*, Toronto, Canada, 2010, (to be published).