CHAPTER X

Impact of Airspace Reconfiguration on Controller Workload and Task Performance

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INTRODUCTION

In the National Airspace System, a key aspect of air traffic management is to adapt to changing traffic demand, traffic flow, and airspace/system constraints while maintaining safe and efficient operations. In the Next Generation Air Transportation System (NextGen), the traffic is predicted to increase substantially, creating an environment in which effective balancing of demand and capacity becomes a high priority.

When a particular airspace cannot meet the traffic demand due to factors such as aircraft density, traffic complexity, or weather, the Air Navigation Service Provider (ANSP) manages the problem by various flow contingency management techniques, such as rerouting traffic flow away from constrained areas, issuing miles-in-trail requirements and/or ground stops.

In Flexible Airspace operations, we expect that the demand-capacity balance can be achieved by selectively managing the airspace capacity in conjunction with managing the traffic demand. Instead, or in addition to, reducing the traffic demand to address the demand-capacity imbalance, sector boundaries can be flexibly reconfigured to redistribute the traffic volume and demand across sectors

(Kopardekar, Bilimoria, & Sridhar, 2007; Lee, et al., 2008). In such operations, the demand and capacity can be calculated for one to two hours into the future to identify sectors that could exceed the traffic threshold as well as sectors that are under-utilized. Using various airspace optimization algorithms, airspace can be reconfigured to manage the existing traffic demand without moving aircraft away from existing routes. A number of airspace optimization algorithms are currently being explored to find the best ways to reconfigure the airspace (e.g., Yousefi, Khorrami, Hoffman, & Hackney, 2007; Klein, Rodgers, & Kaing, 2008; Brinton & Pledgie, 2008; Zelinski, 2009).

EXPLORING FEASIBILITY OF FLEXIBLE AIRSPACE RECONFIGURATION

Flexible airspace management already exists today to a limited extent. For example, sectors are combined daily whenever traffic flow significantly decreases through an airspace and reopened as traffic increases. A wider implementation of flexible airspace management, general questions related to where, how often, and how fast the sector boundary changes can occur need to be examined, because there may be an adverse impact of flexible sector boundary changes on the ANSPs. Better understanding of the ANSPs' abilities to handle the transition is needed. Some of the fundamental questions related to airspace changes and their impact on the ANSPs are as follows:

- Which airspace-related factors (e.g., airspace volume change, number of aircraft affected by the boundary change, etc.) significantly impact controllers during a boundary change?
- How often can airspace be changed?
- When is airspace change feasible?

A human-in-the-loop simulation was conducted in 2009 to address some of the questions posed above. Traffic scenarios with varying types and severity of boundary changes (BCs) were used to test their impact on the controllers. Per each boundary change, metrics such as airspace volume change, number of aircraft, and various task loads (e.g., handoffs, pointouts, etc.) were compared against subjective metrics such as workload and acceptability, as well as the safety implications in terms of separation losses and other operational errors.

PARTICIPANTS

There were four test participants. Three were operations supervisors from Washington Center (ZDC), Atlanta Center (ZTL), and Indianapolis Center (ZOA), and one a recently retired controller for Oakland Center (ZOA) who had actively controlled traffic within the last four 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, retired controllers from ZOA performed the duties of Area Supervisor, two Radar Associates (RAs), and “ghost” controllers responsible for all aircraft outside of the test airspace. 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 or students from the San Jose State University aviation department.

AIRSPACE

The test sectors were adapted from four high altitude sectors in Kansas City Center (ZKC). The four test sectors, i.e., ZKC sectors 94, 98, 29 and 90, were surrounded by the “ghost” sectors that handled the traffic that entered and exited the test sectors.

The flows in the test scenarios consisted mostly of aircraft in level flight, with a small mix of arrivals and departures to and from the area airports. The minimum altitude of these over-flights was FL 290 with maximums being dependent upon aircraft characteristics. In general the East-West flows in these scenarios were slightly heavier than the flows running North-South. Two main traffic scenarios were created for the study. Both scenarios created traffic overload for sectors 94 and 90 while the sectors 98 and 29 had capacity to absorb the excess demand.

EXPERIMENT DESIGN

The experiment consisted of four test conditions. A ***Baseline*** condition with no boundary changes was used to establish the baseline workload and other performance metrics. Three additional conditions consisted of ***Low, Medium,*** and ***High*** severity of BCs (see Figure x.1). Three airspace resectorization algorithms were selected based upon their approach and aggressiveness related to the magnitude of the sector boundary change and were labeled as Low, Medium, and High accordingly. The algorithms that were leveraged for this study are a part of ongoing research effort at NASA to explore different ways to create dynamic sectorizations.

For each BC, we measured various airspace-related factors, BC frequency (i.e., time difference from the last BC) and the total number of aircraft. We expect to correlate these factors with subjective metrics such as workload and acceptability ratings and objective metrics, like operational deviations and errors.

The simulation was conducted over eight days in 2009. There were three days of training followed by 4.5 days of data collection runs that concluded with debrief discussions and questionnaires. There were 16 full data simulation runs in total.

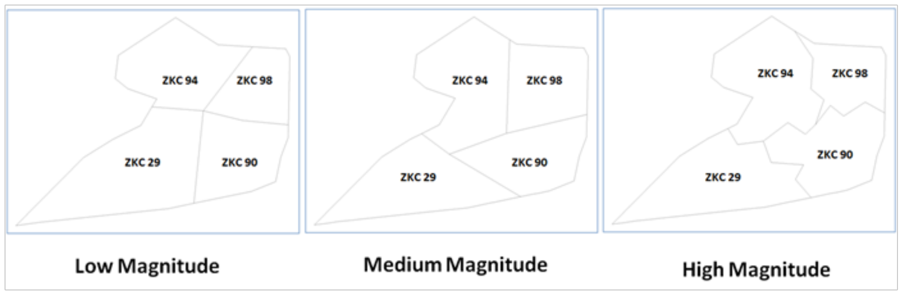

FIGURE x.1: Example of Low, Medium, and High Magnitudes of Boundary Change Severity

TECHNOLOGY ASSUMPTIONS AND TOOL CAPABILITIES

The technology assumptions for the study were modeled after the assumptions in High Altitude Airspace (HAA). For the study, all aircraft were flying under Trajectory-Based Operations, flying along 4-D trajectories at a high Required Navigation Performance (RNP) conformance. They were assumed to be equipped with air-ground Data Communication (Data Comm) with automated transfer-of-communication (Auto-TOC) as they were handed off between sectors. All positions still had ground-ground and air-ground voice communication channels as they do today. The radar controller (R-side) had integrated conflict detection and resolution (CD&R) capabilities integrated into their displays.

The simulation platform used for the study was Multi-Aircraft Control System which provided a high fidelity emulation of the Display System Replacement (DSR) controller workstation. This DSR emulator was highly configurable to mimic both DSR workstations in the field today and future DSRs with advanced decision support tools (DSTs).

For the study, air-ground Data Comm and CD&R were integrated with route planning tool. Conflict detection tool probed for conflicts along the 4-D trajectories and alerted the controllers in case of conflicts. Controllers then used an interactive trial planning tool to plan either a lateral or vertical maneuver to resolve the conflict. A trial plan was constructed and manipulated using a trackball and the route information was displayed graphically. The conflict resolution could also be constructed using an automated conflict resolver, which could be invoked by the controller and used as another DST. Once a resolution was completed the resultant trial plans were uplinked to the aircraft via Data Comm. The advanced air and ground-side DSTs were integrated with Data Comm and the Flight Management System to allow controllers and pilots to exchange and implement 4-D trajectory information quickly. Sector handoff was manually initiated by the transferring controller. When the handoff was accepted, a frequency change uplink message was automatically sent to the aircraft.

In addition to assumptions related to HAA, we assumed that both radar and radar associates had the same displays and tools to monitor and issue clearances to the aircraft. We also assumed that sector boundary changes can be constructed from one position and propagated flexibly both at the sector positions and other locations throughout the Center and beyond (e.g., Command Center). The sector boundary changes were assumed to be accessible to the controllers via a “preview” function which displayed both the current and future sector boundaries on their displays along with the impacted traffic.

PROCEDURE

Upon arrival, participants were given a brief introductory briefing on the Flexible Airspace concept, followed by hands-on training on the airspace, tools, and the traffic scenarios.

FIGURE x.2: Test Area with 4 Radar, 2 Radar Associate, and Area Supervisor Stations

For the training and the data collection, the participants used radar controller stations that were similar to the ones that they use in actual operations. Stations were used as four radar displays in the corners and two RA displays were located between these (see Figure x.2). In addition to these six stations, an Area Supervisor’s station was configured similarly to the controller stations but with extra displays for load awareness. Two side-by-side projectors were connected to the Area Supervisor’s station and projected a Traffic Situation Display with a real-time display of traffic. Once the participants felt sufficiently comfortable with the new tools and NextGen operations in general, they continued their hands-on training with BCs. In a BC, the Area Supervisor previewed the BCs and monitored when the next BC would occur. In the simulation, the sector boundary changes were pre-calculated by various algorithms and scripted to occur at a pre-designated time.

Once the Area Supervisor reviewed the BC and the predicted traffic levels for all sectors before and after each BC, he assigned RA controllers to the sectors that needed the most help. The supervisor first coordinated the plan with the RA controllers (5 to 10 minutes in advance) and then they coordinated with the R-side controller at three minutes prior to the BC. At three minutes, the R-side saw an upcoming BC preview displayed on their DSR screen. Figure x.3 shows what a boundary preview might look like during the simulation.

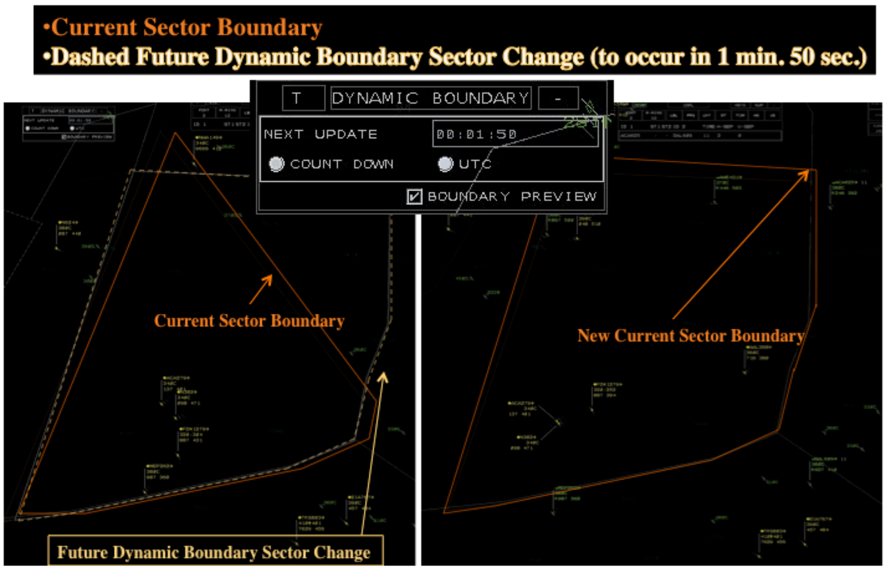

FIGURE x.3: Controller display during a boundary change

The R-side controllers previewed the BCs on their displays. By examining their own sector before and after a BC, controller participants calculated which aircraft should have their control transferred. The sector controller, who no longer owned the airspace but still owned the aircraft, initiated handoffs for the impacted aircraft to the appropriate receiving controller. Radar Associate's help was available to handle workload during this transition. The receiving controller accepted the handoff. The Auto-TOC was then executed via Data Comm. Either the initiating R-side or RA briefed the receiving controller about the traffic situation if necessary. Finally, pilots checked in to the new sector once TOC was completed.

EXPERIMENTAL METRICS

We have collected and analyzed a number of airspace-related factors in this NextGen environment which may impact controller workload and the feasibility of the operations during BCs. We list below the independent and dependent variables collected for the study.

Independent Variables

The Table x.1 describes the airspace-related factors that may have impact on controller workload and operational feasibility during the boundary changes. These metrics are calculated for each BC by averaging the values across the four test sectors. For some metrics such as aircraft count, handoffs, and pointouts, a period of +/- 3 minutes around BCs was used to average the values for the corresponding BC. The duration was chosen because the controllers started to preview the new sector boundaries starting at -3 minutes to the BC and it took approximately 3 minutes after the BC for the controllers to become accustomed to the new sector boundaries.

Table x.1 Potential Factors that Impact Controllers

Variable Name	Description
BC_Frequency	Frequency of boundary changes = time duration (in min) from the last BC to the current BC.
AC_Gained_Lost	Average number of aircraft (AC) that changed geographic sector at the BC. For each BC, average AC gained across four test sectors are the same as average AC lost.
SectorCnt_AC_Gained_Lost	Number of sector pairs (12 possible pairs = 4 sectors X 3 neighboring sectors) that have aircraft that change sectors at the BC. This metric is calculated in case there is an adverse impact due to the number of sector pairs that needs to coordinate rather than the number of aircraft that needs to change ownership.
P_Vol_Gained	Average percentage of volume gained per sector.
P_Vol_Lost	Average percentage of volume lost per sector.
SectorCnt_Vol_Gained_Lost	Number of sector pairs (12 possible pairs) that have sectors that gained or lost volume at the BC.
AC_Count	Average number of aircraft in the sector at +/- 3 minutes around the boundary change.
Conflict_Count	Average number of conflicts in the sector at +/- 3 minutes around the boundary change.
HO_Init	Average number of handoffs initiated per sector during +/- 3 minutes around the boundary change.
HO_Accept	Average number of handoffs accepted per sector during +/- 3 minutes around the boundary change.
HO_Cancel	Average number of handoffs initiated but subsequently cancelled per sector during +/- 3 minutes around the boundary change.
Pointout	Average number of pointouts per sector during +/- 3 minutes around the boundary change.
Sector_Dir_Change	Change in the long axis of the sector (in degrees).
Hausdorff	Calculates “similarity” of sectors before and after the BC.

Dependent Variables

To assess the impact of airspace reconfiguration on controller workload and operational feasibility, the following four metrics were measured and calculated during the BCs (see Table x.2).

Table x.2 Controller Ratings on Workload and Acceptability

Variable Name	Description
PostRun_WL	Workload ratings (1 – 7 scale) for each boundary change taken after each simulation in a post-run questionnaire.
RealTime_WL	Average workload ratings (1 – 7 scale) at +/- 3 minutes of the boundary change, taken real-time during the simulation run.
BC_Workload	Workload ratings at the boundary change – workload ratings in the Baseline condition at the corresponding traffic scenario.
Acceptability	Acceptability ratings (1 – 7 scale) for each boundary change taken during post-run questionnaire.

In addition to the metrics above, metrics related to operational deviation were measured (see Table x.3). These metrics are expected to occur whenever the BCs and/or traffic situation becomes severe and infeasible, which in turn are likely to impact the controller workload and result ultimately in operational deviations.

Table x.3 Metrics Related to Operational Deviation

Variable Name	Description
Late_HO_Init	Number of handoffs that were initiated after the aircraft already entered the downstream sector.
Late_HO_Accept	Number of handoffs that were accepted too late after the aircraft already entered one's own sector (Late handoffs due to late handoff initiations were excluded).
Sector_Bypassed	Number of aircraft that are handed off to the next sector prior to entering one's own sector. This often happens when aircraft is handed off to a sector with short transit time. Short transit time can be due to an inappropriate handoff (instead of pointout) or a bad sector design.

RESULTS

Our initial hypothesis on the impact of sector boundary changes on the controllers was that the BCs would cause high workload whenever a large number of aircraft changed ownership from one sector to another via handoff. The prediction was that large airspace volume changes would require greater numbers of aircraft to change sectors, which would result in excessive workload thereby making the transition infeasible. We also identified and assessed other factors that may be correlated with operational feasibility.

Results were initially analyzed by BC severity conditions and summarized by Homola and colleagues (submitted). The summary is given in the following section but will quickly move onto the main focus of this paper, which is to link the airspace-related factors directly to the workload, acceptability, and performance metrics to examine their relationships.

SUMMARY OF RESULTS BY CONDITIONS

Table x.4 shows the controller workload/acceptability ratings of the BCs by BC condition. The results suggest that both the overall workload and BC workload at the boundary change increased (1 to 7 scale; 1=low; 7=high) and acceptability decreased with increasing BC severity as expected. The absent data in the Baseline condition are due to the questions not being asked of the participants.

Table x.4 Results from Controller Workload and Acceptability Ratings

Metrics	Baseline (No BC)	Low	Medium	High
PostRun_WL		4.75	4.99	5.65
RealTime_WL	4.48	4.75	5.00	5.48
BC_Workload		0.41	0.62	1.10
Acceptability		6.67	6.08	4.65

Table x.5 summarizes the results from factors that may impact the controller workload and performance. Given that controller workload and acceptability ratings were impacted by BC severity conditions, we examined if these factors also correlate with the experimental conditions. The results suggest that most of the factors that we identified, such as aircraft gained/lost, airspace volume change (e.g., P_Vol_Gained), and handoff related events (e.g., InitHO), increased with increasing BC severity as we hypothesized. Factors such as overall aircraft count, conflict count, and aircraft density did not significantly differ as expected since the aircraft in the simulation were left on their original path as much as possible, leaving the demand set and the traffic situation similar across conditions. Table x.6 shows the results related to late handoff initiation/acceptance and handoffs to the downstream sector prior to entering one's own sector (Sector_Bypassed). The results show a general increase as BC severity increased, with an exception of relatively high counts for late handoffs in the Low severity condition. A more detailed look at the data suggested that the high values come mainly from one BC in particular which had numerous late handoffs in two of the sectors. The actual explanation for the deviation is yet undetermined and needs further investigation.

Table x.5 Results from Potential Factors that Impact Controllers

Metrics	Baseline (No BC)	Low	Medium	High
AC_Gained_Lost		1.70	2.27	4.31
SectorCnt_AC_Gained_Lost		3.09	3.50	4.75
P_Vol_Gained		10.04	13.07	24.74
P_Vol_Lost		7.99	11.16	22.51
SectorCnt_Vol_Gained_Lost		3.82	5.08	6.25
AC_Count	18.27	18.05	17.99	17.91
Conflict_Count	0.81	0.85	0.88	0.85
HO_Init	11.50	12.40	12.94	14.10
HO_Accept	10.82	10.92	11.67	11.94
HO_Cancel	0.18	0.48	0.50	0.73
Pointout	1.09	1.58	1.85	2.56
Sector_Dir_Change		23.93	17.22	32.40
Hausdorff		36.35	33.91	49.72

Table x.6 Results from Metrics Related to Operational Deviation

Metrics	Baseline (No BC)	Low	Medium	High
Late_HO_Init	0.05	0.29	0.15	0.73
Late_HO_Accept	0.23	0.38	0.25	0.27
Sector_Bypassed	1.02	1.63	1.85	2.35

Overall, the results from this analysis suggest that BC severity has an impact on both the controller workload and operational feasibility and is correlated with our proposed airspace-related factors. In the following section, this relationship will be more directly examined via correlation and regression analyses.

Analysis of Boundary Change Factors

The examination of the BC factors was done by taking each BC as a sample. The data from the four test sectors were averaged into a single value for the analysis. Some metrics, such as workload and conflict count, were taken over +/- 3 minutes of the BC as an acceptable time duration that was impacted by the BC.

Correlation of Dependent Variables

PostRun_WL and RealTime_WL metrics had high correlation with each other, as expected since they both evaluated workload (see Table x.7). Since these two metrics were highly correlated, subsequent analyses will focus on only one of the variables, namely RealTime_WL. Correlation between the workload ratings and the other two metrics, namely BC_Workload and Acceptability, also had high correlation. Operational deviation factors (e.g., late handoffs) were also correlated with each other and the results show that Late_HO_Init correlated well with Late_HO_Accept but Sector_Bypassed did not correlate well with the other factors.

Table x.7 Correlation between Workload and Acceptability Ratings

Pearson Correlation	PostRun_WL	RealTime_WL	BC_Workload	Acceptability
PostRun_WL	1			
RealTime_WL	0.768**	1		
BC_Workload	0.453**	0.608**	1	
Acceptability	-0.599**	-0.513**	-0.412*	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Correlation of Independent Variables

A number of variants on the airspace volume change and aircraft with ownership change were defined to see which of these factor variants would be most relevant. Unfortunately, five of the factors correlated strongly with each other (see Table x.8). This implies that the later regression analyses will not be able to identify the individual contribution from these factors and when one of the factors is chosen in the model, the others are likely to be excluded since they capture the same variance in the model. These factors also correlated with SectorCnt_Vol_Gained_Lost, HO_Init, Pointouts, and Sector_DirChange, and, to a lesser extent, with AcceptHO.

Table x.8 Correlation of Factors related to Airspace Volume Change

Pearson Correlation	AC_ Gained_ Lost	SectorCnt_ AC_Gained_ Lost	P_Vol_ Gained	P_Vol_ Lost	Hausdorff
AC_Gained_ Lost	1				
SectorCnt_AC_Gained_Lost	0.806**	1			
P_Vol_Gained	0.871**	0.777**	1		
P_Vol_Lost	0.911**	0.803**	0.967**	1	
Hausdorff	0.709**	0.733**	0.856**	0.827**	1

** Correlation is significant at the 0.01 level (2-tailed).

Factors that Impact Overall Workload Ratings

After each simulation run, the controller participants were asked to rate the overall workload at the BC and identify factors that had caused high workload. They listed following factors (accompanied by its simulation metric names) as high workload contributors:

- ***Heavy traffic volume*** – AC_Count
- ***Large number of aircraft that changes ownership*** – AC_Gained_Lost and SectorCnt_AC_Gained_Lost
- ***Tasks initiated by a controller*** –Pointout
- ***Too many overlapping data blocks***

Overall workload ratings (RealTime_WL) were correlated with dependent variables using Pearson correlation with $p < 0.05$. The correlated factors are:

- ***Number of aircraft*** – AC_Count
- ***Aircraft that changes ownership*** – AC_Gained_Lost and SectorCnt_AC_Gained_Lost
- ***Airspace volume change*** – P_Vol_Gained, P_Vol_Lost, and SectorCnt_Vol_Gained_Lost
- ***Sector similarity*** – Hausdorff
- ***Operational deviation*** – Late_HO_Init, Late_HO_Accept, and Sector_Bypassed

Hierarchical Stepwise Regression was used to narrow which of these factors contributed most to controller workload. The stepwise regression was set up in two levels – the first level contained all of the correlated factors described above and the second level contained the rest of the factors. The results from this analysis suggested that three factors, namely, airspace volume change (P_Vol_Gained), overall aircraft count (AC_Count), and late handoff acceptance (Late_HO_Accept), provided good fit to the workload data, resulting in R^2 of 0.683 (see Table x.9).

Table x.9 Factors related to Overall Workload

		b	SE b	Beta	R^2
Step 1					0.367
	Constant	4.44	0.18		
	P_Vol_Gained	0.04	0.01	0.61***	
Step 2					0.588
	Constant	0.64	0.92		
	P_Vol_Gained	0.04	0.01	0.58***	
	AC_Count	0.21	0.05	0.47***	
Step 3					**0.683**
	Constant	0.97	0.82		
	P_Vol_Gained	0.04	0.01	0.59***	
	AC_Count	0.19	0.05	0.41***	
	Late_HO_Accept	0.45	0.14	0.31**	
***p < 0.05, **p < 0.01, ***p< 0.001**					

The workload ratings at the BC seem to be driven by airspace volume change (and the associated highly correlated factors such as airspace gained/lost) and the number of aircraft at the BC. The late handoff acceptance may be driven by high workload, but is also likely to create high workload once they occur.

Factors that Impact BC Workload Ratings

The factors that correlate with workload change from Baseline (BC_Workload) were identified using Pearson correlation with $p < 0.05$. Unlike the overall workload ratings, BC_Workload did not correlate with the overall aircraft count. It was correlated with following variables:

- ***Aircraft that changes ownership*** – AC_Gained_Lost, and SectorCnt_AC_Gained_Lost
- ***Airspace volume change*** **–** P_Vol_Gained and P_Vol_Lost,
- ***Tasks initiated by a controller*** – HO_Init and Pointouts,
- ***Sector direction change***
- ***Sector similarity*** – Hausdorff
- ***Operational deviation*** – Late_HO_Init and Sector_Bypassed

Both aircraft gained/lost and increased pointouts were mentioned in the subjective feedback as workload contributors. Hierarchical Stepwise Regression on the above factors identified only a single factor, namely, handoff initiation (HO_Init) to explain BC_Workload. The model provided good fit the data, resulting in R^2 of 0.501 (see Table x.10).

Table x.10 Factors related to the BC Component of Workload

		b	SE b	Beta	R^2
Step 1					**0.501**
	Constant	-2.56	0.76		
	HO_Init	0.26	0.05	0.71***	
***p < 0.05, **p < 0.01, ***p< 0.001**					

Factors that Impact Acceptability Ratings

After each simulation run, the controller participants rated the overall acceptability of each BC and identify the following factors to cause low acceptability:

- ***Large changes in sector size or geometry*** – P_Vol_Gained, P_Vol_Lost, SectorCnt_Vol_Gained_Lost, and Hausdorff
- ***Too many coordination due to pointouts and handoffs*** – HO_Init, HO_Accept, and Pointout
- ***Too much or not enough airspace*** **–** overall sector volume
- ***Sector shape not aligned with the traffic flow***

The factors that correlate with overall acceptability ratings capture some of the same factors but included many others not mentioned explicitly by the controller participants. The factors were identified using Pearson correlation with $p < 0.05$ and are shown below:

- ***Aircraft that changes ownership*** – AC_Gained_Lost and SectorCnt_AC_Gained_Lost
- ***Airspace volume change*** – P_Vol_Gained, P_Vol_Lost, and SectorCnt_Vol_Gained_Lost
- ***Tasks initiated by a controller*** – HO_Init , HO_Cancel, and Pointout
- ***Sector Direction Change***
- ***Sector similarity*** – Hausdorff
- ***Operational deviation*** – Late_HO_Init and Sector_Bypassed

Despite numerous factors that correlated with acceptability ratings, Hierarchical Stepwise Regression on the above factors identified only a single factor, namely, the number of aircraft gained/lost to explain the acceptability. The model fit the data very well, resulting in R^2 of 0.794 (see Table x.11).

Table x.11 Factors related to the Acceptability Ratings

		b	SE b	Beta	R^2
Step 1					**0.794**
	Constant	7.27	0.23		
	AC_Gained_Lost	-0.54	0.06	-0.90***	
***p < 0.05, **p < 0.01, ***p< 0.001**					

The acceptability of the BC seems to be driven by the number of aircraft that changed ownership as a result of the BC. It is somewhat interesting that the participants considered the airspace volume change to be a contributor to the acceptability and the aircraft ownership change to the workload, while the regression analyses suggest the inverse –i.e., airspace volume change is the main workload predictor and the aircraft ownership change is the acceptability predictor. Since these two metrics were highly correlated, however, these factors can probably be used interchangeably for the regression analyses.

Factors that Impact Operational Deviations

Due to space limitations, only the regression results are reported for the operational deviations (e.g. late handoff initiation/acceptance). For the late handoff initiations, the regression identified the acceptability rating to be the only contributor with R^2 of 0.487 – i.e., low acceptability ratings are likely to result in high number of late handoffs. The late handoff acceptance identified the frequency of the BC with R^2 of 0.251. The relationship between these two factors is not clear and requires further examination.

Finally, the regression analysis for the bypassed sectors identified three factors, namely, aircraft gained/lost, overall aircraft count, and the number of pointouts with combined R^2 of 0.670. The frequency of bypassing a sector seems to be correlated with increased number of aircraft and aircraft that switch sectors, as well as the pointouts that are needed possibly due to bad sector design and/or routes that clip a corner of a sector. Other sector design related factors, such as sector transit time, may provide an additional insight into the traffic situation that causes the bypassed sectors.

SUMMARY AND CONCLUSION

This study explored the controllers' ability to handle the sector boundary changes (BCs) in various conditions from relatively easy (e.g., small volume changes, few aircraft that changes sector ownership, etc.) to very difficult (e.g., large volume and aircraft changes, rapid frequency of the change, etc.). The main questions of the study were identification of the airspace-related factors that predict controller workload and operational feasibility during the BCs and whether the frequency and/or the timing of the BCs adversely impact operational feasibility.

In the study, controllers managed high traffic load during each BC, gave workload/acceptability ratings for each BC and commented on the BCs that were considered problematic. Subjective feedback suggested that overall traffic volume and the task load related to aircraft gained/lost during BCs were the main workload contributors. They also suggested that a BC was less acceptable for severe volume changes and when it required excessive coordination (e.g., pointouts) either due to bad sector design or short transit time. Additionally, workload/acceptability ratings and the airspace-related factors resulted in significant correlations with many of the variables identified by the participants.

Hierarchical stepwise regression narrowed the explanatory variables for workload to be airspace volume change, aircraft count, and number of late handoff acceptance. Since prior research showed aircraft count to be the main predictor of workload, it is notable that airspace volume change was a better predictor than the aircraft count during BCs. Hierarchical stepwise regression of the acceptability ratings identified aircraft gained/lost as the single predictor of the ratings.

A BC component of the workload was isolated by subtracting Baseline workload from the BC condition for the same scenario / traffic at the same time duration. Hierarchical stepwise regression of the BC workload component suggested that the number of handoffs initiated was the single predictor of the BC workload component.

Subjective feedback on workload and acceptability identified aircraft gained/lost during BC and airspace volume change as their main predictors, respectively, while the regression analysis swapped the predictors, which suggests the high correlation between these two predictors might make them interchangeable in this analysis. Unless BC is pre-selected to be at a time when the aircraft count is low, larger volume change will naturally result in an increased number of aircraft that need to change sector ownership. Further studies that control for the aircraft in transition while varying the airspace volume change are needed to tease apart the individual impacts of these two predictors.

In addition, the two predictors, aircraft and volume change, may have had weak correlations if the operational procedure and tools allowed the handoffs to be automated during the BC. In such situations, large volume change may still cause high cognitive workload to monitor the changes but the number of aircraft that change sectors may no longer matter as much. Automated handoff will also likely eliminate handoff initiation as the main predictor of the BC component of the workload.

In the overall analysis, BC frequency was not correlated with either workload or acceptability. Observations also supported that as long as controllers had enough time to prepare for each BC (three minutes in this study), high BC frequency did not pose a major problem. In terms of the timing of the BC, finding and/or creating an appropriate time when fewer aircraft are present would help reduce the BC workload. Participants commented that they would be able to handle large volume changes if they had sufficient transition time to monitor the traffic and prepare for the BC. In actual operations, the BC should not have a fixed preparation/preview time (three minutes in this study); instead, it should be done when the controllers are ready for the change. An important caveat to the concept feasibility is that participants needed a reliable conflict probe to manage the BCs. They reported that they did not have adequate situation awareness of the incoming traffic for separation management without the help of the decision support tools.

Overall, the results and feedback from the study showed that Flexible Airspace is a promising concept worth further development and refinement. A number of tradeoffs may be required in finding the most effective way to address the demand-capacity imbalance while keeping the human controller integrated and functioning meaningfully within the system. Based on the results from this study, further research can begin in addressing these issues.

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