# Cognitive Evaluation of Potential Approaches to Increase the Efficiency of Air Traffic Controller Training and Staffing

by

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# AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# Abstract

Generic airspace, or air traffic control sectors with similar operational characteristics, is an operational concept being proposed as a means of increasing staffing flexibility and reducing training times as part of the Federal Aviation Administration's (FAA's) Next Generation (NextGen) air traffic control (ATC) modernization efforts. A key need for implementing generic airspace is identifying groups of similar sectors with respect to training required for controllers to make transitions between those sectors. Through the development and validation process of the studies performed in this thesis, a structure-based classification scheme was found to be an effective way to classify sectors in order to support a minimal differences training approach to generic airspace. The resulting classes of sectors are expected to have fewer transition barriers and support increased staffing flexibility.

In order to assess similarities of airspace sectors, factors affecting how easily a controller makes a transition from one sector to another were identified using semi-structured interviews with experienced air traffic controllers. The most important factors appear to reflect familiarity with types of operations and common traffic patterns, providing a basis for classifying groups of sectors. The controllers identified some techniques that are easily transferable as well. Some factors that are very specific to transitions were identified as well, such as "*Knowing the Neighbor Sectors*" and "*Coastal* Area" factors.

Based on the most important factors, traffic patterns in 404 high-altitude National Airspace System (NAS) sectors were examined for common traffic patterns. These traffic patterns were used as the basis for two classification approaches, a holistic classification approach and a decompositional classification approach. These approaches are used to classify current air traffic control sectors into classes with common structural characteristics. The results identify

existing sectors with near-term potential as being generic sectors that support a minimal differences training approach to generic airspace. Further analysis with the sector classification results identified that the number of factors incorporated in the classification methods are directly associated with the method's effectiveness.

In order to examine the validity of the developed classification methods and to assess the relative importance of the factors involving transitions identified by the interviews, an online survey was conducted with 56 air traffic controllers. The results indicated that the classification methods developed support controllers' perception of airspace similarities. Some qualitative data gained from the survey provides an insightful aspect for future steps continuing this study such as additional important factors to be considered. Some of these factors are considered as part of the classification schemes developed in this thesis while some are yet to be incorporated. Some of these additional factors were found to be more feasible to be incorporated into future classification schemes than other factors.

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*To my dearest family Dad, Mom, Eura, Jona, and Jon:*

*I dedicate this thesis to you.*

*Without your love and support,*

*I would not be who I am today. Love you.*

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# List of Acronyms

**ARTCC** – Air Route Traffic Control Center ("Center")

**ATC** – Air Traffic Controller

**CPC** – Certified Professional Controller

**FAA** – Federal Aviation Administration

**KSA** – Knowledge, Skills, and Abilities

**MOA** – Military Operations Area

**NAS** – National Airspace System

**OJT**– On-the-Job Training

**SUA** – Special Use Area

# Chapter 1

# Introduction

Air traffic control is a challenging profession involving many complicated time-critical and life-critical tasks and operations. Current training protocols require extensive amounts of training, sometimes requiring up to or more than three years of training before a controller becomes fully qualified. Lengthy retraining is also required when controllers move and control new pieces of airspace. This causes significant staffing inflexibility and makes it challenging for the air traffic control management to respond to staffing shortfalls due to spikes in retirement rates, sickness, or changes in demand for ATC services.

Currently new operational concepts are being developed to address these challenges. The generic airspace concept is an example of such concepts and is described further below in this chapter and in Chapter 2. This thesis examines ways to support generic airspace concept by identifying classes of existing airspaces that a controller can move with easier mobility than the current ATC system.

## 1.1 The ATC Training Challenge

In order to understand the training challenge, the following section briefly describes the current controller training qualification standards and the retraining process.

An airspace, or often referred to as a sector, is a three dimensional zone within controlled airspace in which aircraft are under the control of a specific air traffic controller. Figure 1-1 shows a two-dimensional map of North-East airspaces and each sector is marked with thin black borders. A few of these sectors, usually ranging from six to ten are administratively grouped together into Areas of Specialization (AOS), or often referred to as "areas". These areas are indicated in Figure 1-1 marked with adjacent same colors (e.g., the three red sectors in the top right corner belong in the same "area").

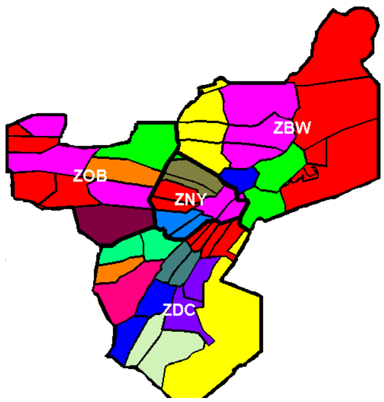



**Figure 1-1. Areas of Specialization (AOSs) with High Altitude Sectors in North-East Centers (adapted from Histon, 2008)**

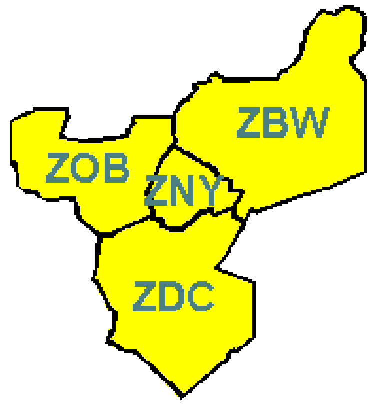



**Figure 1-2. Four ARTCCs in North-East United States**

Several areas are then further organized into a facility called an Area Control Center (ACC), often referred to as a "center" or an Air Route Traffic Control Center (ARTCC) in the United States. A map of four centers (ZOB – Cleveland, ZBW – Boston, ZNY – New York, and ZDC – Washington) in the North-East United States is shown in both Figure 1-1 and Figure 1-2, where each center is marked with thick black boundaries.

In the current National Airspace System (NAS) air traffic control (ATC) system, the typical Certified Professional Controller (CPC) will maintain qualification on only within one area of specialization that is composed of a limited number of sectors typically ranging from six to ten sectors (Histon et al., 2008). A fully licensed controller can move between such sectors on a shift without additional training. However, transferring a controller to a new area of specialization (e.g. one color to another in Figure 1-1) requires significant retraining time and effort, usually varying from a few months to a few years. The next paragraph explains why it takes this much time for a controller to move from one area to another.

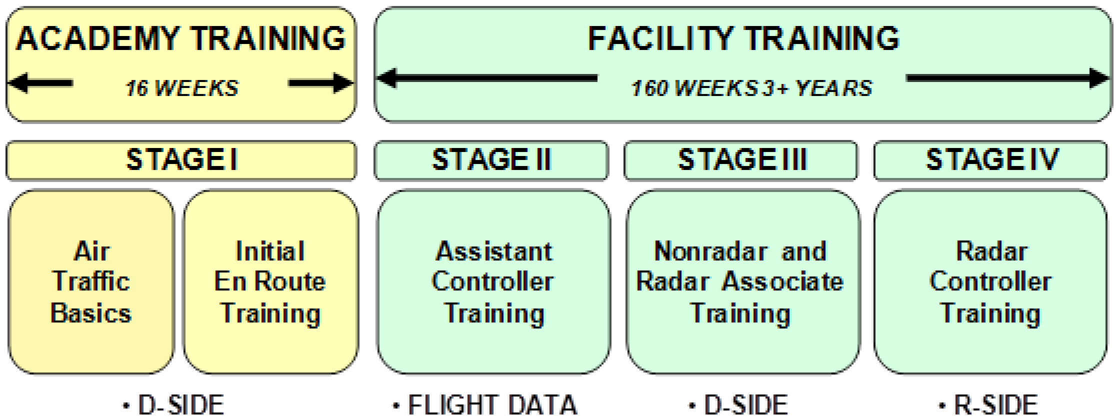



**Figure 1-3. Overview of current en route training process (Histon, 2008)**

Figure 1-3 shows the overview of current en route training process a student must go through to become a Certified Professional Controller (CPC) in the Federal Aviation Administration (FAA). While most knowledge learned in Stage I (as indicated in Figure 1-3), the academic training part, is transferable between all airspaces within NAS, in contrast, Stages II, III, and IV, the facility training part, vary across different areas of specialization. This is because the facility training part requires significant amount of local-specific knowledge and a variety controlling technique details specific to the particular volume of airspaces. For this reason, when a certified controller, who already went through the standard en route training process, moves to another area of specialization, the controller must go through additional facility training specific to the new area. This process is usually called “retraining” or “cross-training” and takes a few months to a few years.

Consequently, staffing flexibility is limited and it is difficult and costly for any air navigation service provider that uses such a system of qualifications, such as the Federal Aviation

Administration (FAA), to respond to different variations in staffing demands. There are several ways of dealing with this problem including operational changes such as increasing staffing flexibility, reducing training times, lowering training costs, and/or more effectively utilizing training resources. One of the operational concepts currently being developed by FAA to address this challenge is the generic airspace concept. For purpose of this thesis, the generic airspace concept was chosen for examination in addressing this problem.

### 1.2 Generic Airspace

Developing generic airspace, or sectors with standardized and common operational characteristics, is a possible means to address the challenge stated above and one of the methods being considered as part of efforts to modernize the ATC system (FAA, 2004). Generic airspace, or sectors with standardized and common operational characteristics, will allow controllers to work a sector with less training. This will allow flexible allocation of human resources based on system need, less constrained by operator knowledge limitations (Mogford, 2010). The greater the standardization, or more similar the sectors, the greater the flexibility to the air traffic control service provider; however, this comes at the cost of locally adapted sector-specific procedures and operations that provide locally tailored and more efficient operations.

Other previous and on-going generic airspace projects include enhanced information visualization such as the Controller Information Tool (CIT), new high-altitude airspace concepts such as the Dynamic Airspace Super Sectors (DASSs). More information on these various generic airspace approaches is further discussed in Chapter 2. While there are various approaches to enable the generic airspace concept, this thesis focuses on one specific approach to the generic airspace concept, the minimal differences training approach. This approach is described further in the next section.

### 1.2.1 Minimal Differences Training Approach

In a minimal differences training approach, classes of sectors are identified that could be made similar, but not necessarily identical. Controllers would receive short, targeted, training on the relevant differences between the generic sectors in a particular class. In this approach, a qualified controller would be able to easily move between the sectors within the class. Such a system would provide greater flexibility and standardization in the ATC system. The classes supporting this minimal differences approach to training would be composed of similar sectors that maximize knowledge, skills, and abilities (KSA) transfer when retraining for the new sector occurs. Maximum knowledge transfer occurs when the knowledge from the old sector can be maximized when learning a new sector, which results in reduced retraining time and effort. Each sector requires different amount and types of KSAs for a controller to be able to control. This thesis supports identifying groups of sectors that share interchangeable KSAs to enable the minimal differences training approach. Figure 1-4, illustrates an example scenario of two sectors having some interchangeable knowledge, skills, and abilities (indicated by the arrows).

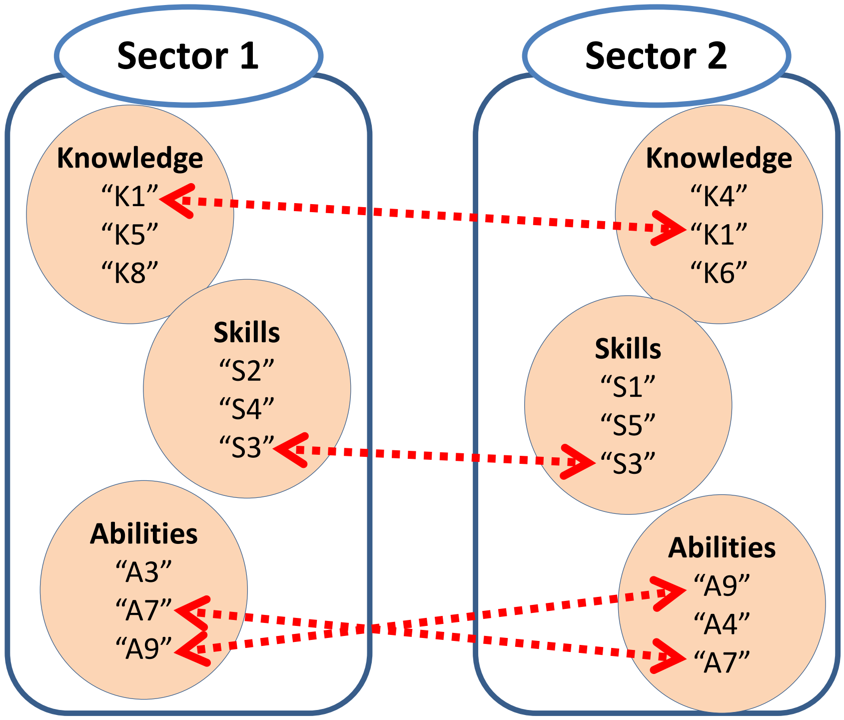



**Figure 1-4. Illustration of some interchangeable knowledge, skills, and abilities (KSA) between two sectors (the red arrows indicate interchangeable KSA)**

In order to support in identifying such groups of sectors, this thesis focuses the analysis on high altitude sectors of National Airspace System (NAS) as the initial step of the minimal differences training approach.

### 1.2.2 High Altitude Sectors

The thesis focuses research on NAS-wide analysis of the similarity of existing high-altitude sectors. MITRE has identified through analysis that high altitude airspace has the least number of airspace knowledge items (Levin, 2007) as shown in Figure 1-5. The figure illustrates the knowledge of items on the x-axis and different altitude level of airspaces in the y-axis.

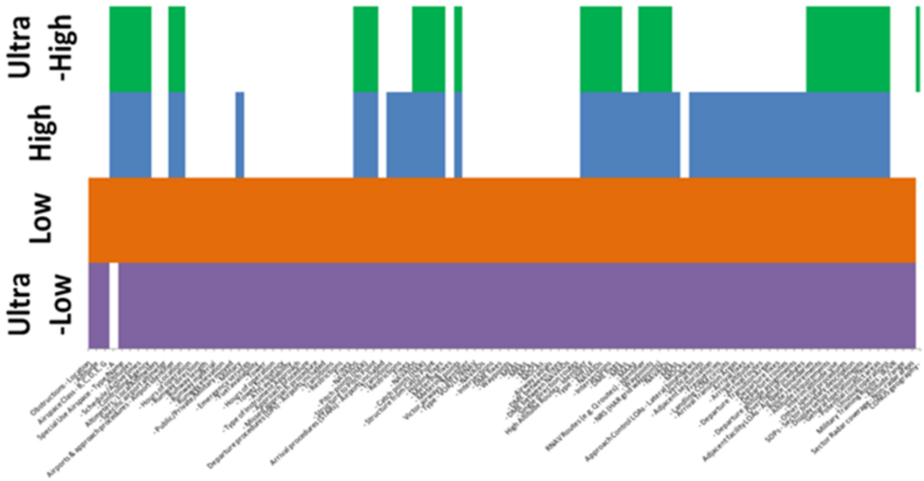



**Figure 1-5. Knowledge of items required for different altitude levels of airspaces (from Histon and Bhagat, 2010, adapted from Levin, 2007)**

The lack of symmetry and chaotic nature of airspaces tends to be maximum at the ground level and as the higher the airspace is at, the effects of localized features begins to decline and there is less variance in the characteristics of the airspaces. As a result, the "knowledge" required to control higher level airspaces is more limited as shown by the knowledge pyramid in Figure 1-5. As such, when attempting to classify these airspaces into classes with the goal of minimal differences in training, high-altitude airspace are an attractive candidate for the initial investigation.

### 1.3 Research Objectives

The theme of this thesis, can be described by the following research question:

*How can we identify groups of airspace sectors that will have fewer barriers to the transition of controllers between different sectors (in order to support minimal differences training approach)?*

As illustrated in Figure 1-6, the thesis goal is arrived from various levels of research problem. First, there is the ATC operation challenge due to the lengthy retraining process in ATC environment. Generic Airspace concept is one way to address this research problem. The minimal differences training approach is one generic airspace concept that could be implemented in both short and medium term time frames. The thesis goal, as stated above, is to support the evaluation of the minimal differences training approach by identifying ways to classify airspace sectors that are expected to have fewer transition barriers for controllers.

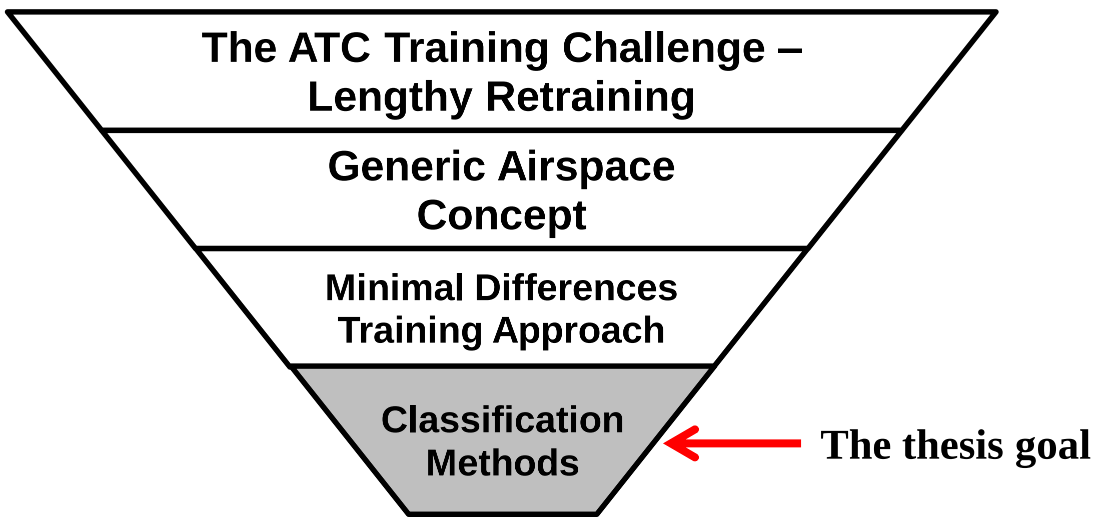



**Figure 1-6. The research goal narrowed down from the problem statement**

To answer the research question stated above, three specific objectives are identified and described below. In order to identify groups of sectors that minimize transition times, first, what it means for two or more sectors to be similar must be defined. To do this, key factors that contribute to the similarities of sectors and are relevant in transition training must be identified. Therefore, the first objective of this thesis is as follows:

Objective 1 – *Identify key factors that affect the transferability of a controller's existing knowledge skills and abilities to a new airspace sector.*

Based on a few of the most important factors identified through achieving Objective 1, a method of identifying groups of sectors that support minimal differences training can be developed. As such, the next objective of the thesis is as follows:

Objective 2 – *Develop a method, based on a few of the most important factors identified from Objective 1, for determining classes of sectors expected to have fewer transition barriers.*

Sample groups of sectors hypothesized to support minimal differences training will be suggested by the initial attempt of grouping sectors using the developed method. Then, the developed method can be evaluated for its relevance in supporting minimal differences training using an online survey through subject-matter-experts. In this validation process, the identified factors from Objective 1 will be verified and measured of their relative importance across a broader group of participants as well. Therefore, the final objective of this thesis is as stated below:

Objective 3 – *Evaluate the developed classification method and validate the key factors identified in Objective 1 through subject-matter-experts.*

According to the evaluation of the developed classification, appropriate next steps required to refine the classification method will be suggested as part of future work.

## 1.4 Thesis Organization

The remainder of the thesis is organized as follows:

- **Chapter 2: Background** contains a review of research related to generic airspace concept and previous work on training and classification associated with ATC operations.
- **Chapter 3: Controllers' Identification of Factors Affecting Sector Transitions** presents the method and the result of interviews that were conducted with ten air traffic controllers. The chapter reports the factors affecting the learnability of a controller when making a transition from one sector to another. These factors are reported by subject-matter-experts through the interviews. Objective 1 of this thesis will be achieved through this chapter.
- **Chapter 4: Classifying Sectors Based on Traffic Patterns** describes the analysis process used to develop two airspace sector classification methods and discusses the implications of these classification methods. Objective 2 of this thesis will be achieved through this chapter.
- **Chapter 5: Validating Perceptions of Airspace Similarity through Subject-Matter-Experts** describes the online-survey study conducted to validate the classification method developed. This chapter also examines the results of the evaluation process and discusses some additional insights provided by these results. Part of Objective 3 of this thesis will be achieved through this chapter.
- **Chapter 6: Validating the Identified Factors Affecting Sector Transitions** describes the online-survey study conducted to assess the relative importance of the factors involving transitions identified from Chapter 3. This chapter discusses the results of the

process and discusses some additional insights provided by these results. The rest of Objective 3 of this thesis will be achieved through this chapter.

- **Chapter 7: Conclusions** summarizes the findings of this thesis and proposes areas for further research.

# Chapter 2

# Background

This chapter provides a review of previous research work relevant in determining which classes of sectors can be expected to have fewer transition barriers. Work was reviewed from the research areas of air traffic controller training (2.1), generic airspace operational concepts (2.2), and ATC complexity factors and metrics (2.3). Though these research areas are different, they are closely interrelated to each other, such as some complexity factors being used for research on advantages and challenges of the generic airspace concept, or some ATC training research being applicable in generic airspace concept.

The following sub-sections of this chapter discuss the relevant research done in each area. The literature review was conducted by reviewing relevant publications from various ATC and Human Factors related sources from the past 20 years such as ATM Seminar, International Symposium on Aviation Psychology (ISAP), Human Factors and Ergonomics Society (HFES), Canadian Aeronautics and Space Institute (CASI), American Institute of Aeronautics and Astronautics (AIAA), and FAA publications. The chapter discusses the limitations of the previous work in approaching the research problem of this thesis and how some parts of the previous work can be applied in this thesis.

## 2.1 ATC Training

As identified earlier in section 1.1, a Certified Professional Controller (CPC) maintains qualification on only within one area of specialization that is composed of a few sectors. It takes significant amount of re-training time ranging from a few months to a few years in order to move a controller to another area of specialization. The main factor contributing to the lengthy re-training process, as identified in Figure 1-3, is on-the-job training, also identified as “facility training” in the figure. Motivated by the opportunity to shorten the lengthy on-the-job training times, or to make the overall training process more efficient, various models, training methods, and tools have been researched and introduced. The previous research, however, has focused on the general aspect of ATC training rather than focusing on the problem of ATC transitions.

### *Reviews and Analyses of ATC Education and Training*

Celio (2005) reviewed the current state of training science, training processes in related fields, and processes used by the military and worldwide ATC service providers to train controllers. Based on this review and analysis, some recommendations were developed for the introduction of high fidelity simulation into the FAA training process to reduce time to train controllers. Key suggestions included the introduction of high-fidelity simulation, incorporating voice recognition and synthesis with their instrument tools.

### *Understanding Key Cognitive Components of Controller's Job*

Redding et al. (1991) approaches the lengthy on-the-job training problem by gaining better understanding of key cognitive components of controller’s job. Redding indicates that, during the on-the-job training process, the knowledge transfer process between instructor and trainee is an informal processes that varies with the individual instructor. In order to eliminate this variability, standardization of teaching practices in which instructors explicitly teach cognitive aspects of ATC is recommended, providing trainees with more consistent training program. The Mental Model, developed by Redding et al. (1991), is suggested to provide a structure for expert knowledge and teaching method to expedite the process of trainees' learning and utilization of that knowledge.

***Setting Common Standards across Different Facilities***

In efforts to reduce time spent on on-the-job training period, ways to strengthen the initial training and to maximize harmonization of the training performance and the standards across different facilities have been researched by Eurocontrol (2003). This research found out that, under the current Eurocontrol Convention, a lot of hours are spent on on-the-job training due to the difference in training programmes between different Member States. The suggestion of this research is to develop clear and commonly adopted objectives to ensure full harmonization of the knowledge required to obtain a candidate license. In addition, they suggested a kind of complexity level based license to be developed and a further study to evaluate the advantages or disadvantages of the establishment of a kind of complexity criteria, which should then justify the necessary transition training period linked with each category (Eurocontrol, 2003).

***Research on Improving Training Methods***

Innovative methods of ATC training such as dynamic selection of learning tasks have been investigated for its effectiveness by Salden et al. (2004). The effectiveness of the method is investigated by looking into the effects of four different task selection methods on training efficiency and transfer in computer-based training for ATC. A non-dynamic condition was compared to three dynamic conditions, in which learning tasks were selected on the basis of performance, mental effort, and a combination of both (i.e., mental efficiency). It was confirmed through the study that the training efficiency of the conditions in which learning tasks were dynamically selected was significantly higher than the efficiency of the fixed condition, which training sequence is predetermined and not adjusted to the individual student.

Similarly, Cavcar, A and Cavcar, M, (2004) discussed the need for new directions for ATC training. They state that ATC employer organizations are usually slow in catching up to the changes in ATC environment because of economic reasons and recommends that knowledge and skills acquired through a college education to promote better performance and flexibility on the job. In the paper, they propose revised knowledge requirements and compare them with United States and French practices. Based on findings of comparison, they propose that professional education or training institutions such as colleges should provide air traffic control specialist training rather than by the employer.

Some tools have been developed in efforts to bring improvements to the current training system. Korneciki (1993) builds a solid foundation for Intelligent Tutoring Systems (ITS) by suggesting its key design features and techniques to be implemented for an intelligent tutoring system for ATC training. Since then, advanced training tools such as scenario based instruction, voice recognition and synthesis, and ITS have been researched and discussed by other researchers such as Camp (2001) and Bolczak et al. (2005). An innovative approach to controller training such as a web-based airspace training system, the Terminal Trainer Prototype, has been developed by the MITRE Corporation to improve efficiency, quality, and standardization across facilities (Weiland, 2010). In contrast to the traditional activities of drawing the airspaces on paper maps, this training system provides interactive training technologies and techniques which enable students to learn and memorize their airspace knowledge. These various technologies and techniques include multimedia tutorials, serious games, simulations, and interactive discovery learning tools. These results in increases in retention and a greater readiness for simulation and on-the-job training, thus reducing the time it takes for the on-the-job training process.

#### ***Summary of ATC Training***

As described above, various ways of improving ATC training system have been suggested including developing and improving ATC training methods and tools. The generic airspace concept is another way to reduce training time; previous work on it is described in the next sub-chapter.

### 2.2 Generic Airspace Concept

Generic airspace, or sectors with standardized and common operational characteristics, is one of the methods being considered as part of efforts to modernize the ATC system. The generic airspace concept will allow easier mobility of controllers between airspaces than the current system.

Various techniques and tools have been researched and developed by researchers to enable generic airspace concept. Representative generic airspace research includes Trajectory Based Airspace-generic (TBA-g) (Bearer et al., 2010), Airspace Redesigns to Accommodate Generic Sector Operations (Kalbaugh et al., 2011), and generic airspace application tools such as the Controller Information Tool (CIT) (Mogford, 2010). These research works as well as a few more relevant works are discussed below.

#### ***Identifying Generic Sectors***

Trajectory Based Airspace-generic (TBA-g) is one of the methods being researched to identify generic sectors (Bearer et al., 2010). TBA-g is perhaps the approach that resembles this thesis' approach most closely. Both TBA-g and this thesis work are motivated by the opportunity to reduce controller training time resulting in greater workforce flexibility and focus on finding groups of sectors that can be classified as generic sectors within the existing NAS. TBA-g is an airspace that is characterized by aircraft operating in level cruise with infrequent climbs or descents, sectors with low to moderate complexity, sectors with low to moderate traffic volume and less difficult crossing and merging of traffic flows. Bearer et al., (2010) analyzed, defined, and identified sectors within the NAS that might be suitable to become TBA-g. The main limiting factor of this TBA-g approach in finding generic airspaces is that it is mainly applicable to the sectors with low to medium traffic volume and complexity. For this reason, only limited amount of sectors met the TBA-g criteria and further research is recommended for investigating how non-TBA-g sectors can be redesigned to be TBA-generic sectors.

***Redesigning Non-Generic Sectors to Meet Generic Airspace Criteria***

The possibility of redesigning non-Generic en route sectors to meet generic airspace criteria have been examined by Kalbaugh et al. (2011) at MITRE. They explored four redesign options in the analysis; the options were rerouting traffic flows between sectors, redefining lateral sector boundaries, redefining vertical limits of the sector, and dividing a sector into smaller parts. All of these redesign methodologies experienced major challenges. Redesigned sectors had increased flight miles (or less efficient operations) and possibly increased traffic volumes in the neighbor sectors (creating higher potential workload for controllers in the neighboring sectors). Despite these challenges, three out of ten sectors they applied the redesign analysis on could meet a Generic Airspace criteria developed by Burkman (2010). They recommend that additional research to be conducted to determine the feasibility of some of the sectors that partially met Generic Airspace criteria.

### *Generic Airspace Application Tools*

One of the main research projects currently being conducted to explore the concept of generic airspace is the development of various NextGen automation tools such as the Controller Information Tool (CIT), data link, and Conflict Detection and Resolution (CD&R) (Mogford, 2010). These tools are designed to focus on reducing the training and memorization required to manage air traffic by helping controllers reduce the time required to learn and adapt to the sector by facilitating familiarization. In order to facilitate this familiarization, the tools provided the necessary sector and traffic flow information to enable a controller to manage an unfamiliar sector. This study tested whether controllers can manage unfamiliar sectors with an acceptable level of workload, efficiency, and safety, in a generic airspace environment that includes NextGen automation tools and specific sector data. The results addressing workload, traffic management, and safety, as well as controller and observer comments, supported the generic sector concept. The effectiveness of these tools is still being validated through various Human-in-the-Loop experiments (Mogford, 2010).

### *Other Techniques Enabling Generic Airspace Concept*

The next two paragraphs discuss the techniques enabling generic airspace concept. The traffic abstraction algorithm developed by Sabhnani et al. (2010) extract the traffic structure in terms of standard flows and critical points (conflict and merge points), which can be used to identify traffic structure in any piece of airspace. This is a useful technique in enabling generic airspace concept and the paper proposes future steps to use these traffic abstraction results in developing generic sector designs that allow ease of ATC transition to the new airspace.

### *Applicable Technique to Enable Generic Airspace Concept: Dynamic Airspace Super Sectors (DASS)*

A new concept of simplified high-altitude airspace called Dynamic Airspace Super Sectors (DASS) was introduced by Alipio et al. (2003). This research work is not directly related to generic airspace concept but takes a similar approach, motivated by the opportunity to decrease controller workload and allow higher densities of aircraft to be safely monitored. DASS is a network of one-directional, high density highways in the sky connecting major airports in the United States. The study showed that specialized routing by itself may not be a good option due to DASS increasing number of aircraft and increased workload in each center. However, the study concludes that the DASS system may be a viable option for the future if DASS aircraft can be separated from non-DASS aircraft, which may reduce workload (Alipio et al., 2003). It could be challenging to adapt the DASS system as this system requires some modification to the existing airspaces. However, if adapted properly, DASS would be excellent candidates of generic airspace sectors.

### *Summary of Generic Airspace Concept Related Research*

As discussed in section 2.1 and 2.2, there have been various approaches to make ATC training more efficient or enable the generic airspace concept. However, the review also found that there has been no research conducted in the approach of identifying multiple groups of, or classifying, existing sectors that are hypothesized to share similar operational characteristics that allows a controller to make transitions between them with minimal retraining. In order to identify such classes of sectors that support minimal difference training approach, first, ATC factors that impact a controller's airspace transition must be identified. The next sub-chapter explores the research that has been done in identifying and developing ATC complexity factors and metrics, and examines whether any of these research have identified ATC factors specific to controllers' sector transitions.

## 2.3 ATC Complexity Factors and Metrics

Understanding ATC complexity factors, the factors that makes a sector "complex", is a crucial step in developing a sector classification system that support minimal differences training; this is because most often the level of ATC complexity in a sector is what contributes to the length of retraining. Various ATC complexity factors have been reported. Some efforts have been put into developing a systematic model or a tool to determine ATC complexity of sectors. Another researcher, such as Christien (2002) has extended the research further by applying ATC complexity measurement into developing a model that classifies the current European sectors into different classes based on their complexity. The identification of structure-based abstractions, (Histon et al., 2001), is also crucial as the abstractions can be used as the foundation of traffic pattern analysis used to classify sectors. In this sub-chapter, these various research works done in the light of ATC complexity factors and metrics are reported.

***Typical ATC Complexity Factors***

Comprehensive complexity factors lists can be found in reviews by Hilburn (2004) and Majumdar and Ochieng (2001). Typical complexity factors are aircraft density, the proportion of aircraft changing altitudes, sector size, and sector shape. Mogford (1995) also collected many ATC complexity factors through a review and synthesis of the literature in efforts to aid in improving sector design techniques and managing controller workload. Some relevant ATC complexity factors are traffic mixture of arriving/departing vs. overflying traffic (Davis, et al. 1963), the number of arrivals, special flights, traffic volume and *weather condition* (Kuhar, et al.

1976), sector geometry (Buckley, et al. 1983), background load (Arad, 1964), coordination with other controllers (Schmidt, 1976), mixture of aircraft types (Grossberg, 1989). Another study was conducted to identify factors that contribute to airspace complexity by Mogford et al. (2009). A final list of 16 complexity factors was developed and is suggested as a reference for future research in the area.

### *Frameworks or Models Evaluating ATC Complexity*

Other than identifying multiple ATC complexity factors, a solid framework for developing and evaluating a model of the perceived complexity of an air traffic situation was initially suggested by Pawlak et al. (1996). Pawlak et al. focuses on measuring ATC complexity based on the traffic characteristics that impact the cognitive abilities of the controller. Other various ways of measuring air traffic control complexity include non-linear vector field model of air traffic developed by Delahaye et al. (2004), dynamic density (DD) model by Kopardekar et al. (2007). As one of the on-going complexity measures development and validation research, Kopardekar et al. (2007) developed a quantifiable metric for air traffic complexity by combining the effect of various factors that contribute to sector level air traffic control complexity.

Building in part on the Pawlak et al. (1996) framework, Histon et al. (2001) identified three important structural abstractions, standard flows, groupings, and critical points and concluded that the underlying structure of the airspace is relevant in many of the complexity factors. It is suggested that these structural abstractions reduce the difficulty of maintaining situational awareness, particularly the projection of future traffic situations. These structural abstractions become the fundamental basis for the airspace classification methods that support minimal differences training approach later presented in this thesis.

***ATC Complexity Measurement or Visualization Tools***

A tool that can measure and visualize such as the complexity map has been developed by Lee et al. (2007). This complexity map displays the state of the sector by measuring the control activity and provides detailed insight into the control activity required to handle an entering aircraft as well as the impact of environmental changes. Some scalar measure of air traffic complexity can be extracted from the complexity map. Similarly, Delahaye and Puechmorel (2000) developed two interesting approaches of measuring air traffic complexity, an air traffic complexity indicator based on the structure and the geometry of the traffic and a dynamic system theory that uses the Kolmogorov-Entropy to measure the global disorder of the aircraft system when it evolves with time. Through these approaches, Delahaye and Puechmorel made observations such as the fully organized situation (parallel flow) does not generate complexity at all either from the either from the geometrical or dynamical system point of view.

***ATC Complexity Indicators and Sectors Classification***

Christien (2002) put significant effort looking into ATC complexity and used the complexity indicators as a basis to develop a model that classifies existing European sectors into clusters. Christien combined ATC operational advice with statistical analysis to compile a list of relevant complexity indicators. The validated six complexity indicators are number of flights, number of conflicts, aircraft performance mix, flow entropy, amount of climbing/descending traffic and size of sector (Christien, 2002). These indicators' influence and interaction vary amongst sector types. Using these variances of sectors as a basis, two approaches to classify the sectors were explored. The first method is based on a K-means classification and the second method is based on hierarchical divisive method named DIVAF. As a result of performing the two classification methods on 677 sectors, DIVAF method produced four clusters and K-means method produced six clusters.

The comparison between the results from both methods showed that the homogeneity of the clusters with the K-means method is better than the DIVAF method, but the DIVAF method enabled more direct interpretation of resulting clusters (e.g., could immediately understand why sectors belong to the same class). The results of classifying the European sectors showed that the classification model developed produces a meaningful classification and understanding of sectors' complexity. Christien suggests that the results from this study to be used to improve future controller workload and sector capacity predictions at macroscopic level.

This research work is highly relevant to this thesis: both research works attempt to classify existing airspace sectors depending on each sector's complexity without adding any alterations to the ATC system. However, the major difference between two works is that Christien's work attempts classification with a broader level of motivation (e.g., improve future controller workload) whereas this thesis focuses classifying sectors specifically to reduce controllers' transition times between sectors. Another difference is that Christien put much effort into developing an automatic and non-subjective method to classify sectors, whereas this thesis attempts classification with more qualitative approach, using controller interviews, surveys, and visual traffic pattern analysis.

### ***Summary of ATC Complexity Factors and Metrics***

As listed, there has been significant effort exerted by various researchers looking into complexity factors and developing complexity metric system. These complexity measurement studies and metrics have been discussed for its application to developing ATC automation tools, reducing air traffic controllers' cognitive workload, and to develop easier training material. However, from the literature done as part of this research, there has been no work in identifying complexity factors specific to transition training.

### 2.4 Chapter Summary

In summary, while opportunities for improvements in the current training system have been identified including the generic airspace concept approach, and extensive research has been previously conducted in identifying important air traffic control (ATC) complexity factors, none of these approaches have focused on identifying ATC factors that are specific to transition training nor any of the approaches explicitly examined the potential of identifying common classes of sectors that would require reduced or minimal training for a controller to easily move amongst them.

In order to identify such classes of airspaces, first, ATC factors relevant to a controller's sector transitions must be identified. Then, based on these factors, classes of airspaces that are hypothesized to have fewer transition barriers can be identified. The next chapter, Controllers' Identification of Factors Affecting Transition Time, identifies some of those important ATC factors specifically related to sector transitions, self-reported by subject-matter-experts.

# Chapter 3

## Controllers' Identification of Factors Affecting Sector Transitions

This chapter presents the key factors that affect transfer of knowledge and success in new sectors; these factors were identified using semi-structured interviews with air traffic controllers.

As discussed in Chapter 2, previous work identified important ATC complexity factors and metrics. However, none of these approaches focused on identifying factors related to a controller's sector transitions (learning a new sector as part of certifying in a new area of specialization). Identifying factors affecting controller's sector transitions is an essential step in this research as it builds the basis for understanding what it means for two or more sectors to be similar in the minimal differences training concept. The identified factors affecting transition time can then be used as a basis for developing a method for determining classes of sectors expected to have fewer transition barriers, supporting the minimal differences training approach.

The result of the interviews described below is the identification of 10 important ATC operational factors as well as some cultural factors affecting a controller's sector transition. The following sections describe the interview method, the factors reported by participants, how these factors compare to other ATC complexity factors, and how they can be used in a classification scheme to identify sectors supporting a minimal differences training approach to generic airspace.

### 3.1 Method

In order to probe controllers' past experience transitioning between airspace sectors and to identify factors that made those transitions easier or more difficult, semi-structured interviews were conducted with 6 retired and 4 active air traffic controllers. As listed in Table 3-1, there were three questions (Q1, Q2, and Q4) focused on identifying important ATC operational factors regarding sector transitions. One question (Q3) focused on identifying different structural patterns they've dealt with in the past and some standard procedures that can be associated with such structural patterns. One additional question (Q5) as listed in Table 3-2 was asked to identify any cultural factors affecting sector transitions. The answers from these questions were consolidated and organized after the interviews; key factors affecting transfer of knowledge and success in new sector that were mentioned in responses to these questions were identified and counted.

**Table 3-1: List of interview questions probing relevant operational factors in transitions**

| # | **Question** |
|---|---|
| 1 | Was there a sector you made a transition to where it was easy to learn because the sector was "similar" to the one you've controlled before? If so, in what ways was it similar? What kind of operation procedures/skills from the previous sector were you able to apply to the new sector? |
| 2 | Was there a sector that was more challenging to learn? What made the transition difficult? |
| 3 | What kind of did "structural pattern(s)" exist in the sector(s) you controlled in the previous AOS? Are there any standard procedures in this structure (e.g. cross) which could be used in other sectors? What type of procedures would be different in other sectors which has a same structure? |
| 4 | If you were to describe the sectors you previously controlled to a controller about to operate it for the first time, what are the most important factors (airspace elements) affecting its operation? Are these different for each AOS you have been in? |

**Table 3-2. List of interview questions probing relevant cultural factors in transitions**

| | |
|---|---|
| 5 | What kind of cultural differences can you say you could notice between different facilities (AOS) when you made transitions (e.g. Air traffic control procedures, policies, organizational structure/influence, motivating factors, etc.)? Did any of these differences affect the transition process? If yes, how? |

***Procedure Details and Participants***

The interviews were conducted over the phone and each interview took approximately one hour. Hand-written notes were taken during the interviews. With the participant's permission, each interview session was recorded in order to clarify the written notes taken during the interview later on. The study participation was voluntary, and the participants were informed before the interview that they could decline to answer any questions if they wish and withdraw from the participation at any time.

All participants were, or had been, a certified air traffic controller who had made at least one transition from one area of specialization to another (which includes at least one sector transition) in the past. Participants were recruited by extending invitations to a limited set of active and retired controllers known through personal contacts. 6 retired controllers, and 4 active controllers participated. 9 participants were from the United States while 1 participant was a controller from Canada. The average number of years of air traffic control experience of the participants was 22 years. The average number of sectors one participant has controlled is 11. The average number of transitions participants made between different areas of specialization is 3. All participants included some years of experience with en route low altitude sectors as well as high altitude sectors. Some of these participants had experience of working with some special use airspaces and/or at terminal airspaces.

### 3.2 Results

The written notes and the recordings of the interviews were reviewed to identify common factors affecting sector transitions as reported by the participants. Ten distinct ATC operational factors affecting sector transitions were identified by the participants and these factors are discussed in section 3.2.1. Some cultural factors affecting sector transitions were also identified by the participants and they are discussed in section 3.2.2.

#### 3.2.1 Operational Factors Affecting Sector Transitions

The identified ATC operational factors affecting sector transitions by controllers are graphically represented in Figure 3-1 and listed in Table 3-3. The factor that the most participants reported to be important is *Traffic Flow Pattern* followed in order by *Weather Condition*, *Knowing the Neighbor Sectors*, *Hotspots*, *Aircraft Types*, *Traffic Complexity*, *Coastal Area* (*East vs. West Coast)*, *Arrival/Departure Flows*, *Sector Area Size*, and *Special Areas*.

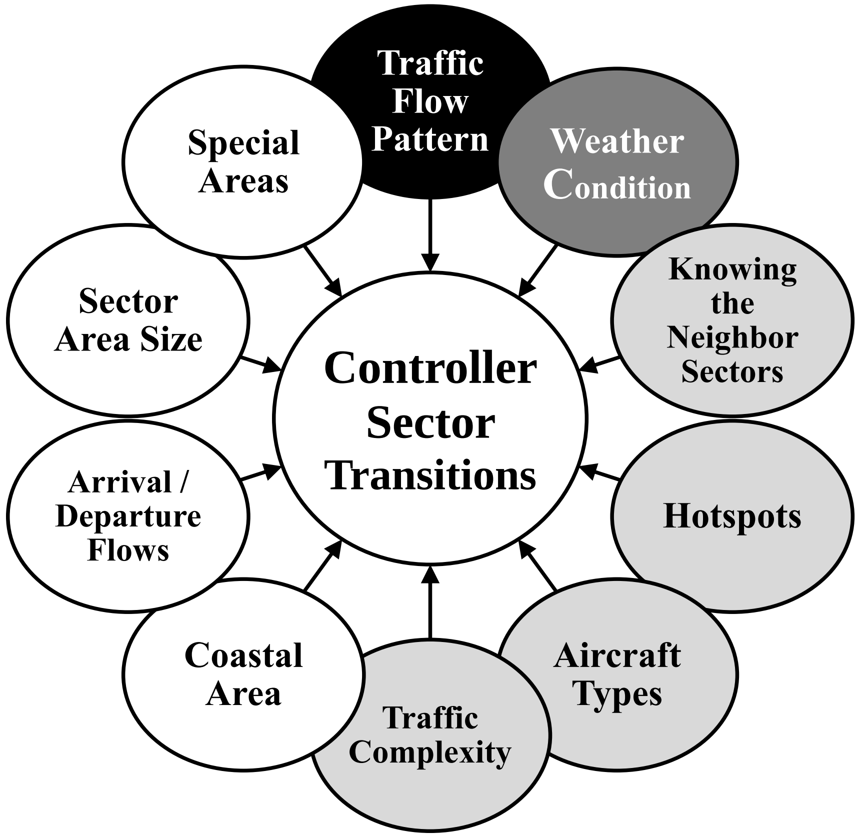



**Figure 3-1. Identified common factors affecting sector transitions**

**Table 3-3: List of factors identified by controllers**

| Factor | % of participants reporting |
|---|---|
| **Traffic Flow Pattern** | 50% |
| **Weather Condition** | 40% |
| **Knowing the Neighbor Sectors** | 30% |
| **Hotspots** | |
| **Aircraft Types** | |
| **Traffic Complexity** | |
| **Coastal Area** | 20% |
| **Arrival / Departure flows** | 10% |
| **Sector Area Size (allowed maneuvering space)** | |
| **Special Areas e.g. Military zones (MOA)** | |

The following text describes each identified factor and how controllers described its importance in learning a new airspace.

***Traffic Flow Pattern***

This is the factor the largest number of participants identified to be an important factor affecting transfer of knowledge and success in new sector. Five participants (50% of participants) self-reported that having the experience of dealing with a similar traffic flow pattern (e.g., moving from a sector with a dominant cross flow to another sector with a dominant cross flow) helps significantly. The participants indicated that when a controller is already familiar with the operations associated with a certain traffic pattern from previous experience, moving to another sector with a similar traffic pattern would allow some operational details to be transferable. Asking Q3 allowed participants to identify example traffic patterns from their past that they were able to transfer some operation techniques from the old sector to a new sector with a similar traffic flow pattern. Some example quotes from the controller interviews supporting these assertions are reported and discussed below.

The three most frequently cited structural patterns participants reported as having easily transferred standard operational techniques are a merging traffic pattern, a crossing traffic pattern, and arrival/departure traffic pattern. Some participants reported more than one traffic pattern.

Five participants reported they were able to transfer some techniques from an old merging traffic pattern sector to a new merging traffic pattern sector. Some controllers stated, "*very busy merging traffic are important to have an experience of*". Some ATC techniques used in a merging traffic pattern that were transferable are flow control, sequencing technique, and speed control.

Three participants reported they were able to transfer some techniques from an old crossing traffic pattern sector to a new crossing traffic pattern sector.

Four participants reported they were able to transfer some techniques from an old arrival traffic pattern sector to a new arrival traffic pattern sector and/or from an old departure traffic pattern sector to a new departure traffic pattern sector. A controller stated, "*moving from an arrival sector to another arrival can be easy*".

Some other transferable techniques not specific to a traffic pattern the participants reported are the scan technique where the controller is trained to look at conflict points, separation techniques, and developing the skill to "*look for similar flows*" so they can "*relate to previous sectors*". One controller indicated that every sector has different points where traffic comes together and conflicts occur, and knowing the degree of complexity of these merging or crossing traffic and where these occur is critical. The controller also indicated that this kind of "technique" can be transferable but only partially and some local-specific details will have to be learned.

The participants noted that the location of these specific patterns with respect to the sector boundary is important as well. Participants stated they "*…might be able to do the same thing for the new sector - just depends where the location of these specific patterns are*", and "*the way the sectors are designed around traffic flows is important*".

Another important identification made by some controllers was that even if two sectors share similar traffic patterns, the difficulty of learning the new sector is dictated by the level of complexity of that sector. One controller said "*it was easy to learn the new sector because it did not have as much merging traffic* ".

In summary, for the *Traffic Flow Pattern* factor, participants indicated some specific example traffic flow pattern such as a merging pattern, crossing pattern, or an arrival/departure flow pattern as noticeable patterns important to be matched in transitions. They identified some specific transferable techniques associated with traffic patterns, the importance of location of these patterns, as well as the complexity associated with each pattern. The traffic patterns identified through these interviews match the previous work on easily transferable mental models and abstractions in ATC by Histon (2008).

***Weather Condition***

Four participants (40% of participants) indicated that having to deal with similar kind of *weather condition* in the past could be helpful when learning a new sector. They indicated that having the experience of some extreme weather such as thunderstorm seasons can be beneficial if moving to another sector with similar extreme *weather condition*. This is because the knowledge and skills required to deal with such situations has already been acquired through past experience and therefore is not required to be taught as extensively as it would be for a controller with no such experience. Some controllers indicated that having the knowledge and experience of dealing with certain operation details that are associated with weather, such as jetstream, tailwind, general wind pattern, is valuable if moving to a sector with similar *weather condition*. As one participant stated "*I learned to be mindful of what the wind is doing at all times and this skill came useful when I moved to the sector xxx which had unusual wind pattern*".

***Knowing the Neighbor Sectors***

Three participants (30% of participants) emphasized that knowing operations, procedures, and traffic patterns of neighbor sectors is crucial. As illustrated in Figure 3-2, having the experience of controlling sector X in this figure would develop the familiarity of traffic patterns of its neighbor sectors such as sector Z, a sector not in the same area of specialization.

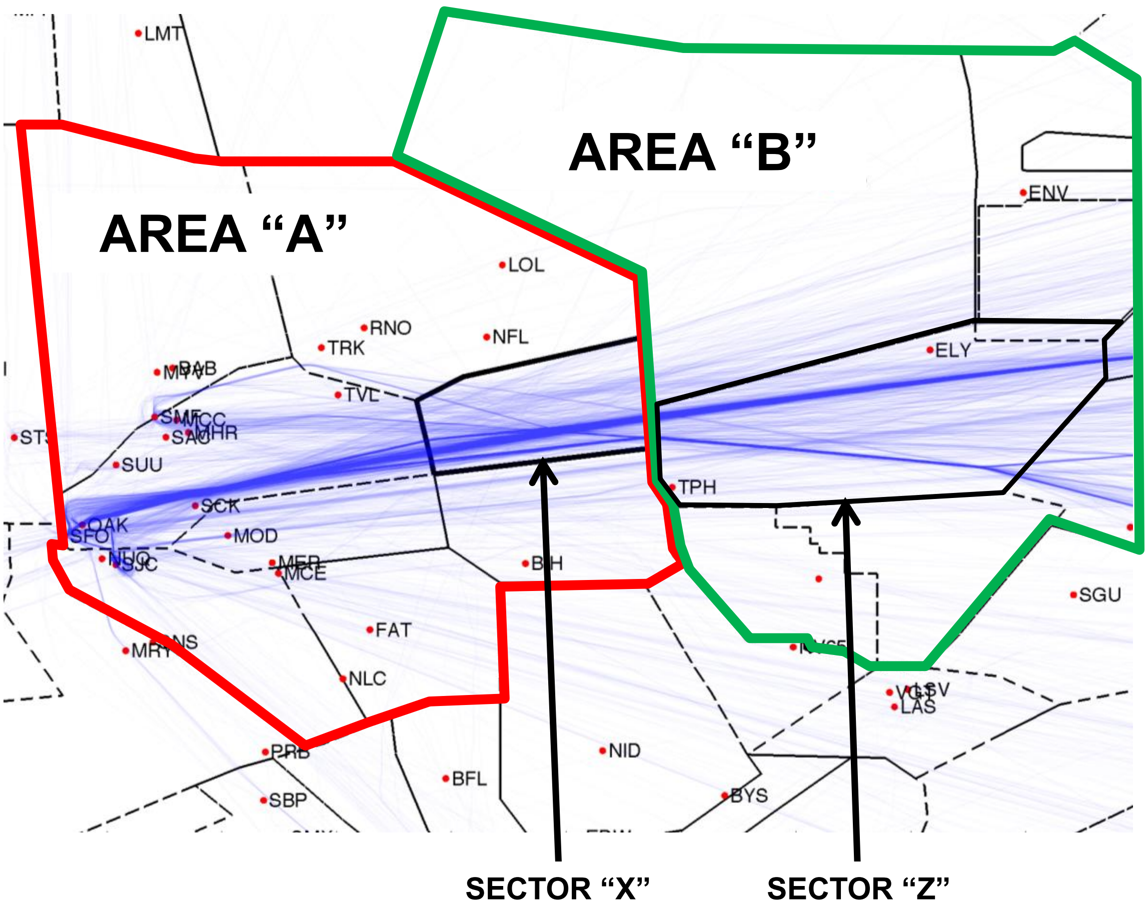



**Figure 3-2. Illustration of “knowing neighbor sectors” factor**

Participants indicated that having the knowledge of the neighbor sectors is crucial because many of the operation details are dictated by knowing what the traffic is doing around the controlling sector, knowing what the controller can expect from the other sectors around them, and knowing what they will be expecting the controller to deliver to them. Due to this familiarity developed, the participants indicated that moving to a sector near the old sectors would require significantly less effort to learn.

***Hotspots***

Three participants (30% of participants) indicated that knowing where the hotspots are is critical when learning to operate a sector for the first time. “Hotspots”, sometimes referred to as “choke points”, “traps”, or “critical points”, are specific locations in a sector where complications are prone to occur. The identification of hotspots as an important factor in a controller’s sector transition matches the previous work done by Histon (2008). Histon also identified critical points as an important abstraction which allows a controller to reduce cognitive complexity thus making it easier to learn and perform appropriate ATC activities.

Figure 3-3a and Figure 3-3b shows an example of a critical point. Figure 3-3a shows an example of a critical point due to abrupt aircraft trajectory change pattern and Figure 3-3b is a critical point due to a merging traffic pattern. It is worthwhile noting that these hotspots, or critical points, are directly related to traffic patterns of a sector, as indicated in the figures.

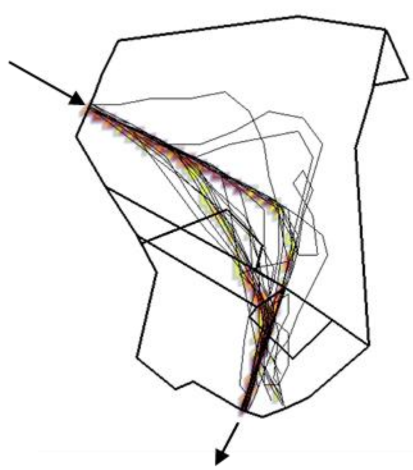


**Figure 3-3a. Critical point due to aircraft trajectory changes (Histon, 2008)**

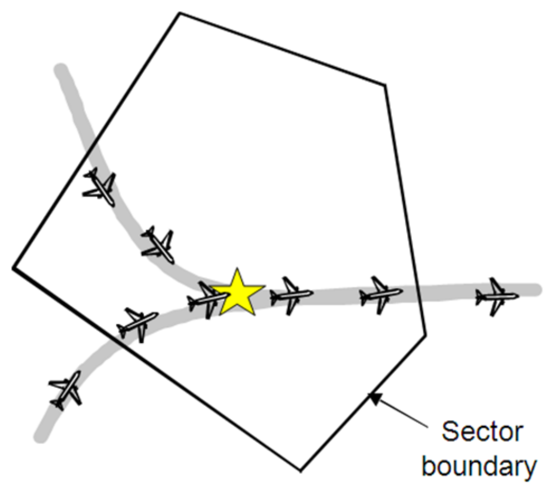



**Figure 3-3b. Critical point (star) where a merging traffic pattern occurs (Histon, 2008)**

Some controllers reported that locations of these hotspots can be important but it is difficult to find two sectors that share similar hotspot locations. As one participant stated, “the basics of ATC and trick spots of the sector is the key in learning a new sector”, where the controller is referring the trick spots of the sector as “hotspots”. Some controllers referred these tricky spots in a sector as “the secret spots of the sector” or “the traps”.

***Aircraft Types***

Three participants (30% of participants) indicated that having the experience of dealing with certain aircraft types helps in learning a new sector with similar aircraft types. This is because the controller would be familiar with the capability of these aircrafts and thus know what operational procedures to take accordingly without having the effort to learn new details. A controller said *“you gotta know what the aircrafts in your sector can do or cannot do. If you don’t know the aircraft types in the new sector, you gotta learn ‘em.”* in supporting the identification of this factor as an important factor in learning a sector.

***Traffic Complexity***

Three participants (30% of participants) indicated that the overall complexity of the sector is important to be matched between the old and the new sectors when learning a new sector. They reported that the reason is because moving to a similar level of complexity sector provides the controller with the confidence that they “can do this”. Participants also indicated that moving to a less complex sector would make it easy to learn the new sector as well. As reported in the *Traffic Flow Pattern* section above in this chapter, some controllers identified that even if two sectors share similar traffic patterns, the difficulty of learning the new sector depends on the level of complexity of the sector. As one controller commented "*it was easy to learn the new* *sector because it did not have as much merging traffic.*" In addition, the results indicated that controllers felt that in some cases the knowledge, skills, and abilities associated with certain traffic patterns can only be transferred easily in one direction. This was generally from a more complicated sector to a less complicated sector. The participants identified that usually the traffic volume of a sector is a good indicator of the general complexity of a sector.

***Coastal Area (East vs. West Coast)***

Two participants (20% of participants) reported that the familiarity a controller develops of a certain coastal area (East vs. West) is very significant. This factor is similar to *Knowing the Neighbor Sectors* factor, but in a larger geographical scale. One participant stated "*…by working in one (coastal) area for years, you develop a significant familiarity of major flows that are happening*". To illustrate, a controller with a lot of experience in the West (e.g., Oakland Center) would have a much more thorough knowledge of the major flows on the West coast (e.g., North-South flow from Seattle to Los Angeles) than would a controller from the East coast (e.g., Boston Center). This type of knowledge helps controlling a sector significantly, and the knowledge is transferable if the controller moves within the same coastal area.

***Types of Flows, Sector Area Size, and Special Areas***

One participant (10% of participants) indicated that knowing which arrival/departure flows make up the "major" flows in the sector helps in grasping the key operational concepts when learning a new sector. The participant indicated that it particularly helps to have the experience of having to deal with similar types of flows (e.g., having to deal with high volume arrival flows and moving to another sector with also high volume arrival flows).

One participant also indicated that having used to work with a certain sector size sometimes dictates what controlling techniques the controller is familiar with. The technique usually varies due to the variety of allowed maneuvering space depending on the sector. The allowed maneuvering space dictates which techniques to use even for a same operational goal (e.g., vectoring versus speed control). For this reason, moving to another sector with a similar sector size sometimes allows some operation details to be transferred.

Another participant indicated that having the experience of dealing with special areas (than none) help in learning another sector with special areas.

### 3.2.2 Cultural Factors Affecting Sector Transitions

In addition to the important ATC operational factors affecting a controller's sector transition, in Q5 controllers were asked to identify any relevant cultural factors associated with ATC sector transitions. The question as listed in Table 3-2 asks the participants, "*What kind of cultural differences can you say you could notice between different facilities (AOS) when you made transitions? Did any of these differences affect the transition process? If yes, how?*". In order to clarify the meaning of cultural differences in the question, example cultural factors such as organizational structure/influence and motivating factors were used to explain to the participants what an example cultural factor could be.

Asking this question resulted in 100 percent of the interview participants reporting that they experienced cultural difference between different facilities. Nine participants (90% of these participants) said that these cultural differences were significant and only one participant (10% of the participants) indicated that they experienced a slight cultural difference between facilities. Some quotes from the interviews include "*there was a night and day cultural difference* *between facilities*", "*Very difficult to break the culture/habit of the sector*", and "*Everybody does things differently*". The result of the percentage of participants reporting (100%) and the tone in the participants' quotes as stated above reflect the significance of cultural difference between facilities.

Ten culturally different factors reported include the difference in management, teaching style, teamwork and coordination, and level of expectations, published holding patterns, the letters of agreement, the composition of traffic, interpretation of the manual, and the amount of "freedom" in using specific control techniques.

One controller stated "*some procedures which you must learn are not a written rule but culturally learned*" which illustrates how some ATC procedures can be culturally different across different facilities. An example of a culturally learned experience identified by a controller was a situation where a certain "legal" procedure is "culturally banned" from use within the facility due to a certain situation specific to the facility. This culturally banned procedure is "clear direct Modesto" which is a command mutually understood not to be used within the facility because its neighbor center dislikes when the aircrafts passed to their sectors had been cleared direct to Modesto. Controllers culturally have learned to take appropriate alternatives although there are no such written rules. Some controllers indicated this type of knowledge is "intangible" and needed to be gained in time. Some controllers emphasized the fact that they had to learn "*the new way of doing things*" or "*adjust and learn all the peculiar techniques*" to do "*the same thing*".

### 3.3 Discussion

As a result of the interviews with controllers, ten important ATC operational factors affecting a controller's sector transitions as well as ten cultural factors were reported by the participants. The results of the interviews provide insights into which ATC operational factors should be considered in the development of identifying classes of sectors expected to have fewer transition barriers in order to support a minimal differences training approach to generic airspace. The following section reviews the insights provided by the factors as well as challenges identified for the process of developing an effective sector classification scheme.

The *Traffic Flow Pattern* factor was identified to be significant not only due to its high frequency of being cited in the interviews but also because other factors perceived to be important in a controller's transition can be encapsulated by the traffic flow pattern. Such identified important factors that are highly correlated to the traffic flow pattern are *Traffic Complexity*, *Traffic Volume*, *Types of Flows* (arrival, departure, or en route flows), and *Sector Area Size* factors.

Other factors reflecting geographically specific knowledge and experiences, such as *Weather condition* or *Coastal Area*, were also prominent. These additional identified factors could be used as a basis for evaluating the appropriateness of previous classification schemes for the purpose of identifying sectors that would have minimal training differences. Schemes based solely on complexity or solely on traffic patterns can be limited and additional research is needed to examine how many of the additional factors are relevant for establishing classes of similar sectors. Combinations of factors will create more accurate classification scheme than a classification work based on one factor. However, care must be taken because the interpretability of the resulting classification scheme can be diluted by combining or adding additional factors.

Many of the factors identified in this study can be also found in the ATC complexity factors literature review done by Mogford et al. (1995), such as *weather condition*, arrival and departure flows, and special areas. This is unsurprising given the strong correlation between complexity and the challenge of learning. Although some of the factors identified in this study and the ATC complexity factors previously identified overlap, the significance of this study is its identification on important factors specifically related to a controller's ATC sector transitions. The interesting and new factors with respect to training that were identified through this interview are the importance of *Knowing the Neighbor Sectors* and *Coastal Area* factor.

The results from the interviews also showed that there are factors beyond ATC operational factors, the cultural factors, which would play an important role in the success of an implementation of the minimal differences approach to generic airspace. The discovery of these cultural differences affecting a controller's transferability is significant as no previous research have yet identified such factors. Knowing that there are some significant cultural differences between sectors that controllers experience in transitions and knowing what these cultural factors are can provide insights into future research needs. One of the possible ways to address these cultural differences between facilities is to identify ways to standardize ATC procedures across the NAS. For example, Eurocontrol, in 2002, suggested a fully recognized license that can be used throughout an air traffic management system. In addition, some research from organizational behavior can be adopted as part of the classification methods in the future in order to look for ways to deal with cultural difference in management, teamwork, coordination, and level of expectations between different facilities.

As an initial step of this research, the mostly cited factor, the *Traffic Flow Pattern* factor, is used as a basis for developing an effective classification scheme. This process is further discussed in detail in Chapter 4. Then, the relative importance of these identified factors will be assessed and the effectiveness of classification scheme generated based on traffic patterns will be measured by expanding the reach to a larger number of subject-matter-experts through a survey. The details on the methods and the results of the online survey are presented in Chapter 5.

### 3.4 Chapter Summary

In summary, in order to assess similarities of airspace sectors that support minimal differences training, factors affecting transfer of knowledge and success in new sector were identified using semi-structured interviews with controllers. From the interviews, ten important ATC operational factors and several significant cultural factors affecting a controller's sector transitions were identified. Insights of which factors are to be considered and what cautions should be taken into consideration while developing classification scheme that supports minimal differences training approach were discussed in this chapter.

New ATC factors that were not identified from previous research works, such as *Knowing the Neighbor Sectors* and *Coastal Area* factors were identified through the interviews. Some specific ATC techniques that are easily transferable were identified from some controllers as well.

The most significant factor reported, traffic pattern, is immediately being used as a basis for developing classification methods as part of the thesis work. The development process and the sample resulting classes of sectors expected to have fewer transition barriers are presented in Chapter 4. The effectiveness of developed classification scheme as well as the relative significance of identified factors in this chapter will be measured and assessed through an online survey Chapter 5.

# Chapter 4

# Classifying Sectors Based on Traffic Patterns

In order to identify multiple classes of existing sectors that would allow a controller to make transitions with minimal training time, this chapter presents two classification methods developed based on traffic flow patterns.

Chapter 2 of this thesis indicated that there has been no previous work on identifying important ATC factors directly related to a controller's sector transitions. Identifying such factors, however, is a key step in assessing similarities of airspace sectors that support minimal differences training. Without understanding which factors affect sector transitions, it is impossible to understand which factors need to be used as a basis to identify similar sectors that would support shorter transition time. Accordingly, through semi-structured interviews with controllers, Chapter 3 identified the key factors that affect the transferability of knowledge and success in a new sector. The information gained through Chapter 2 and Chapter 3 builds a solid foundation enabling the development of the classification methods.

The following section in this chapter reports the process in developing the two classification methods, the holistic classification method and the decompositional classification method. First, the motivation behind using *traffic patterns* factor as the basis for developing the classification methods is explained. Next, several key traffic patterns that are hypothesized to play a significant role in defining classes of similar sectors are presented. These key traffic patterns were identified by observing commonly occurring traffic patterns across existing NAS high-altitude sectors. Then, these commonly occurring significant traffic patterns are used as the basis in developing the two classification methods. Finally, the developed classification schemes are applied to the existing sectors and classes of sectors expected to consist of similar sectors are identified. These classes are expected to be similar to each other, and hence, the sectors within a group are hypothesized to have fewer transition barriers. The effectiveness of one of the developed classification methods will then be evaluated for its effectiveness in Chapter 5.

### 4.1 Traffic Patterns as the Basis of a Classification Approach

Traffic patterns, also referred as structural features, structural pattern, or structures, is used as the base factor in developing the classification methods for determining classes of sectors expected to have fewer transition barriers. This section explains the rationale behind choosing the traffic pattern factor as the basis for the classification method.

According to the result from Chapter 3, the factor considered to be the most important in a controller's transition is the *Traffic Flow Pattern* factor (Table 3-3). Moreover, *Traffic Flow Pattern* factor also fits well with previous work on the importance of structural abstractions by Histon (2008). Structure has been shown to play an important role in controller cognitive complexity and has been suggested their importance of supporting easily transferable mental models and abstractions in ATC (Histon, 2008). Histon (2008) defines structural features as "the physical and information elements that organize and arrange the air traffic control environment". Structure appears to form the basis for abstractions that reduce the difficulty of maintaining situational awareness (Histon et al., 2001) and air traffic controllers use airspace structure to lower cognitive complexity and enable them to control increasing numbers of flights at a time (Zelinski, 2008). Sectors with similar structural features support similar simplifying abstractions, and have similar types of knowledge associated with them. These structural similarities should thus support the minimal differences approach to generic airspace. Therefore, structural features are a useful perspective from which to identify similar sectors.

For the reasons explained above, the key traffic patterns are used as a basis for the classification method presented in this chapter. The next step, presented in the following section 4.2, is to identify commonly occurring traffic patterns in the existing airspaces that are expected to play a significant role in defining classes of similar sectors. These key traffic patterns are identified by examining commonly reoccurring traffic patterns in the 404 NAS-wide high altitude sectors.

### 4.2 Commonly Occurring Traffic Patterns

In order to identify key traffic patterns and common classes of sectors, radar track data, collected through the Enhanced Traffic Management System (ETMS), were analyzed for two seven day periods (07/13/2009-07/19/2009 and 9/21/2009-9/27/2009). Radar tracks were plotted for flights that spent at least 10 minutes inside each high-altitude sector. High-altitude airspaces were ideal candidate for an initial investigation of potential generic airspace as MITRE has identified through analysis that high altitude airspace has the least number of airspace knowledge items (see 1.2.2). As such, 404 high-altitude NAS-wide radar track maps depicting current sector operations were reviewed for recurring common traffic patterns and key structural features (Cho, et. al, 2011). An example of a high-altitude sector radar track map used is shown in Figure 4-1.

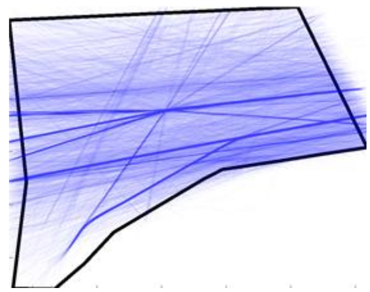


**Figure 4-1. Example of a radar track map used**

From this review, several commonly occurring traffic patterns (Table 4-1) were identified and were used as the basis in developing the two classification methods presented in this chapter. These traffic patterns are listed below in no particular order. Patterns 1 and 2 are consistent with previously reported structural patterns (e.g. Histon, 2008) and the rest of the patterns show repeated aircraft behavior that have similar consequences for controller mental models (Histon, 2008).

**Table 4-1. Eight Identified Commonly Occurring Traffic Patterns**

| | |
|---|---|
| Pattern 1 | Standard Flows |
| Pattern 2 | Critical Points |
| Pattern 3 | Crossing Flows |
| Pattern 4 | Merging/Splitting Flows |
| Pattern 5 | Star-crossing Flows |
| Pattern 6 | Flow Trajectory Change Points |
| Pattern 7 | Vertical Handoffs |
| Pattern 8 | Common Maneuver Patterns |

*Pattern 1 - Standard Flows*

In most sectors, there are one or more distinct concentrated standard flows across the sector. These standard flows are indicated in distinct dark concentrated lines in radar maps as shown in Figure 4-2. Figure 4-2 shows an example sector with three standard flows.

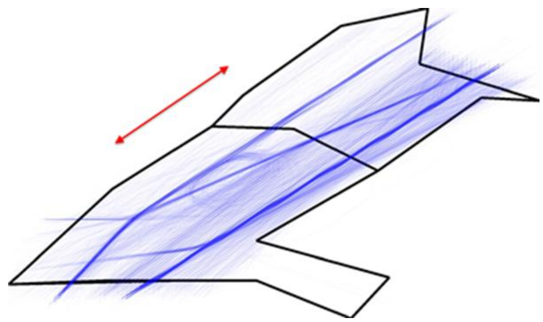


**Figure 4-2. Standard flow**
**(with the red arrow indicating the directionality of the sector)**

These flows usually represent the pathways controllers use to organize aircraft in an airspace for easier management or the consequences of procedures, jet routes and filed flight plans. Standard flows are the foundation for simplifying abstractions used by controllers to reduce cognitive complexity (Histon, 2008). Hence, commonalities in the standard flows between sectors are thought to be important factor for identifying similar sectors.

The standard flow pattern is the foundation for identifying other key traffic patterns as they are observed to be organized in several different shapes such as a parallel flow, a cross flow, a merge/split flow, and more. Some of these traffic patterns are discussed in more details below.

***Pattern 2 - Critical Points***

Another key feature identified in multiple sectors was the presence of critical points, where flows cross, merges, and/or split (Figure 4-3). Similar to standard flows, critical points also serve as a basis for many other traffic patterns found in this review such as a cross flow, merge/split flow, and a star-cross flow.

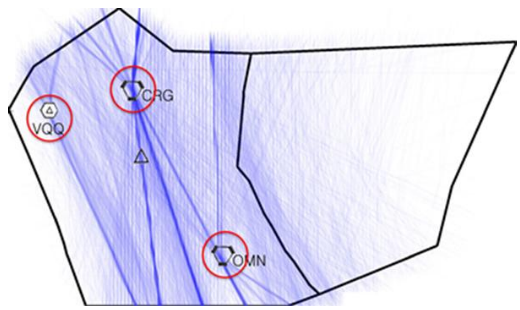



**Figure 4-3. Critical points identified by red circles**

The relative location of the critical points, especially with respect to each other and sector boundaries, as well as the type (e.g., merge point vs. cross) can significantly impact cognitive complexity (Histon, 2008; Hilburn, 2004). Critical points support simplifying abstractions and are important considerations for identifying similar sectors.

***Pattern 3 – Crossing Flows***

One of the commonly occurring traffic patterns in a sector was a crossing flow traffic pattern. Not only was this pattern a commonly occurring pattern, it also was observed to be one of the most common dominating traffic patterns in a sector. As shown in Figure 4-4, the dominating traffic pattern in this sector is a crossing factor.

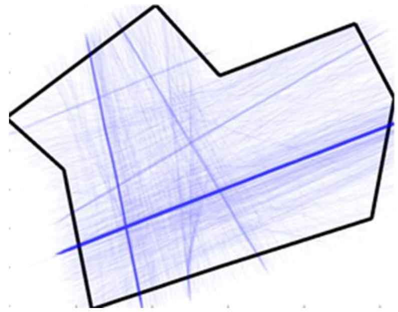


**Figure 4-4. An example sector with a crossing flow**

***Pattern 4 – Merging/Splitting Flows***

Another commonly occurring dominating traffic pattern are merging or splitting flows. Due to the limitation of the radar track maps not being able to provide the directionality information of the flows, it could not be identified whether these patterns are merging flows or splitting flows. As such, both merging and splitting flows were classified as one traffic pattern. An example sector with this traffic pattern as a dominating traffic pattern is shown in Figure 4-5.

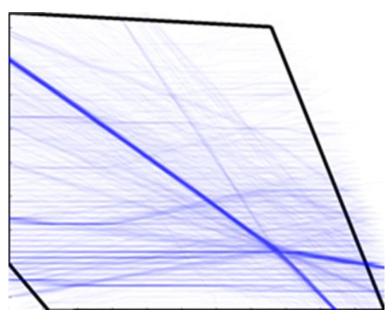


**Figure 4-5. An example sector with a merging/splitting flow**

***Pattern 5 – Star-crossing Flows***

Star-crossing flow traffic pattern was observed in many sectors as a sector's dominating traffic pattern as well. Any sector that has this pattern as a dominating pattern usually was observed to be “busy” or “complex” due to the number of standard flows involved in the sector. An example sector with a dominating star-crossing flow is shown in Figure 4-6.

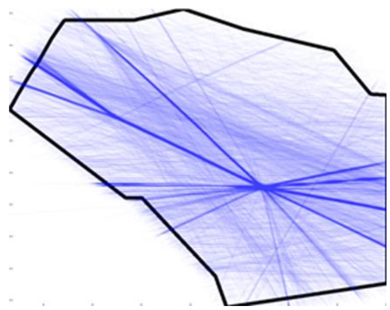


**Figure 4-6. An example sector with a star-crossing flow**

***Pattern 6 - Flow Trajectory Change Points***

Trajectory change points associated with flows (Figure 4-7) typically occur due to special conditions/restrictions such as keeping the flow within the lateral and/or vertical boundaries of the sector. The location of trajectory change points relative to other flows and the sector boundary is an important consideration for assessing sector similarity.

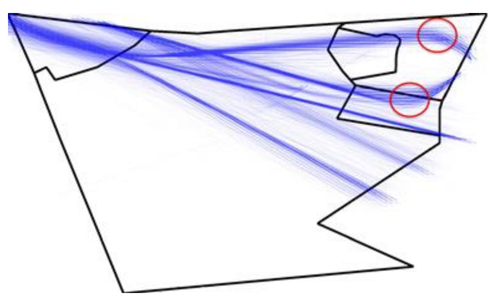


**Figure 4-7. Flow trajectory change points**

***Pattern 7 - Vertical Handoffs***

The radar track analysis also identified a key feature associated with aircraft being handed off and transitioning into or out of sectors vertically. In Figure 4-8, two flows can be seen terminating in the middle of the sector. The locations of the vertical handoffs, and their relationship with other flows in the sector (e.g. climbing or descending below a crossing flow) will likely affect how similar these characteristics need to be in order for two sectors to be considered similar.

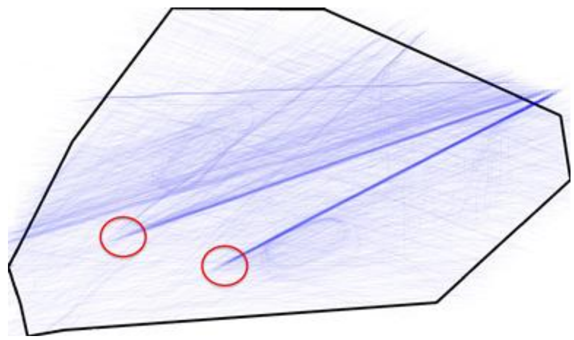


**Figure 4-8. Vertical handoffs**

***Pattern 8 - Common Maneuver Patterns***

Two common maneuver patterns were also identified: the race-track holding pattern illustrated in Figure 4-9a, and the path stretching pattern illustrated in Figure 4-9b. Both of these features require free maneuvering airspace to be present in the sector. The location in the sector, and how it interacts with other elements such as military airspace, will likely affect how similar these features need to be in order for two sectors to be considered similar.

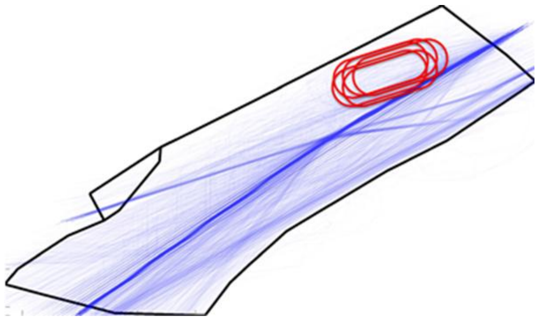


**Figure 4-9a. Race track maneuver pattern**

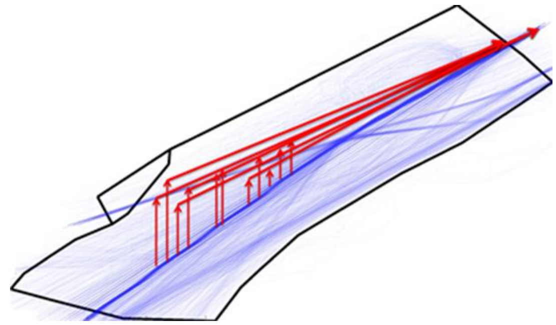


**Figure 4-9b. Path-stretching maneuver pattern**

***Summary***

The key traffic patterns, or the structural features, as identified above can now be used as the basis for identifying operationally similar sectors. As recognized from the previous research (Histon, 2008), when sectors with similar traffic patterns are grouped together, it is hypothesized that they share similar operational characteristics and types of knowledge necessary to operate the sector, thus such classes are expected to support the minimal differences approach to generic airspace.

## 4.3 Holistic Classification

Using the commonly occurring traffic patterns identified above as the basis, the holistic classification approach was developed. The details on the development process as well as the results of classifying 404 NAS high-altitude sectors according to this method are presented in this section.

### 4.3.1 Approach

The holistic classification method is developed based on the approach of identifying similar sectors based on the overall, or the holistic, structural appearance of a sector, without explicit accounting for individual structural features. For this reason, only the most dominating traffic pattern in a sector was considered in this classification method.

***Holistic Classification Component I – The Traffic Patterns***

For the holistic classification approach, only the most dominating traffic pattern in a sector was considered. The most dominating traffic patterns in a sector tend to be single flows, crossing flows, merging/splitting flows, parallel flows, and star-crossing flows, and these five traffic patterns are used as the basis for this classification method. The traffic patterns such as flow trajectory change points, vertical handoffs, or maneuver patterns were rarely the dominating features of a sector and are not used as the basis for this classification method.

***Holistic Classification Component II – Concentration of Flows***

In addition to the five traffic patterns being used as Component I for the holistic classification method, different concentrations of flows were used as a second basis (Component II) for the classification method. Some sectors' standard flows that form the dominating traffic pattern of that sector either were moderately concentrated or heavily concentrated. An example of the density of flows difference is shown in Figure 4-10. The sector on the left shows an example case of moderately concentrated flows whereas the sector on the right shows an example case of heavily concentrated flows. As such, the first two categories of Component II of the holistic classification method are "moderately concentrated standard flows" and "heavily concentrated standard flows".

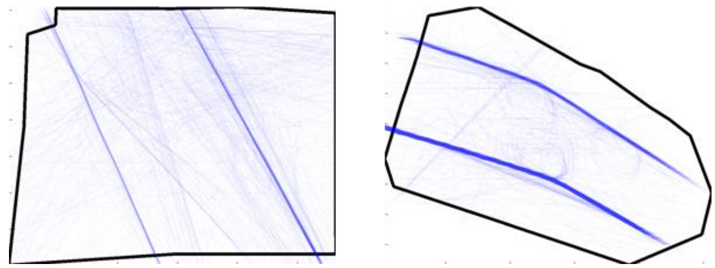


**Figure 4-10. An example of flow concentration difference**

The third category of Component II of the holistic classification method is the existence of background traffic. An example of background traffic difference is illustrated in Figure 4-11. The sector on the left of this figure demonstrates a case with almost no or minor background traffic whereas the sector on the right demonstrates a case with densely distributed background traffic.

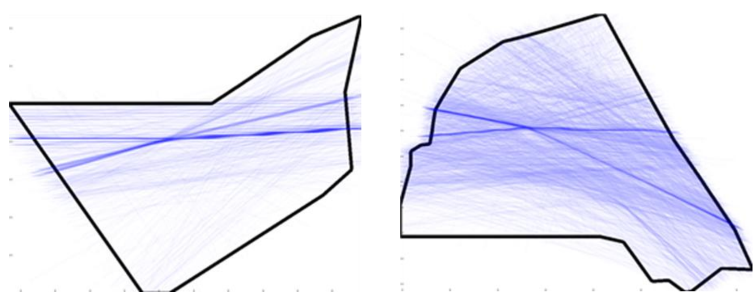
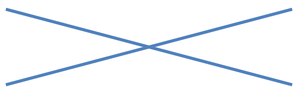
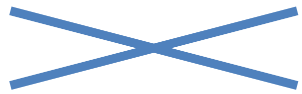
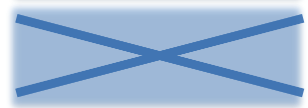
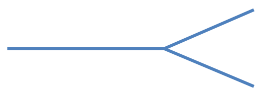
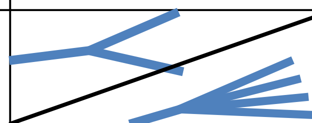
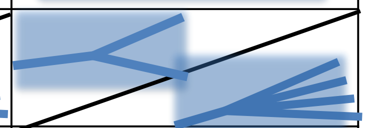
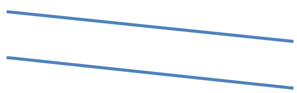
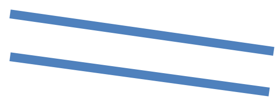
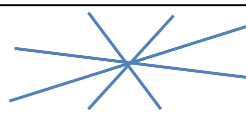
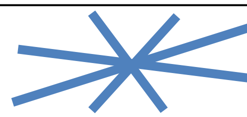
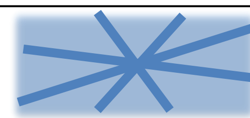


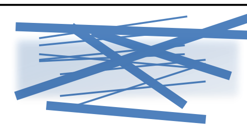
**Figure 4-11. An example of background traffic difference**

### *The Holistic Classification Scheme*

The holistic classification scheme is developed based on the two components discussed above, the five traffic patterns, different concentration of flows as well as the background traffic difference of a sector. The holistic classification scheme is presented below in Table 4-2.

**Table 4-2. Visual and Canonical Guide for the Holistic Classification Scheme**

| | Moderately Concentrated flows | Heavily concentrated flows | Heavily concentrated flows with densely distributed traffic in the background |
|---|---|---|---|
| Single flow |  |  |  |
| Crosses |  |  |  |
| Merges /splits |  |  |  |
| Parallel flows |  |  |  |
| Star-crosses |  |  |  |

| | Almost no traffic | Complex traffic |
|---|---|---|
| Others | |  |

The main part of the holistic classification scheme (Table 4-2) is illustrated in the upper part of the table and is comprised of 15 classes. The "Others" section, located bottom part of the table, were created to accommodate sectors that simply do not have enough traffic to consist of any standard flows or the sectors that are too complex that one dominant traffic pattern is difficult to be identified.

The main part of the holistic classification scheme, the 15 classes, is composed of the two main Components discussed earlier. The five rows organize the five different types of flows, or traffic patterns, and three columns organize different concentration of flows and the level of background traffic. In addition, some merges/splits flows seemed more dispersed than standard merges/splits flows. Therefore, an additional sub-category, the fanning flows class was added as part of the merges/splits flows category.

### 4.3.2 Classifying 404 sectors using Holistic Classification Method

The same radar traffic maps used to identify traffic patterns were used to categorize the 404 high-altitude sectors based on the developed holistic classification scheme. Each sector was classified into only one class. To illustrate how each sector was categorized into different classes, four example radar traffic maps mapped to each of its class are shown in Figure 4-12.

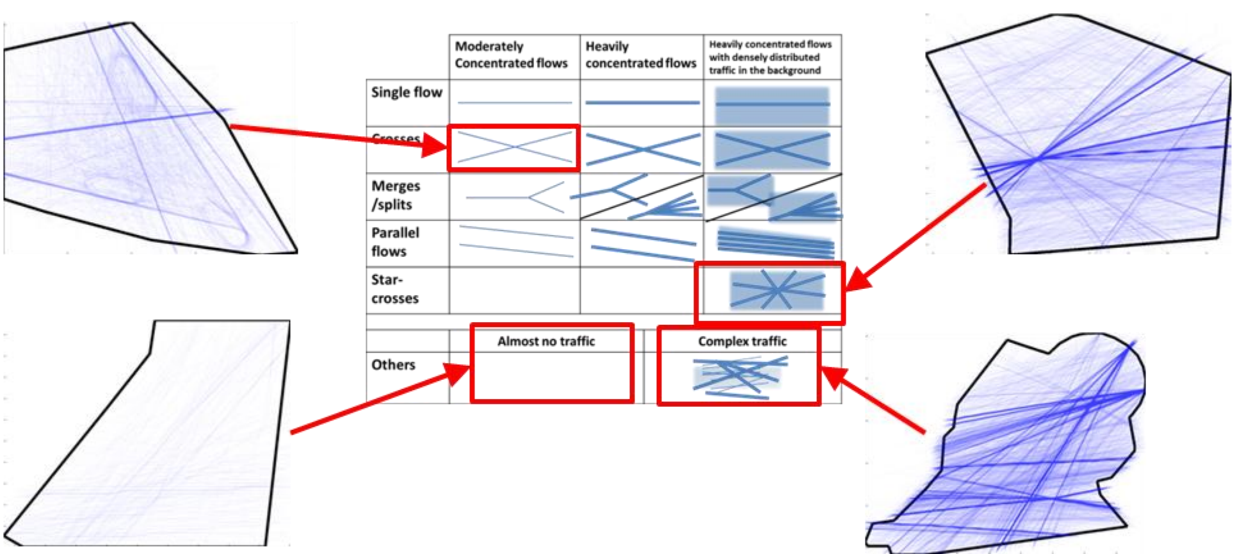
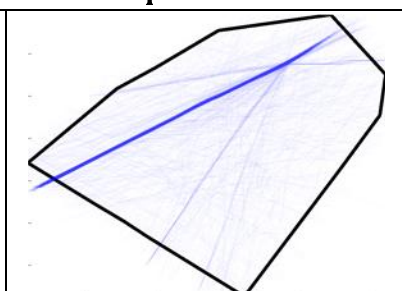
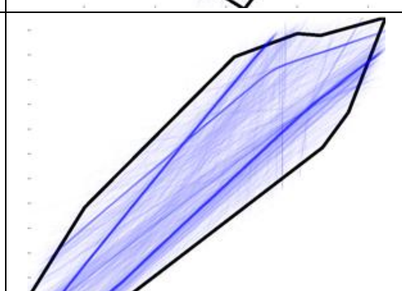
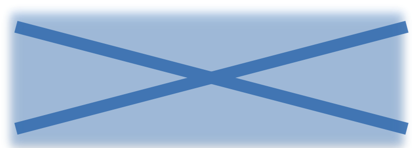
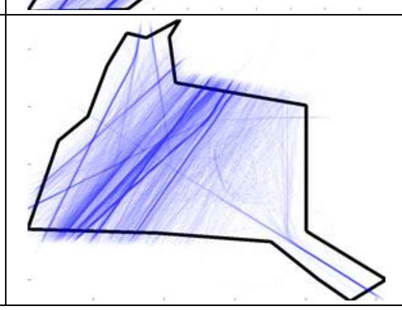
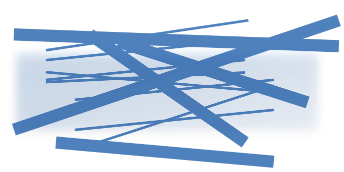



**Figure 4-12. Example radar traffic maps for two classes**

During the classification process, not all sectors had exactly one dominant structural feature. Some sectors were more difficult, or less obvious, to be classified into one class due to the existence of multiple structural features in the sector. To enforce a consistent classifying process, certain minor rules were followed.

First, each sector was examined carefully to identify the *most* dominant feature in the sector. For example, a star-cross flow can be observed in the sector "a" shown in Table 4-3. However, it is evidently illustrated in the figure that one of the star-cross flows is significantly more heavily concentrated than, and hence dominates, the other flows in this sector. For this reason, this sector is classified to belong to the "Heavily Concentrated Flows – Single Flow" class.

**Table 4-3. Example sectors with multiple structural features**

| Example Sector | | The sector's class |
|---|---|---|
| **a** |  | **Heavily concentrated flows – Single Flow** |
| **b** |  |  **Heavily concentrated flows with densely distributed traffic in the background – Crosses** |
| **c** |  |  **Complex Traffic** |

In the cases when there was more than one equally dominant feature in a sector, the number of the most dominant features in the sector dictated which class the sector belongs to. If there were exactly two most dominant features in a sector, crosses, merges/splits, or star-crosses features were prioritized over single flow or parallel flows classes. The reason for prioritizing crosses, merges/splits, or star-crosses over single flows or parallel flows is that operational characteristics are hypothesized to be more complex when the structural features involve confliction points. Thus, choosing the more “complex” structural feature of the two equally dominant structural features would be more accurately predicting the overall difficulty of the sector. For example, if a sector consists of equally dominant cross flow and a single flow in a separate part of the sector as shown in the example sector “b” in Table 4-3, the sector was categorized to be in the crossing flow class. In addition, heavily distributed background traffic can be observed in this sector. As such, this sector is categorized to belong in the "Crosses & Heavily-concentrated flows with densely distributed traffic in the background" class.

In the cases where there were more than two dominant features in a sector, they were categorized to be the *Complex traffic* class in the *Others* category. As shown in the example sector c in Table 4-3, more than two dominant structural features are observed including several crossing flows, merge/split flows, as well as parallel flows. With sectors like this example sector, it is difficult to predict the main structural feature that dictates the key operational characteristics in learning the sector. For that reason, they are categorized to be "Complex traffic" sectors.

### 4.3.3 Results

A comprehensive list of sectors in each class can be found in Appendix A. Table 4-4 shows the consolidated version of the results, the frequency of sectors in each class of the holistic classification method.

**Table 4-4. The frequency result of sectors in the Holistic Classification Scheme**

| | Moderately Concentrated flows | Heavily concentrated flows | Heavily concentrated flows with densely distributed traffic in the background |
|---|---|---|---|
| Single flow | 1% | 3% | 0% |
| Crosses | 3% | 5% | 7% |
| Merges /splits | 0% | 6% / 7% | 3% / 5% |
| Parallel flows | 2% | 9% | 2% |
| Star-crosses | 0% | 0% | 10% |
| | | | |
| | Almost no traffic | Complex traffic | |
| Others | 3% | 33% | |

The value in the centre of each classification cell in the table represents the percentage of sectors categorized into that class. Approximately 64% of the 404 NAS-wide high-altitude sectors were classified into the main part of this classification method, the 15 classes. Some classes had no sectors (0% frequency count) such as the single flow with dense background traffic class, moderately concentrated merge/split flow class, moderately concentrated or heavily concentrated star-crosses classes. Sectors with a single flow usually had low traffic volume, which might explain why there were no sectors with a single flow and densely distributed traffic in the background. As discussed in section 4.2, Pattern 5 – Star-crossing Flows, any sector with a dominant star-crossing flow pattern usually was observed to be "busy" or "complex" due to the number of standard flows involved in the sector. This perhaps explains why no sectors matched to the two star-crosses flow classes that do not have the densely distributed traffic in the background.

3% of the sectors had extremely low traffic counts without any dominant structural features (due to no obvious standard flows observed) and were categorized to be "almost no traffic" class. 33% of sectors were categorized to be a "complex traffic" class due to its possession of multiple dominant traffic patterns (e.g. two crosses with a merge and a parallel flow).

#### 4.3.4 Discussion

The result of the holistic classification approach in Table 4-4 represents an initial break-out of the types of traffic patterns and preliminary estimates of the relative frequency that can be found across sectors in the NAS. The classes that are identified provide a basis for identifying classes of sectors that are expected to be similar enough to support a minimal differences approach to training in order to support controller qualification across the sectors in the class.

Several challenges were identified in using the holistic approach to classification. No attempt was made to account for altitude differences in aircraft trajectories. Including altitude distinctions would lead to additional classes being identified; features such as crosses might have different training implications if they are generated by traffic at varied and procedurally segregated altitudes. Moreover, the representations used did not distinguish between directions of flight, making it difficult to definitively distinguish between merges and splits; other contextual cues can be used, but for the purpose of this preliminary analysis a single class was identified.

## 4.4 Decompositional Classification

Two shortcomings with the holistic approach motivated consideration of an alternative approach. First, the holistic classification approach does not explicitly include the effects of key structural features such as the presence of standard maneuver patterns. In addition, 33% of sectors were classified as “complex traffic” sectors due to their possession of multiple dominant structural features. However, there may be important opportunities for generic airspace sectors based on similarities between sectors within the “complex traffic” class.

Based on the commonly occurring traffic patterns identified in section 4.2, the decompositional classification approach was developed. The details on the development process as well as the results of applying it to the classification of 75 NAS high-altitude sectors are presented in this section.

### 4.4.1 Approach

The decompositional classification method uses combinations of individual structural features appearing in a sector. The decompositional classification method uses individual structural features as building blocks and explicitly accounts for combinations of structural features to classify sectors into common classes.

All of the traffic patterns identified in section 4.2 form the basis for identifying classes of similar sectors in this method: standard flows, critical points (due to their distinct characteristics, critical points are broken down into merge and crosses), distinct trajectory points, vertical handoffs, and holding maneuvering patterns. These structural features form the six main elemental features of this method and are illustrated in Figure 4-13.

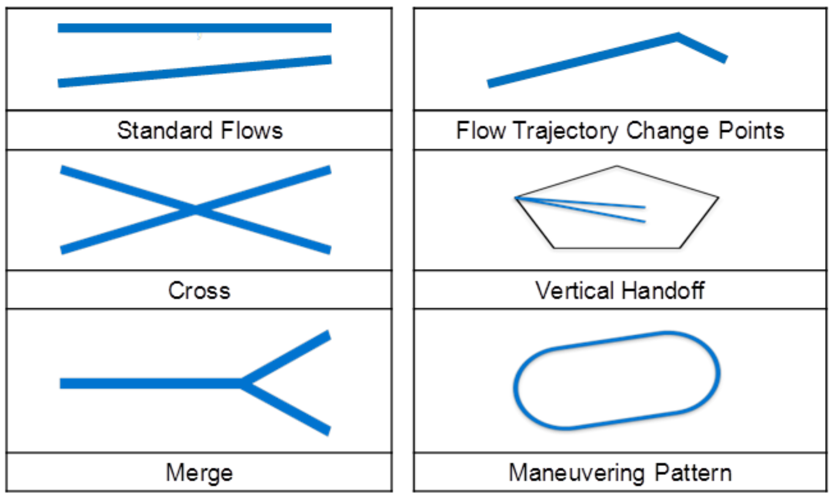



**Figure 4-13. The elemental structural features for the decompositional classification**

Using these elemental structural features, similar sectors can be identified based on the combinations of these elements in a sector. An example of the decomposition of a sector is shown in Figure 4-14. There are three elemental features present in this sector: a crossing flow, a merge/split, and a holding pattern. The order of elements is not considered in the method. For example, in the example illustrated in Figure 4-14, the sector can be decomposed into the same three elements, a cross, a merge/split, and a holding pattern, regardless of a particular order of decomposition.

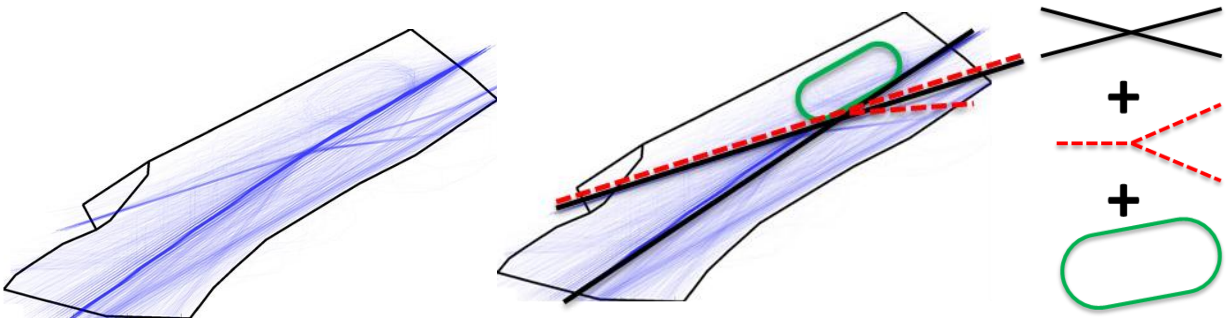


**Figure 4-14. A sector with three structural features and the notional algebra for the sector**

The method also does not distinguish a relatively importance, or "weight", to each elemental feature. In other words, in the current decompositional classification method, all the elemental features are considered equally important and one element's existence over the other does not dictate the *Traffic Complexity* of a sector. However, from the preliminary analysis done as part of this thesis, it can be predicted that some elements such as standard flows perhaps can be considered more important as this structural pattern form the basis for crossing flows, merging/splitting flows, and flow trajectory points elements. Similarly, it is predicted that the relative importance of the rest of the elements can be determined with further analysis as well.

Based on the measurement and observation of the elements' distribution in the sectors, different methods were examined to group and identify how common classes of sectors could be identified. Initial analysis was done across 75 high-altitude sectors using the same radar track maps and the results are reported in the following section.

### 4.4.2 Identifying Elements Using Decompositional Classification Method

In order to explore the viability of using the decompositional approach to identify classes of sectors with similar structural features, the number of elemental structural features in a reduced class of high-altitude sectors was obtained. Radar-track maps for 75 sectors from 5 centers were examined to determine preliminary estimates of the number of structural features (as identified in Figure 4-13) in each sector. The following criteria were used in developing a preliminary evaluation of the frequency of each structural feature:

- Standard flows are concentrations of aircraft trajectory that follow similar along-track paths and with a concentration which visually appears to be denser relative to other flows,
- When two or more standard flows merge within a sector, the number of standard flows is determined by the number of input flows.
- The cross, merge, distinct trajectory change points, and vertical handoff elements were only counted if associated with a standard flow.
- Maneuver patterns did not need to be part of standard flows in order to be counted.

***Results – Frequency of Structural Features***

The frequency of each of the six elements in the decompositional method was determined for 75 sectors in 5 centers. Appendix B lists the 75 sectors and the frequency of each structural feature for all sectors.

Figure 4-15 shows that a significant range of standard flows was observed, with some sectors having 8 or more standard flows. The broad distribution indicates one of the core challenges in developing generic airspace: there is significant variability in the presence of standard flows, a core element of structure, known to impact controller abstractions and cognitive complexity.

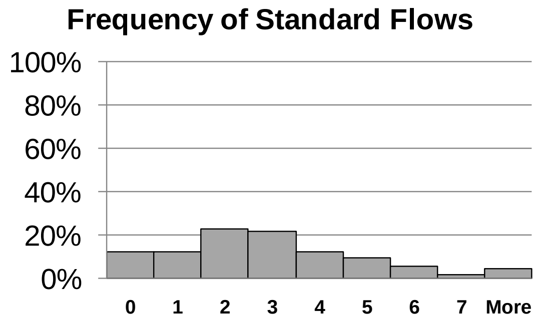



**Figure 4-15. The distribution of frequency of standard flows appearing in a sector**

In contrast, Figure 4-16 shows that the distributions of cross, merge, and trajectory change points share a common distribution. For these three elements, it was observed that approximately 50% of the 75 sectors did not have each element and very few sectors (less than 10%) had four or more instances of a feature.

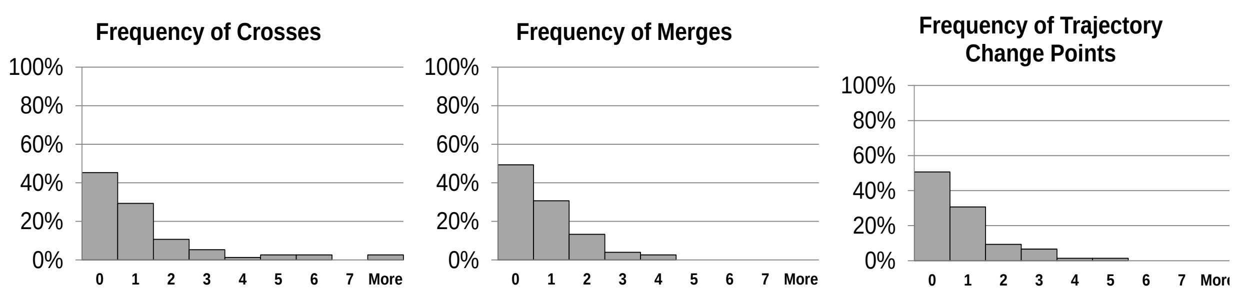



**Figure 4-16. The distribution of frequencies of crosses, merges, and trajectory change points appearing in a sector**

Some structural features (e.g., standard flows) are integral parts of other structural features (e.g., crosses). As a result, some of these distributions are dependent on others. For example, a minimum number of standard flows required for a cross or a merge element to exist is two, meaning that crosses or merges cannot exist in sectors with a single or no standard flow. Figure 4-17 shows the distribution of sectors with zero or at least one cross or merge flow. It can be observed in the graph that at least 70% of the sectors had at least one cross or merge flow. This number is smaller than the frequency of two or more standard flows observed in Figure 4-15, which is 80%. This confirms that crosses or merges cannot exist in sectors with a single or no standard flow. This also predicts that 10% of the 75 sectors have parallel flows since these sectors had two or more standard flows but did not have either cross or merge flows.

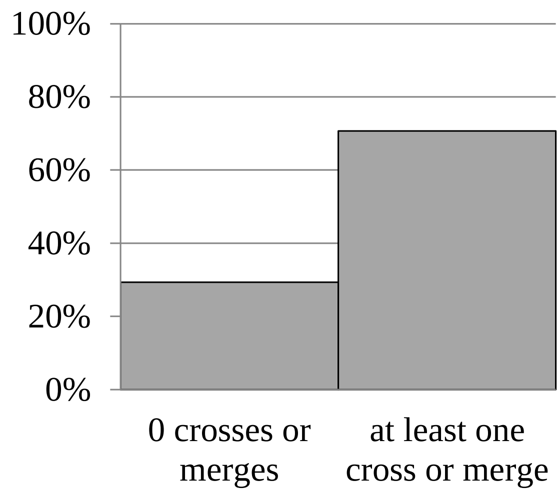



**Figure 4-17. Frequency of sectors with either crosses or merges**

Finally, Figure 4-18 shows that many sectors do not have vertical handoffs or holding patterns. The holding patterns was mostly found in sectors in one particular center suggesting that center differences may play a significant role in determining the feasibility of the generic airspace concept.

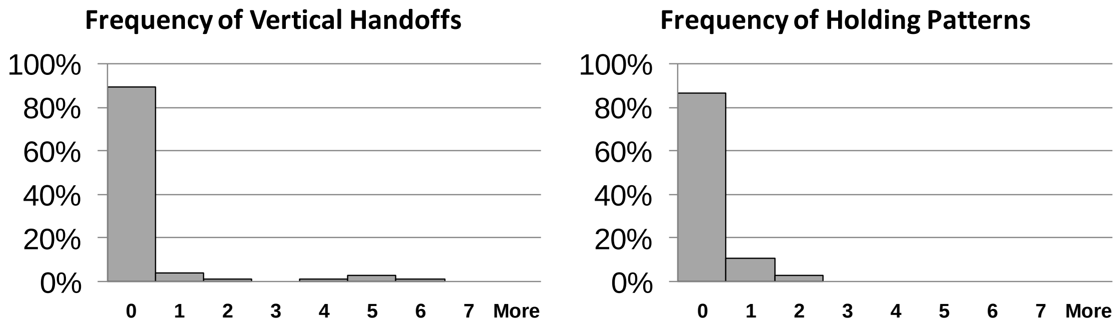



**Figure 4-18. The distribution of frequencies of vertical handoffs and holding patterns appearing in a sector**

### 4.4.3 Classifying Sectors Using Common Patterns of Structural Features

The observations of the frequency of structural features in each sector can be used to identify sectors with common combinations of structural features. These common combinations of sectors are expected to provide similar cognitive characteristics. However, care must be taken as the broad distribution observed in the frequency of elements distribution (as illustrated in section 4.4.2) indicates a challenge in developing generic airspace. When there is significant variability in the presence of each element, it can result in a dilution of the classification scheme: the more variability of classes there are, the smaller number of sectors in each class, which defeats the purpose of classifying sectors. To combat this challenge, a few different ways of grouping and identifying common classes of sectors from the observed data are presented below.

***Grouping Method #1***

One of the simpler ways, though not considered further in this thesis, is using a weighted combination of features to determine the overall complexity of the sector, similar to the complexity based classification described by Christien (2002). Weights for each elemental feature can be estimated based on their relative significance (e.g., cross assigned weight of "1" unit, a hold a weight of "2" units etc…). Then, the score may be determined from the weighted sum of elements in each sector and sectors with same scores can be grouped together. This has the advantage of simplicity and segregating sectors depending on their complexity, but loses much of the information gained by explicitly decomposing the sector into its individual elements. A further challenge with this method is determining the appropriate significance of each element and assigning the correct weight for each unit.

***Grouping Method #2***

More involved techniques, based on multi-dimensional clustering techniques and other formulations of multi-class classification algorithms are other ways of assessing similarity of combinations of elements. To illustrate how the observations presented above can be used to identify potential sector classes, Figure 4-19 plots the number of standard flows and the number of crosses for each sector. Each sector is represented by a single point in the figure; for instance, one of the observed sectors has 10 standard flows and 14 crosses. In order to provide proper visualization of the number of sectors at each point in the graph, a small "noise effect" was added to the observations. Clusters of common sectors in Figure 4-19 can be clearly identified, as well as sectors that appear to be unique. For example, classes of similar sectors can be observed with sectors with zero crosses and one, two, or three standard flows. Additional classes of multiple, similar, sectors can be found with two standard flows and a single cross, and three standard flows and one or two crosses.

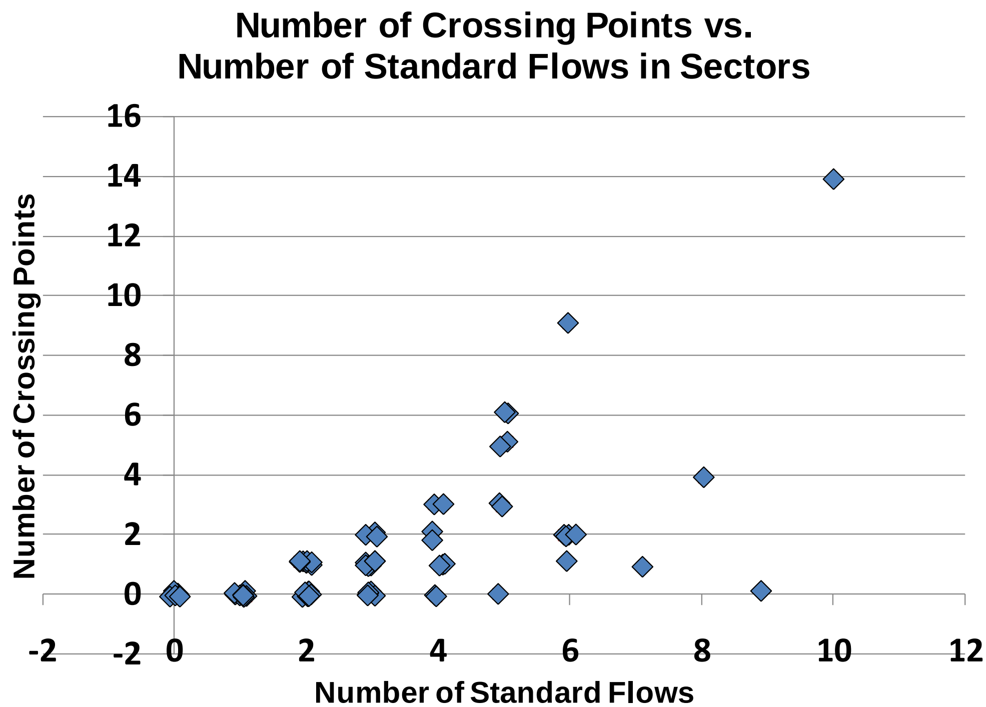



**Figure 4-19. The distribution of two structural features in 75 sectors**

In some other cases, such as the distribution observed in the upper right side of the graph in Figure 4-19, a cluster of multiple sectors sharing the same combination of standard flow and crosses cannot be observed. On the basis of this method, these sectors would not be considered as candidates for generic sectors, as it is expected that the required abstractions would be too cognitively different from other sectors for a minimal differences training approach to be successful.

One possible way to combine clusters into different classes is illustrated in Figure 4-20. Further effort is needed to assess cognitive aspects of combinations of these classes. In some cases it is likely that the precise number of structural features is not as relevant as the relative number of elements. For example, the standard flow abstraction suggests sectors with three standard flows and no crosses will likely be very cognitively similar to sectors with four standard flows and no crosses. In the absence of crosses, the flows can be considered independently, and sector operations may be sufficiently similar that these sectors can be easily transferred between.

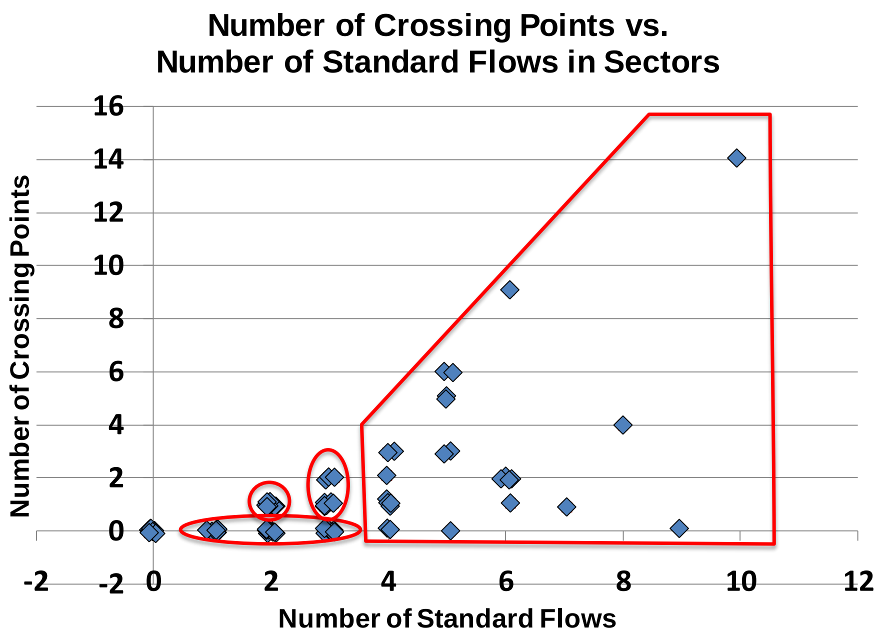



**Figure 4-20. A Possible Way of Combining Clusters into Classes**

### *Effectiveness of Expanding the Number of Features in a Classification*

There are a finite number of sectors, and developing schemes that incorporate an excessive number of factors will limit the size (and therefore the value and the practicality) of a class of generic sectors. Additional analysis was performed to examine the effectiveness of expanding the number of features incorporated to identify classes of similar sectors. It was stated earlier that the large number of classes can dilute the classification scheme and defeat the purpose of classifying sectors. This is because the more classes there are, the smaller the number of sectors results in each class.

In order to examine this problem, different combinations of elements (ranging from 1 to 6) were created; each combination is considered a dimension level (Table 4-5). The combinations represent successively adding an additional structural feature to the previous dimension level. At each dimension level, sectors with the same values for each element are grouped together into a class; the number of classes and the number of sectors in each class could then be determined.

**Table 4-5. The List of Dimension Levels**

| **Dimension Level** | **Element Combinations** |
|---|---|
| Dimension 1 | Standard Flows |
| Dimension 2 | Dimension 1 + Crosses |
| Dimension 3 | Dimension 2 + Merges |
| Dimension 4 | Dimension 3 + Vertical Handoffs |
| Dimension 5 | Dimension 4 + Trajectory Changes |
| Dimension 6 | Dimension 5 + Holding Patterns |

All 75 sectors are broken down into a unique "dimension" across all the dimensions measured. For instance, for a sector that has 5 standard flows, 2 crosses, 0 merges, 0 vertical handoffs, 0 trajectory changes, and 1 holding pattern, its signature for 6-dimension level would be “5-2-0-0-0-1”. This is applied to all 75 sectors, each sector producing 6 different "dimensions" for each 6 dimension levels (e.g., the signatures for six dimensions of the example sector would be "5", "5-2", "5-2-0", 5-2-0-0", "5-2-0-0-0", "5-2-0-0-0-1").

After 6 dimension levels were identified for all 75 sectors, unique classes, or classes, were identified for each dimension level. For instance, there were 11 unique classes identified for dimension level 1 (e.g., when only one element, the number of standard flows, was involved to create classes). In contrast, there were 45 unique classes identified for dimension level 6. As observed in Figure 4-21, the number of unique classes increases as the number of elements increases.

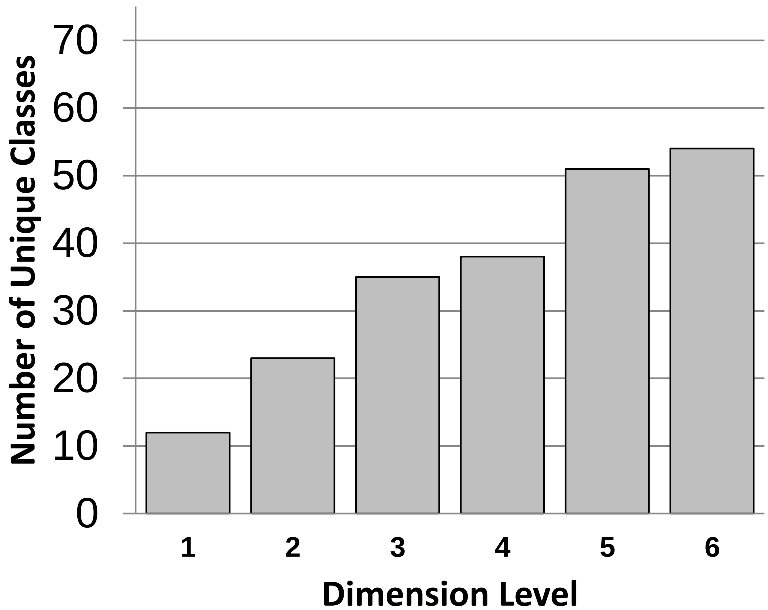



**Figure 4-21. Frequency of Resulting Unique Classes Depending on the Number of Elements Used (Dimension Level numbers indicates the number of elements)**

The following analysis examines how the size of the classes (the number of sectors belonging to each class) changes as the number of elements involved to create classes increase. As illustrated in Figure 4-22, the size of each class decreases as the number of elements increases. Over 80% of the classes with 6 elements consisted of only one sector in each group meaning less than 10% of the classes with 6 elements consisted of more than one sector in each group.

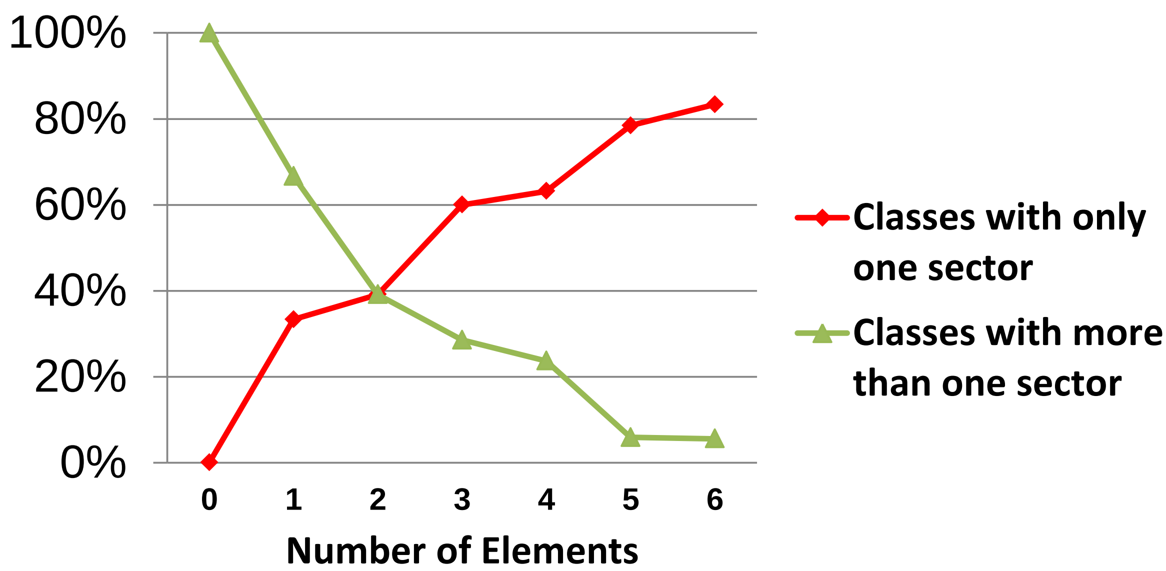



**Figure 4-22. The Proportion of Classes with One Sector or More than One Sector**

As shown, this analysis emphasizes the importance of narrowing down the features that are most important for transitions in order to produce more effective classes.

### 4.4.4 Discussion

The decompositional classification method involves complicated combination analysis and significant effort; therefore the initial analysis was limited to 75 sectors in 5 centers. In the future, the analysis could be expanded to all 404 high-altitude sectors to obtain results spanning the entire NAS. Similar to the holistic classification method, due to the limitations on the data used for the analysis, the impact of aircraft being at different altitudes was not considered. Similarly, direction of flight (important for distinguishing between merge and split points), and the directionality of standard flows was not considered.

A key advantage of the decompositional approach presented here is that other complexity factors, including traffic density, peak traffic, presence of weather, and Standard Operating Procedures (SOPs), can also be incorporated into the assessment of similarities between sectors.

However, as this was a preliminary effort at quantifying the relative frequency of the structural features for the decompositional approach, several important characteristics were not accounted for. As such, traffic patterns such as star-crossing patterns or parallel flows which were used in the holistic classification method were not incorporated in this method to be the elemental structural features. More investigation should be done in the future to look into which factors should be included or excluded to be the elemental structural features for the decompositional classification. In addition, these estimates were obtained using qualitative analysis of the radar-track maps of each sector; additional work could determine more systematic methods of assessing quantitative measures. Further work can take advantage of efforts to develop a method for extracting critical points directly from flight trajectories (Zelinski, 2008). Despite these limitations, the analysis results provide a basis for developing techniques for identifying common combinations of structural features and classes of sectors.

In addition, the additional analysis was performed to examine the effectiveness of increasing the number of elements in classifying sectors. The result of the analysis emphasized the importance of narrowing down the features that are most important for transitions in order to produce more effective classes.

### 4.5 Chapter Summary

Radar track data for 404 high-altitude sectors were used to identify several key traffic patterns and similarities in these traffic patterns provide a basis for identifying classes of generic sectors.

Using these commonly occurring traffic patterns identified, two distinct methods to classify sectors were presented. The holistic approach, based on assessing the overall structural appearance of a sector, was used to identify 17 classes of high-altitude sectors. The second, decompositional, approach was proposed as the basis for comparative analyses of structural features of the sectors.

Through the classification process, a broad distribution of number of standard flows per sector was observed. This indicates some challenges in developing generic airspace as standard flows are a core element of structure known to impact controller abstractions and cognitive complexity. Further analysis with the classification results identified that the number of features involved with classification methods directly relate to the effectiveness of the classes. This finding stresses the importance of finding the optimal number of features to be used in the classification.

The identification of classes of sectors with similar structure provides a basis for assessing the potential of near-term deployment of generic airspace. A successful classification scheme would produce classes of similar sectors that controllers understand and agree that they are similar in supporting minimal differences training. As such, the effectiveness of one of the developed classification schemes, the holistic approach, will be measured through a survey using the resulting classes. The holistic classification method is chosen to have its effectiveness measured as this classification method was applied to all of the NAS high altitude sectors and the resulting classes that are expected to consist of sectors that are similar to each other were identified. This validation process is further described in Chapter 5.

# Chapter 5

# Validating Perceptions of Airspace Similarity through Subject-Matter-Experts

The identification of classes of sectors with similar structure provides a basis for assessing the potential of near-term deployment of generic airspace. The holistic classification method developed in Chapter 4 produced 17 distinct classes of 404 high-altitude NAS sectors that are expected to have fewer transition barriers. A valid classification scheme would generate classes of similar sectors that controllers understand and agree that they are similar in supporting minimal differences training. The objective of the work presented in this chapter is to:

Chapter Objective: *Test the effectiveness of the holistic classification method against the perceptions of a broad group of air traffic controllers.*

To test the perceptions, a survey was developed and administered to a large group of air traffic controllers. In the survey, the effectiveness of the holistic classification scheme was determined by observing if participants agree that sectors from the same class (based on the classification method) are similar and support easier transfer of knowledge, skills, and abilities. Five chosen classes, based on the structure-based components of the classification scheme, were used to measure how effective each component of the holistic classification scheme is. The results showed that participants significantly agree with four of the five components of the classification method, and the overall result identifies that the structure-based classification technique is an effective way to determine similar sectors that support minimal differences training approach. Based on the results, the holistic classification scheme is adjusted and a revised scheme is presented.

The following sections describe how the survey was designed, report what the results of the survey, and discuss the implications of the results.

## 5.1 Survey Design

This survey tested the effectiveness of structure-based classification through a series of sector traffic pattern image comparisons. The goal of this survey is to validate the appropriateness of the identified classes based on structure-based, or traffic pattern, components of the classification scheme.

### 5.1.1 Setting up Comparisons

The holistic classification scheme previously identified 17 classes as shown in Table 4-2. The survey was designed to focus on limited subset of these classes, five specific classes chosen based on the main structure-based components of the classification scheme. This survey focuses on the main part of the classification, the 15 main classes in the upper part of the classification (highlighted in Table 5-1). The main part of the classification scheme, the upper 15 classes, is based on two key fundamental traffic pattern, or structure-based components: different types of flows (organized in five rows) and different concentration of flows (organized in three columns). The five rows represent five different types of flows and three columns represent different concentration of flows and the level of background traffic (discussed in more details in 4.3).

**Table 5-1. The 15 classes tested (highlighted with red box) for their validity in the survey**

| | Moderately Concentrated flows | Heavily concentrated flows | Heavily concentrated flows with densely distributed traffic in the background |
|---|---|---|---|
| Single flow | 1% | 3% | 0% |
| Crosses | 3% | 5% | 7% |
| Merges /splits | 0% | 6% / 7% | 3% / 5% |
| Parallel flows | 2% | 9% | 2% |
| Star-crosses | 0% | 0% | 10% |

| | Almost no traffic | Complex traffic |
|---|---|---|
| Others | 3% | 33% |

The survey was designed around several testing factors, each designed to probe a distinct part of Table 5-1. As there was some initial concern about the effectiveness of the question design, the first testing factor was designed as methodological check. Two classes thought to be dramatically different were selected for comparison; if differences were not found on this testing factor, it would provide an indication that there was a problem with the survey methodology. This is called testing factor #1 in Table 5-2. Secondly, in order to measure how effective the holistic classification scheme is more systematically, the basis of the holistic classification method, the structure-based components must be tested for their appropriateness.

As such, five additional testing factors (testing factor #2 ~ #6) based on these structure-based components were chosen. Only a limited subset of classes was used (i.e., six testing factors) to test the key dimensions of the classification method because participants were expected to have only a limited amount of time to complete the survey (e.g., 30 minutes). Comparison questions were developed for each of these testing factors, as presented in Table 5-2, to measure controllers' perception of airspace similarity. For each testing factor, a testing class and a distractor class are chosen. A testing class is the class being tested for similarity against the distractor class.

**Table 5-2. Six Testing Factors Chosen for the Survey**

| **Testing Factors** | | **Testing class** | **Distractor class** |
|---|---|---|---|
| **#1** | Methodological check, hypothesized large class difference | Single flows | Star-cross flows |
| **#2** | Flow concentration | Heavily concentrated cross flows | Moderately concentrated cross flows |
| **#3** | Background traffic | Cross flows | Cross flows with densely distributed traffic in the background |
| **#4** | Different types of flow #1 | Cross flows | Merge/Split flows |
| **#5** | Different types of flow #2 | Cross flows | Star-cross flows |
| **#6** | Different types of flow #3<br>(A sub-class: merge/split vs fan) | Merge/Split flows | Fan-in/out flows |

***Testing Factor #1: The Methodological Check***

The first testing factor is the hypothesized large class difference comparison for a methodological check. For this testing factor, the single-flow class (the testing class) is tested if it is significantly different from the star-cross class (the distractor class). These two classes are in different rows and different columns in Figure 5-1, and would generally be expected to have large differences in the knowledge, skills, and abilities. In other words, it is hypothesized that if a controller is trained in a sector with a single-flow traffic pattern, it is much easier to make transitions to another sector with a single-flow traffic pattern than it is to make transition to sectors with star-cross traffic pattern. As this is a methodological check comparison, a significant difference for this comparison is expected. If a significant difference between these two classes is not achieved from the survey, the effectiveness of the survey design questions would be uncertain.

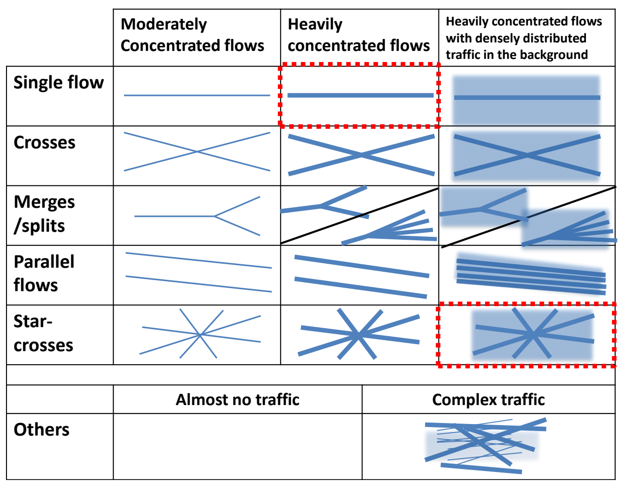



**Figure 5-1. Two Chosen Classes (dotted boxes) for the Methodological Check**

***Testing Factor #2 & #3: Flow Concentration and Background Traffic Difference***

The second and third testing factors, flow concentration and background traffic difference, test if the columns in the holistic classification method (Table 4-2) are an effective way of determining similar sectors that have fewer transition barriers. Testing factor #2 (as highlighted in dotted boxes in Figure 5-2) examines if flow concentration plays a significant part in determining classes of "similar sectors" that support minimal differences training. In other words, if knowledge, skills, and abilities transfer would be maximized when a controller makes a transition to a similar level of concentration of flows rather than to a different level of concentration flows. For this specific testing factor, a heavily-concentrated-cross class is chosen as a testing class and moderately-concentrated-cross class is chosen as a distractor class, as shown in solid boxes in the left table in Figure 5-2. Similarly, appropriate testing class and distractor class are chosen to measure the effectiveness of Testing factor #3, the level of background traffic difference, shown on the right table in Figure 5-2.

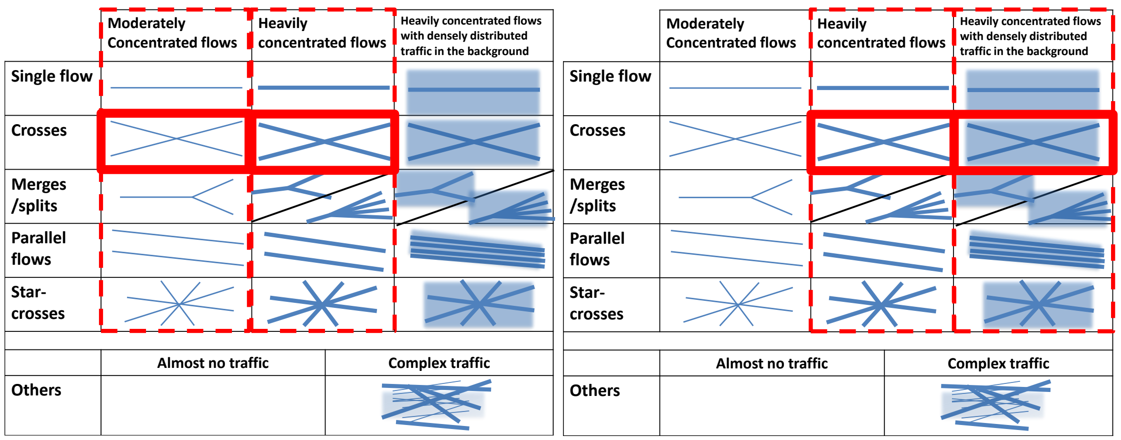



**Figure 5-2. Classes (solid boxes) used for *Flow Concentration* comparison (dotted boxes) on left and *Background Traffic Level* comparison on right**

### *Testing Factor #4, #5, & #6: Different Types of Flows*

The fourth, fifth, and sixth testing factors test if the rows in the holistic classification method (Table 4-2) are an effective way of determining similar sectors that have fewer transition barriers. Testing factor #4 examines if the difference between cross flows and merge flows play a significant role in determining classes of "similar sectors" that support minimal differences training. In other words, this testing factor measures if knowledge, skills, and abilities transfer would be maximized when a controller makes a transition from a cross-flow sector to another cross-flow sector as opposed to a merge-flow sector.

Similarly, testing factor #5 measures the difference between crosses (two standard flows involved) and star-crosses (more than two standard flows involved at a single cross), and testing factor #6 measures the difference between merge and fan flows.

### 5.1.2 Sector Selection for Testing factor

For each testing factor (Table 5-2), 9 pair-wise similarity comparison questions were developed. Each question presented the survey participant with one sector from the testing class, and presented two choices. Each choice was a sector, one also belonging to the testing class and one belonging to the distractor class. Figure 5-3 illustrates how these sectors were selected for the 9 pair-wise comparison questions for one testing factor. The three large ovals in Figure 5-3 represent classes (the testing class for the first two ovals and the distractor class for the third oval) and the small circles in these ovals represent sectors in each class. In order to create each comparison question, the following process was followed.

1. From the Testing Class, one sector is randomly chosen to be the “Test Sector” (Sector A) and used repeatedly for three questions for the same testing factor. For each testing factor, three “Test Sectors” (Sector A) are chosen.

2. Excluding the three “Test Sectors” chosen from Step 1, a “Similar Sector” (Sector B) is chosen randomly from the Testing Class.

3. From the Distractor Class, a “Distractor Sector” (Sector C) is chosen randomly.

4. As long as there are no two questions with the same combination of Sector A, B, and C, Sector B and Sector C can repeatedly be chosen again for different questions, if chosen randomly.

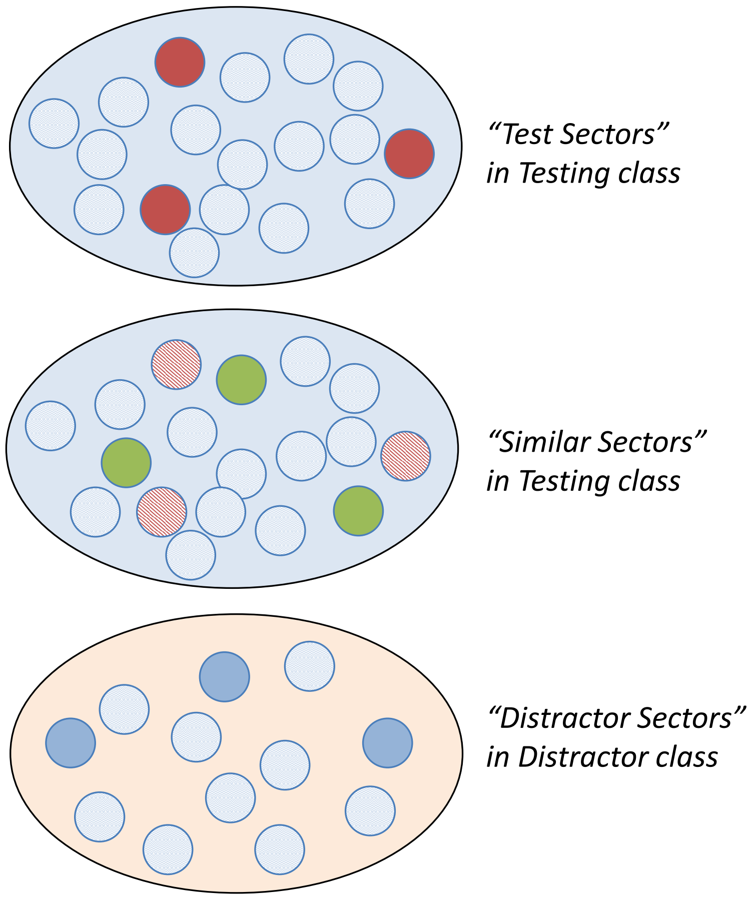



**Figure 5-3. Testing factor Methodology – Sectors Selection**

Each question's composition can be explained further using the diagram shown in Figure 5-4. As illustrated, each question is composed of three sectors, Sector A, Sector B, and Sector C. Sectors A and B are selected from the same class, the "Testing Class", and Sector C is selected from the "Distractor class" (Figure 5-3). Figure 5-4 demonstrates an example of a pair-wise similarity comparison for testing factor #2, the flow concentration difference. A full list of sectors chosen using this method for the 54 questions in the survey can be found in Appendix C.

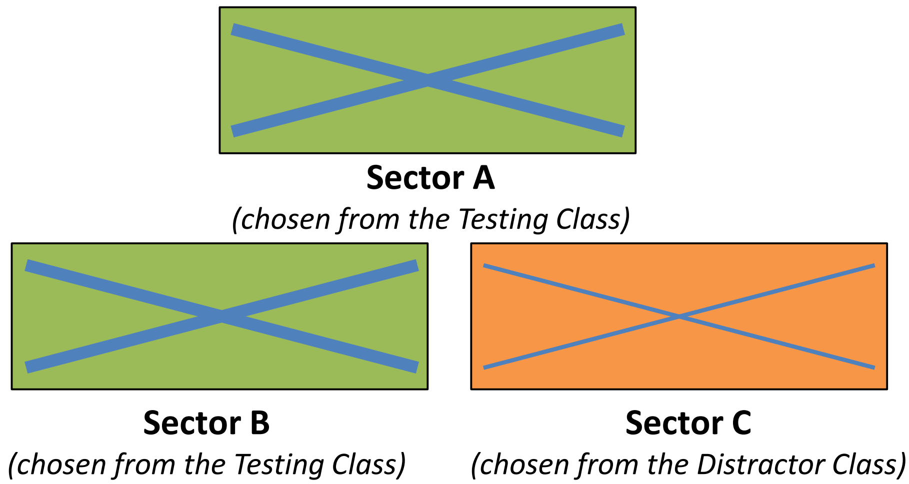
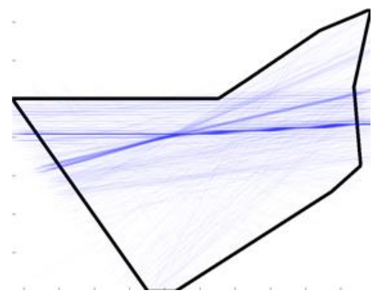



**Figure 5-4. An Example of Pair-Wise Similarity Comparison**

### 5.1.3 Survey Questions

Each comparison question produces a binary choice answer from participants – having to choose between Sector B and Sector C. Each question asks, "*Assume you are certified on and have experience controlling this sector (Sector A - above). Consider the two sectors below. Which sector do you feel has the most interchangeable knowledge, skills, and abilities with Sector A (above)?*". As specific directionality of transferring skills is not supported in the current holistic classification method, it was critical that participants do not choose an "easier" sector as this can easily endorse the directionality of transferring skills (e.g., moving from A to B is easy but B to A is not). As such, the wording for this question was chosen as above to reflect the concern.

The same radar track maps that were used for the developing the classification scheme were used for the 54 survey comparison questions. In order to focus the testing factor on the traffic pattern only, any additional information such as the name, location, altitude level, and other information of the sector were excluded in the images shown in the survey. An example of a comparison question used for the survey is illustrated in Figure 5-5.



*Assume you are certified on and have experience controlling this sector (Sector A - above). Consider the two sectors below. Which sector do you feel has the most interchangeable knowledge, skills, and abilities with Sector A (above)?*

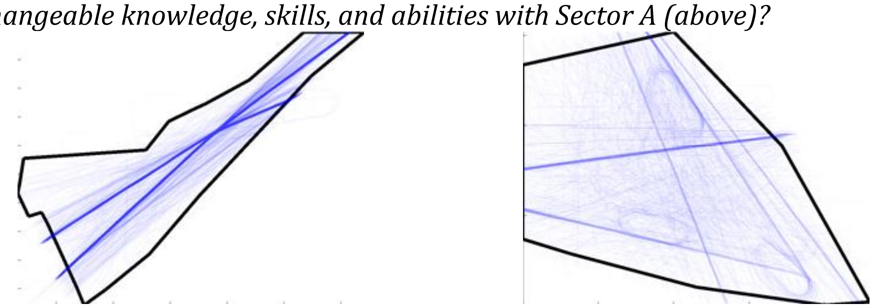


**Figure 5-5. A Sample Question for Survey - Part I**

The limited amount of information given in the images shown can lead participants to assume variable factors necessary in order to make the judgement. To minimize this variability and to ensure their choices are conditioned by the difference in traffic patterns of both sectors only, several assumptions were stated. These assumptions were shown for all 54 comparison questions and are shown in Table 5-3. These assumption statements were presented to minimize any bias caused by assumptions such as ensuring they assume the same mix of airliners and business jet traffic, or ensuring they assume same altitude range for all sectors as assuming different conditions for these factors could easily affect their choices.

**Table 5-3. Assumptions Statement for Questions for Survey – Part I**

| *Assumptions are the same for all 54 radar track map comparison questions.* |
|---|
| 1. The maps in the following questions represent two weeks of radar track maps.<br>2. The following maps show only two-dimensional information and no information is provided on the direction of the travel for any of the traffic.<br>3. There is no information provided on the specific location of the sector.<br>4. There is no information provided on the locations of fixes and navigation aids.<br>5. Assume all sectors have an altitude range of FL290 to FL600.<br>6. Assume there are no particular letters of agreement.<br>7. Assume there is a mix of airliner and business jet traffic.<br>8. Assume there are no location specific weather phenomenon that affect sector operations. |

## 5.2 Survey Procedure

The survey in Chapter 5 and Chapter 6 were conducted together, although each part has been analyzed and is presented separately. The following survey procedure details are applicable for both parts of the survey.

Survey questions were posted using www.surveygizmo.com site using an online survey format. Participants filled the questionnaire either in their own personal computer or other personal devices such as tablet or a smartphone that allows an Internet browser.

The question order was randomized across all 54 questions in Part I of the survey (Chapter 5) as well as across 10 questions in Part II (Chapter 6) to minimize any bias that might occur due to a specific order of questions presented. The questions were randomized within each part only and the two parts were presented as separate sections at all times. Part I was always completed first before participants were allowed to move on to Part II of the survey. Each question in Part I was asked one question at a time and participants were not allowed to go back and change answers. The 10 questions in Part II were presented in one continuous screen with the order of the questions randomized within Part II. All participants were encouraged to answer all 54 comparison questions for Part I of the survey and 10 ranking questions for Part II of the survey. Participants were free to leave any questions blank if they did not feel comfortable answering them.

In addition, the position of the binary choices for all questions in Part I, Sector B and Sector C, were randomized. Space was made available for comments on individual 54 comparison questions in Part I to explain their choices and overall comment for Part II to identify any additional relevant factors.

### 5.2.1 Participants

***Recruitment Process***

Retired or active air traffic controllers were recruited to participate in this study. Participants were required to be a certified air traffic controller in order to participate in this study. Participation was voluntary and participants were not remunerated for their involvement with this study. Recruitment letter and flyers were distributed using common ATC website forums and web ATC network groups such as www.liveatc.net, www.stuckmic.com, www.avcanada.com, and www.linkedin.com. Controllers' work emails from personal contacts were also used to recruit participants.

***Participants Demographics***

There were a total of 56 retired or active air traffic controllers who responded to the survey. 38 (68%) of the participants were from the United States, 6 (11%) were from Canada, 2 (4%) were from France, 10 (19%) were from other countries (Table 5-4). Participants' years of experience as a controller ranged from 2 years to 37 years with 41 (73%) participants having more than 5 years of experience (Table 5-5). The distribution of level of ATC experience of the participants is shown in the graph in Figure 5-6.

**Table 5-4. Nationality of the Participants**

| | |
|---|---|
| United States | 38 |
| Canada | 6 |
| France | 2 |
| Other countries with one participant for each country (Australia, Guam, United Kingdom, Germany, Israel, Sweden, Qatar, United Arab Emirates, Netherlands, Kenya) | 10 |

**Table 5-5. Level of Experience of the Participants**

| | |
|---|---|
| Years of experience more than 5 years | 41 |
| Years of experience equal to or less than 5 years | 15 |

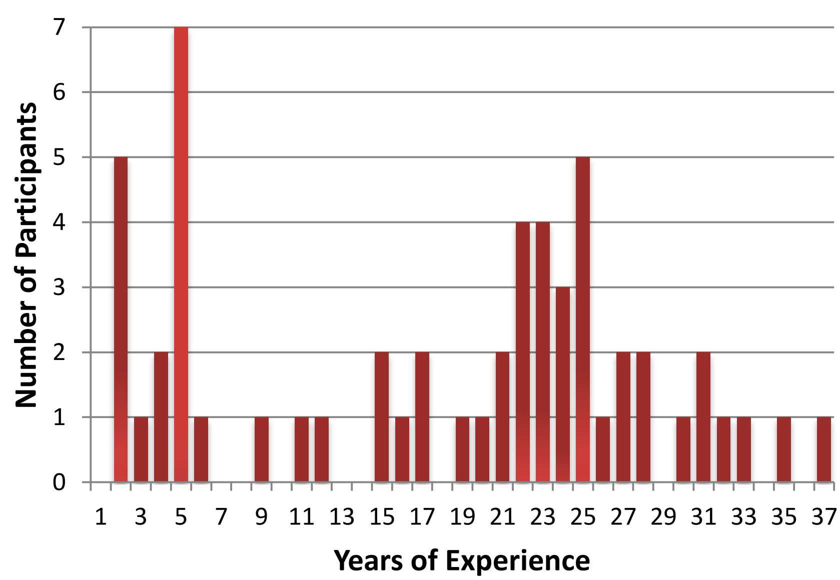



**Figure 5-6. Distribution of Years of Experience**

***Participant Response Quality Control***

Several following steps were taken in order to ensure all 56 responses were from certified controllers and were valid. Firstly, the survey was made available to a filtered audience (air traffic control related professionals) through participant recruitment advertisements made only on professional ATC-related networks and controllers' work emails from personal contacts. Secondly, before participants were allowed to answer any survey questions, they were asked to make a pledge on the survey that they are certified controllers. Thirdly, the data collected was checked using inter-rater reliability measures to ensure each individual's responses for both Part I and Part II of the survey were significantly different from random guessing.

### 5.2.2 Data Analysis

The data was collected through the tool surveygizmo.com provides in the format of a .csv file. The data was processed and analyzed using Microsoft Excel and IBM SPSS to find statistical findings. The results for Part I of the survey are discussed in the following section of this chapter and results for Part II of the survey are discussed in the next chapter.

## 5.3 Results

The survey questions were designed, as discussed in section 5.1, so that participants had to make a binary choice for each comparison question. If the participants are selecting the sector from the same test class rather than from the distractor class, this is taken as support for the classification scheme. One of the binary choices is Sector B, the "correct answer" according to the holistic classification method. The frequency count of participants choosing Sector B for each testing factor was obtained in order to measure how much participants agreed with the classes presented. There are 9 comparison questions for each testing factor, so the frequency count across all 9 questions was obtained in order to calculate the percentage of responses agreed with the class. For example, there were 504 observations for the methodological check; of those 504 observations, in 415 the participants selected Sector B, yielding a correct response rate of 82%. The observed correct response rate for each testing factor is shown in Table 5-6. The likelihood of these observed response rates occurring by random chance were tested using non-parametric statistical tests (described below).

**Table 5-6. The Response Rate Results for Survey**

| **Testing factor** | | **Percentage of responses consistent with classification scheme** |
|---|---|---|
| Methodological Check | Methodological check, hypothesized large class difference (Single flow vs Star Crosses) | 82% |
| Testing factor #2 | Flow concentration | 84% |
| Testing factor #3 | Background traffic | 80% |
| Testing factor #4 | Different types of flow #1 (Cross vs Merge/Split) | 73% |
| Testing factor #5 | Different types of flow #2 (Star vs Cross) | 93% |
| Testing factor #6 | Different types of flow #3 (Merge vs Fan) | 50% |

### 5.3.1 Statistical Significance Validation

A Binomial Exact Test was conducted using SPSS to measure statistical significance of the survey results. The null hypothesis of a Binomial Exact Test, 50%, refers to the perfectly random result meaning either the option A or B is not significantly different from one another. The null hypothesis in this survey would mean that the testing class is not significantly different to the class it is being compared to, the distractor class. In other words, it means there is no significant difference between the two classes being compared. Binomial Exact Test was conducted on each of the six testing factors to determine if the observed frequency of response for each factor is statistically different from the expected frequency from the null hypothesis (50%). A significant result indicates that the null hypothesis should be rejected, indicating that controllers chose sectors from the "similar" class at a rate better than expected from pure random chance.

The results indicate that there is a statistically significant difference for the methodological check (testing factor #1), as shown in Table 5-7. The methodological test, testing factor #1, was conducted as validation of technique and it is not surprising to see 82% of the time participants agreed.

Statistical significance was obtained for testing factors #2, #3, and #4 ($p < .01$) as well, as shown in Table 5-7. This means the proportion of participants agreeing with the classes for each of the testing factors #2, #3, and #4 are significantly larger than the null hypothesis value, 50%. For these testing factors, the hypothesis that the population mean is 0.5 was rejected at the .05 alpha level.

One factor, testing factor #6, was observed to be not statistically significant ($p = 0.894$). This means participants did not agree that the knowledge skills and abilities associated with a Merge flow class and the knowledge skills and abilities associated with a Fanning flow class were different. Therefore the null hypothesis is retained, and it is concluded that these two classes are not significantly different from one another.

**Table 5-7. Statistical Significance Test Results**

| **Testing factor** | Statistical Significance | Confidence Interval |
|---|---|---|
| Methodological Check | $\underline{p} < .01$ | .789 ~ .855 |
| Testing Factor #2 | $\underline{p} < .01$ | .810 ~ .873 |
| Testing Factor #3 | $\underline{p} < .01$ | .763 ~ .833 |
| Testing Factor #4 | $\underline{p} < .01$ | .688 ~ .766 |
| Testing Factor #5 | $\underline{p} < .01$ | .911 ~ .954 |
| Testing Factor #6 | $\underline{p} = 0.894$ | .450 ~ .540 |

The response rates are illustrated in a graph with their confidence level in Figure 5-7. As observed in this graph, while the confidence level for testing factor #5 is high, the confidence levels for other testing factors seem low. In order to look into this further, the examination of the response rate to individual questions is shown in Figure 5-8.

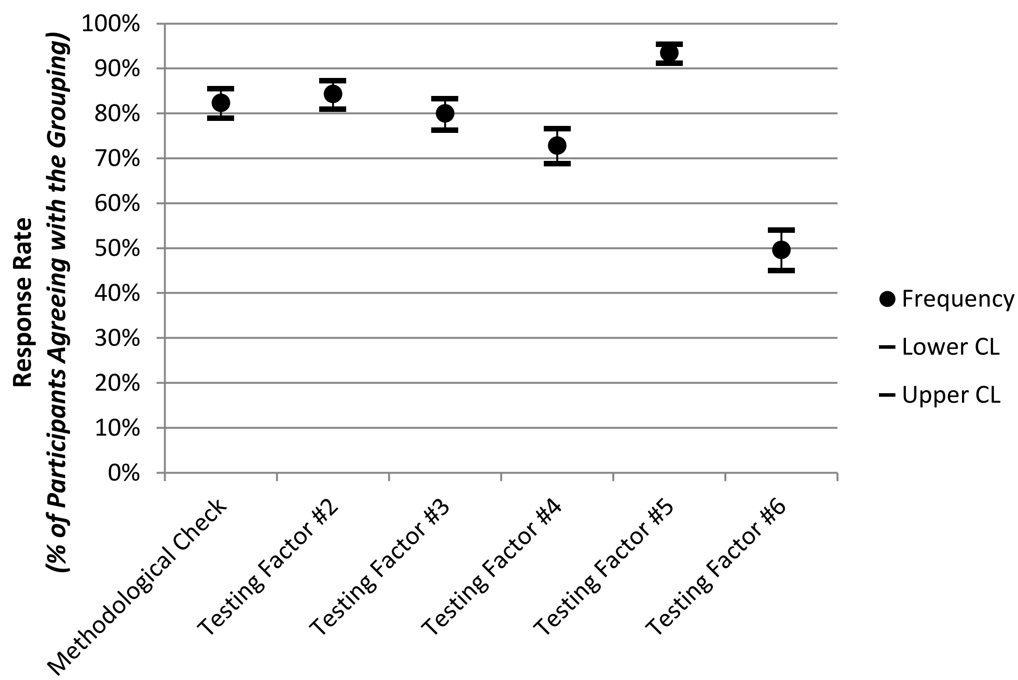



**Figure 5-7. Response Rate with their Confidence Intervals**

In Figure 5-8, large circles indicate the average response rate reported in Table 5-6. As shown in Table 5-7, blue large circles indicate the significant response rates whereas the red large circle indicates the non-significant response rate. The black small dots indicate the distribution of each of the 9 comparison question results for each testing factor. As discussed in the survey design section (Section 5.1 above), 9 different comparison questions were designed for each testing factor. To determine each testing factor's significance, the response from all 9 comparison were combined to obtain the overall response rate for each factor. The variation of the individual black dots in the graph explains the variations caused by unique combinations of radar maps used for each question.

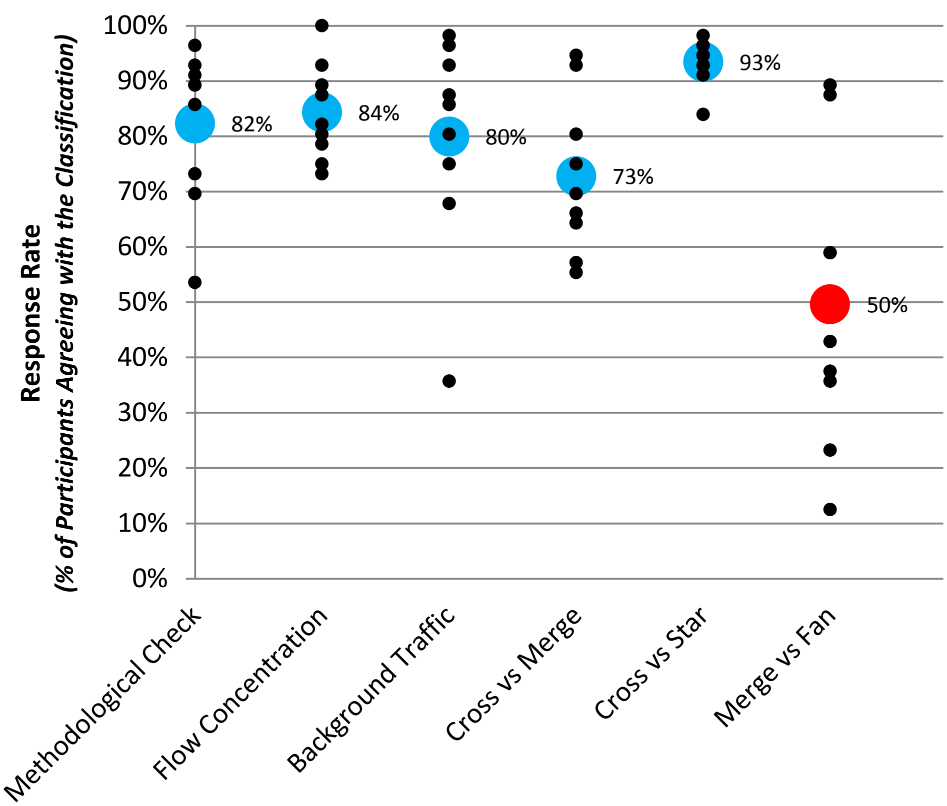



**Figure 5-8. The Response Rate Results for Survey**

The examination of the response rate to individual questions as shown in Figure 5-8 revealed further insights through follow-up analysis on individual comparison questions.

### 5.3.2 "Outlier" Individual Comparison Questions

As observed in Figure 5-8, several individual comparison questions yielded exceptional response rates, some with exceptionally high response rates of agreement and some noticeably lower response rates of agreement. Some of these individual results were selected for further analysis to gain insights into what additional conditions may have affected controllers' decisions. These selected cases are listed in Table 5-8 and analyzed further below.

**Table 5-8. Follow-up Observations**

| **Factors** | **Interesting Case Test Numbers (See Appendix)** | **Sector A** | **Sector B** | **Sector C** |
|---|---|---|---|---|
| Methodological Check | #121 = 54% | ZAU52 | ZAU24 | ZID91 |
| Testing Factor #2 (Flow Concentration) | #212 = 100% | ZDC52 | ZID89 | ZTL06 |
| Testing Factor #3 (Background Traffic) | #311 = 36% | ZFW98 | ZOB64 | ZAB70 |
| Testing Factor #6 (Merge vs. Fan) | #612 = 13% | ZBW33 | ZHU65 | ZNY49 |

For the individual case #121, 54% of the participants selected the sector from the same test class and rejected the distractor sector. The traffic patterns of the sectors involved with this case are shown in Figure 5-9. From examining the figure, it is hypothesized that while the faint background traffic with star crossing pattern is being recognized by participants, the dominant flow in sector A is being equated with the one in sector B. Further analysis is recommended in the future in order to look into this case further.

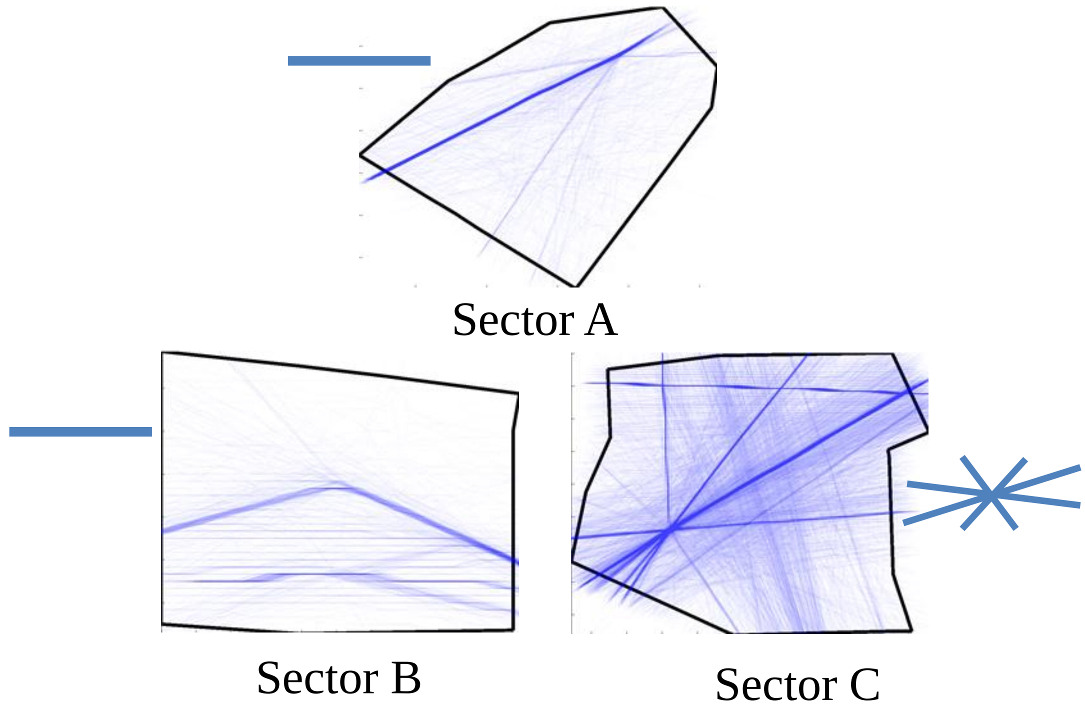



**Figure 5-9. Sectors for Individual Case #121**

For the individual case #311, another case with non-statistically significant results, some predictions can be made why participants chose Sector C to be more similar to Sector A by examining the traffic patterns of these three sectors in Figure 5-10. As part of the classification exercise performed according to the holistic classification scheme, Sector A in Figure 5-10 was not categorized to be in the class with heavy background. This is because relative to other sectors that were categorized to be in the class with heavy background, this sector's traffic background (Sector A in Figure 5-10) was determined not to be as heavy. However, it is predicted that participants considered Sector A and Sector C in this case to be more similar due to their level of background similarity (i.e. Sector A and Sector C's traffic background level is more similar than Sector A and Sector B's traffic background level). Another prediction is that participants thought Sector B is not similar to Sector A because Sector B consists of vertical handoffs.

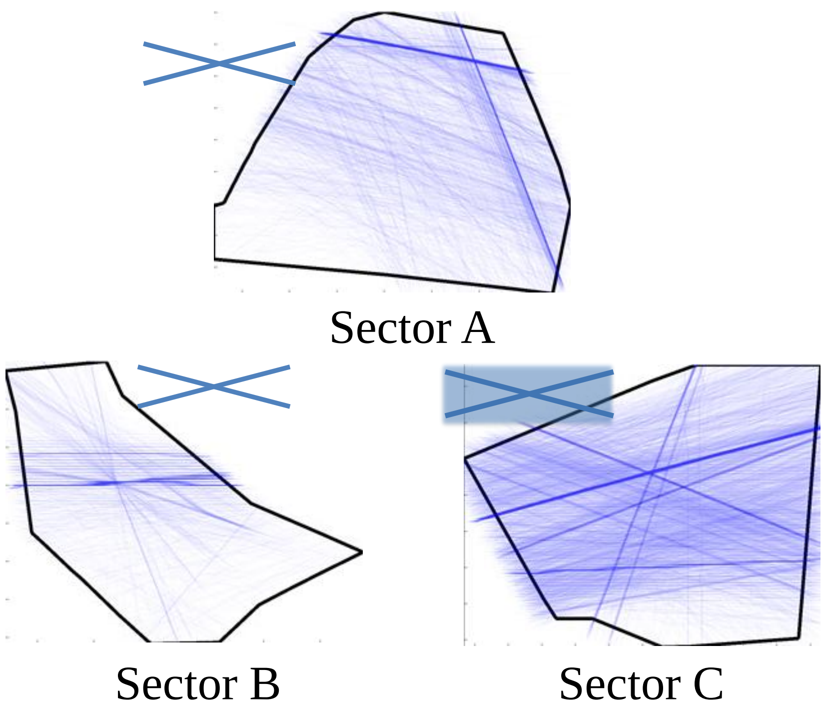



**Figure 5-10. Sectors for Individual Case #311**

Another interesting individual case is the test (Case #212) case with 100% of the participants agreeing with the class. The sectors of this question are shown in Figure 5-11. One interesting observation from this question is that the two sectors from the same class (Sector A and B) not only share very similar flow concentration but also that they both have crossing with very similar angles (i.e., they both have very "narrow" type of crosses). Moreover, they both share very similar location of crosses. This suggests that the reason the controllers agreed with this class is perhaps not only due to the concentration flow similarity.

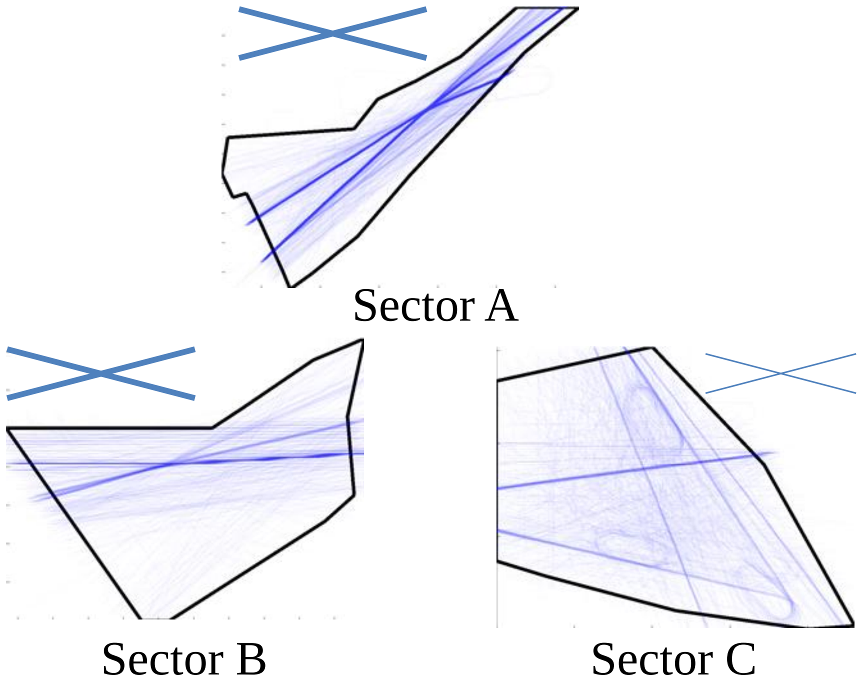



**Figure 5-11. Sectors for Individual Case #212**

Another interesting case is the individual case #612 as shown in Figure 5-12. For this case, only 13% of the participants indicated that Sector B is similar to Sector A, which means 87% of the participants indicated that Sector C is similar to Sector A. In order to determine if this result is significant disagreement, a post-hoc analysis was conducted for this specific case. The same Binomial Exact Test was run for this follow up analysis, except with different degrees of freedom (now N = 56) and a Bonferroni correction applied, resulting in significance level set at $p < 0.01$. The results showed that there was a significant disagreement for this individual case, #612 ($p < .01$, with confidence interval from .056 to .228). The significant disagreement means that the subject-matter-experts chose the distractor class to be the sector that belongs in the same class as the Sector A (the testing class).

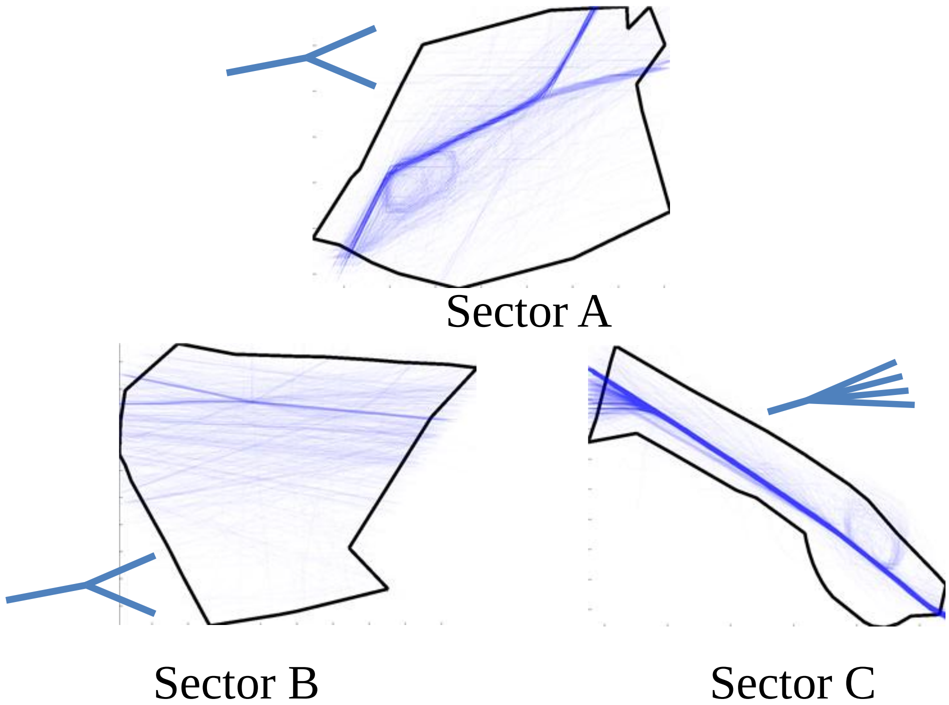



**Figure 5-12.Sectors for Individual Case #612**

When examining the traffic pattern of the sectors for this case (Figure 5-12), it can be observed that Sector A and Sector C share very similar flow concentration. It is evident that participants did not choose Sector B to be similar to Sector A due to the similarity of their merge flow pattern. Another similarity observed between Sector B and Sector C is the existence of race-track maneuvering pattern.

### 5.4 Discussion

Overall, the quantifiable results from the survey, as illustrated in Table 5-6 and Figure 5-8, showed significant support for the structure-based classifying conditions used in the holistic classification method. Controllers agreed that knowledge, skills, and abilities are more easily transferable between structurally similar sectors, or sectors with similar traffic patterns, than the ones with not structurally similar sectors. By testing specific components of the holistic classification method individually, the five testing factors, it was possible to determine how structurally similar sectors need to be in order to support minimal differences training. The validated structural components as per the survey results are the concentration of flows, the level of densely distributed traffic in the background, and some different types of flows. The only factor that was not agreed to be effective for using to develop the classification was the sub-class difference, the Merge flow class versus the Fanning flow class (as highlighted in Figure 5-13).

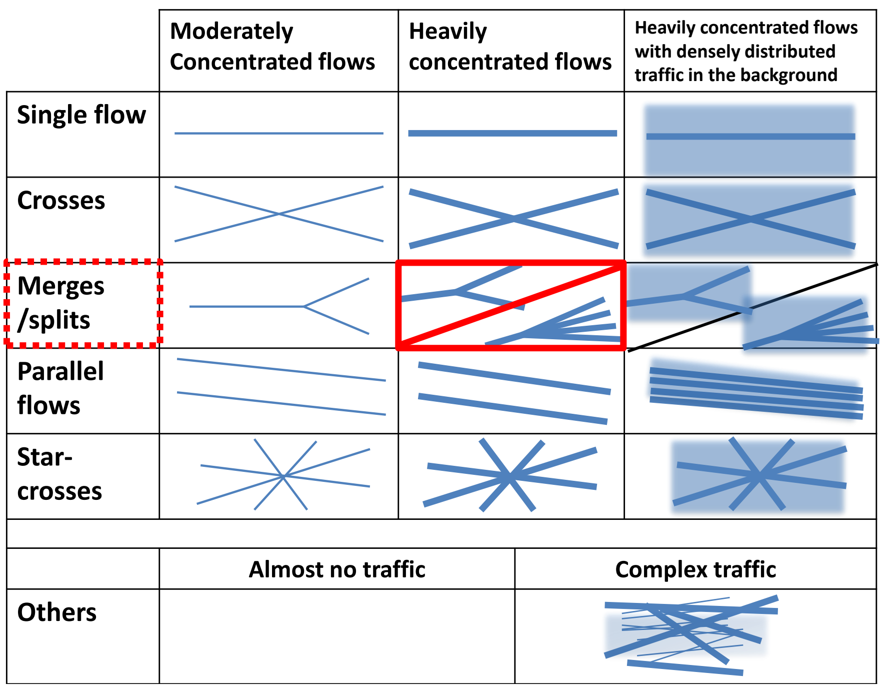



**Figure 5-13. Non-significant Testing Factor #6 – Merge/Split flow class vs. Fanning flow class**

From the result, it can be concluded that controllers did not see significant difference between knowledge, skills, and abilities associated with these two classes. As such, the holistic classification method is adjusted accordingly and the new holistic classification method is shown in Figure 5-14. In the modified classification method, the sub-classes, "fanning flows" are removed as this testing factor was found not to be significant from the survey.

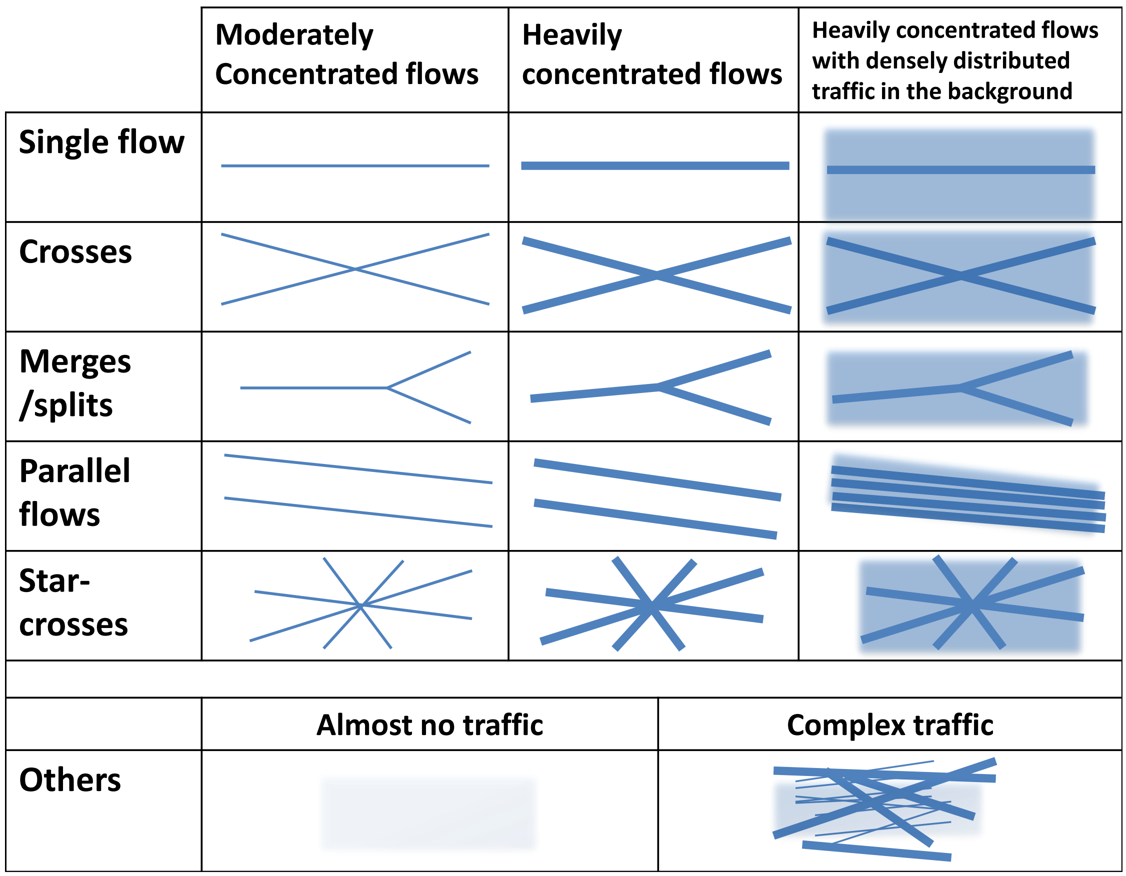



**Figure 5-14. The modified holistic classification method**

### 5.4.1 Decision Making Factors Identified through Comments

While the results from the quantifiable data of the survey for Part I indicates that most of the classifying conditions such as the different concentration of flows and different types of flows used in the holistic classification method is effective, this does not limit the classification method to be bounded by these conditions only. The qualitative data from this survey from the comments provides an insight to the next step of developing more effective classification scheme that support minimal differences training approach.

Throughout the survey, participants occasionally left comments for some questions explaining their choices. These comments were helpful providing useful insights into more detailed controller's perception of similar airspaces are in terms of knowledge, skills, and abilities transfer. Although not all participants left comments explaining their choice for all questions, a variety of comments for each question provided insight to why participants were making the selections they did. By examining these comments, some specific decision making factors were identified by the controllers. The most frequently cited factors are overall complexity/difficulty of a sector, the location of critical points, the holding patterns, area/size of a sector. These factors are discussed further in section below.

***Overall complexity/difficulty of a sector***

Many participants indicated that they chose a “similar” sector based on the overall difficulty, or the overall complexity, of the sectors. 25% of the comments addressed their decision being affected by sectors’ overall complexity / difficulty. One participant commented, “the sector I haven't chosen is much more difficult”, indicates that the participant did not think the other sector shared interchangeable knowledge, skills, and abilities because the sector is simply much more “difficult” sector than the other sector. The common characteristics of sectors controllers tend to describe as “very difficult sector” consisted of many crosses or a sector with a very narrow shape that significantly limits its maneuvering space as the example shown in Figure 5-15.

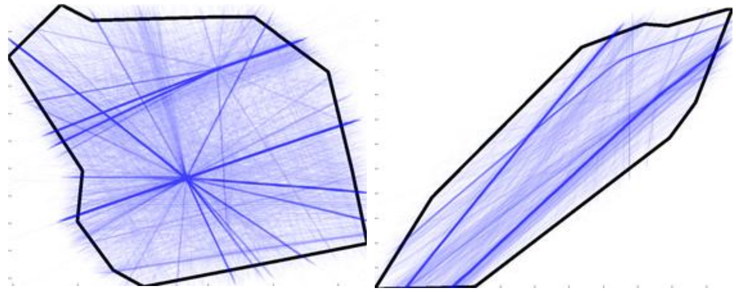


**Figure 5-15. Examples of very “difficult” sectors**

Multiple participants indicated that sectors with multiple crosses require "full attention" watching all aircrafts throughout the sector, and exceptional scanning techniques that cannot easily be developed. For this reason sectors with multiple critical points may be the most difficult to learn and require significant amount of experience specific to that sector. An example comment from a participant avoiding to choose the sector requiring very good scanning techniques is “Sector A requires most of the attention to one location. This is also true with the sector I chose. The sector I did not choose would require very good scanning techniques”.

Creating a class based on the same location of critical points may be infeasible as the locations of multiple critical points cannot be exactly the same in two sectors. However, the numbers of critical points, the number of flows associated with a critical point, the angle of crosses, or the closeness of critical points to the sector’s boundary are factors that can be considered in order to develop more detailed classification scheme.

In general, narrow sectors and sectors with multiple critical points were identified as most "complex/difficult" traffic to work with and the most difficult to learn. Considering the *complexity* of a sector as the most important factor as identified in the survey, the sectors with either condition may need to be grouped separately due to their more challenging requirement on specific skills and techniques that take longer time to develop. Grouping these "difficult" or "complex" sectors together also may mean that transferring within this class may be easier than transferring to this class from another class.

***The Location of Critical Points***

10% of all comments explained that these controllers based their decision based on the location of critical points in the sectors. Some controllers refused to choose sectors with critical points near the boundary of the sector regardless of its similar traffic pattern to the Sector A. An example pair of sectors (similar traffic pattern but with the location of critical point being different) is shown in Figure 5-16.

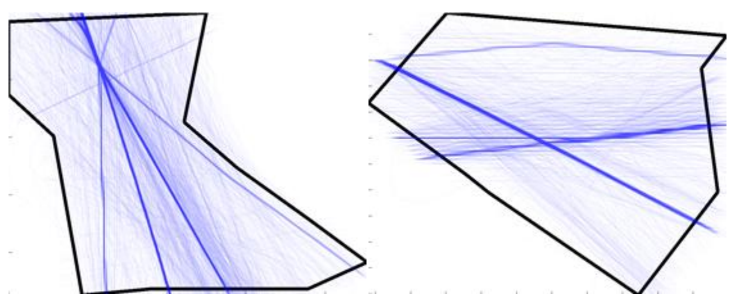


**Figure 5-16. An example of two different locations of critical points**

A controller commented "*Sector A has crossing traffic well within its sector. The sector I did not choose has crossing traffic near the sector boundary requiring the trainee to learn to separate traffic before it enters his sector*". Other comments indicating the significance of the locations of critical points is "*did not choose because of the merge near boundary*" and "*The sector I chose is very similar to Sector A. There are two confliction points but they are almost in the same location as Sector A.*".

From these comments, it can be observed that the amount of time given to resolve any confliction in a sector can be a significant factor dictating the difficulty of the sector. Perhaps having the experience of controlling confliction points near the boundary of a sector will allow the controller to adapt to another sector with confliction points near the boundary. It can be observed that having the confliction points well within the sector is easier to learn and control than sectors with confliction points near the boundaries.

Future work should explicitly include the directionality of the flows in order to help classify the sectors more accurately according to the location of critical points. For an example, knowing the directionality of flows will identify whether the confliction point is at the entering position or leaving position, which can change the level of difficulty of the left sector in Figure 5-16 dramatically.

***Holding Pattern***

12% of the comments indicated that controllers often based their decision on choosing similar sectors depending on the existence of a holding pattern in a sector. For all questions that involved a sector with a holding pattern, controllers commented on the holding pattern. An example sector with a holding pattern is shown in Figure 5-17.

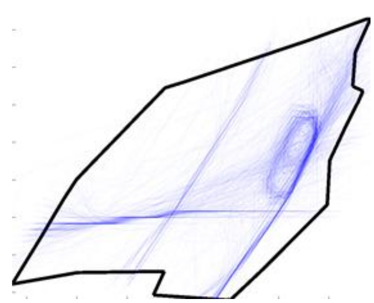


**Figure 5-17. An example sector with a holding pattern**

Controllers indicated that a sector with a holding pattern is more difficult, requiring longer time to learn the sector. Example comments include "*The sector I did not choose has a holding pattern near the boundary which requires lots of attention*" and "*holding patterns and every day usage of holding is extremely complex*".

Controllers also were able to figure out that a sector is an inbound sector when the sector had a holding pattern. Some controllers commented "*The sector on the left appears to be an inbound sector as evidenced by the presence of a holding pattern*" and "*Sector A is an inbound sector, shown by the holding pattern*".

These comments are insightful for refining the classification scheme further. Even though the current holistic classification scheme does not include holding patterns, the comments from this survey indicated that the experience of dealing with a holding pattern can be a very transferrable skill to another sector with a holding pattern. It was identified that techniques such as holding patterns or knowing how to put all aircrafts in trail to fly the specific narrow airway (to accommodate for a narrow airspace) might be easily transferable techniques transferable when moving to another sector with similar conditions (e.g., narrow space with limited amount of "room/airspace"). Moreover, developing classes based on a traffic pattern such as a holding pattern will also group inbound sectors together due to this specific traffic pattern's characteristic. This specific class would allow skills and techniques associated with not only holding patterns but also with an inbound sector easily transferable.

***Sector Area Size***

Many controllers (15% of the 230 comments) based their decision on choosing a similar sector based on the similarity of the shape and/or area of sectors. Controllers particularly commented often that a long and thin sector permits only a limited amount of space for maneuvering any aircrafts in the sector, making this sector exceptionally difficult sector to control requiring special techniques to learn. An example of such sector is shown on the left side in Figure 5-18. A controller commented *"Sector A is very long and thin. This makes it more of a ""spacing"" sector than anything else. The width of the sector would make it very difficult to use radar vectors for separation*.".

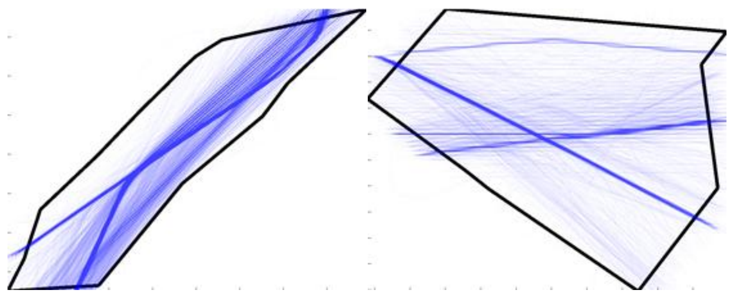


**Figure 5-18. An example of two sectors with very different area and shape**

On the contrary, controllers commented that a sector with "extra room" is an easier sector to learn. An example comment indicating that the sector with an "extra room" is easier is "*Sector A is skinny with crossing traffic, which would make training on a bigger sector with crossing traffic easy*" indicates that moving from the smaller and narrower sector to the larger sector would be much easier than the other way.

## 5.5 Chapter Summary

In summary, the overall result of the survey indicates that the structure-based classification technique is an effective way to determine classes that support minimal differences training determined through the survey.

The objective stated earlier in the chapter was successfully achieved. The objective is re-stated below:

Chapter Objective: *Test the effectiveness of structure-based classification techniques against perceptions of broader group of controllers.*

The first part of the survey addressed the objective stated above by evaluating the effectiveness of the current holistic classification scheme. The survey tested six structure-based factors that were used as a basis for the holistic classification scheme. Overall, the statistical result from the survey confirms that the holistic, structure-based classification, identified similar classes of sectors. Five of the six components factors tested were agreed to be an effective basis. Based on the factor that was found not to be significant, the holistic classification scheme was adjusted accordingly. The survey results show that when sectors share similar concentration of flows, share similar level of background traffic, or share similar types of flows (crosses, star-crosses, merges/splits, and single flows), controllers feel that the ability to interchange knowledge, skills, and abilities between sectors increases.

In addition, the follow-up analyses on the results of individual questions as well as the comments left by the participants provided further insights into other factors relevant to determining similar sectors. Some factors such as the location of critical points may be infeasible to be incorporated into the classification scheme as the locations of multiple critical points cannot be exactly the same in two sectors. However, it was identified through the study that the number of critical points, the number of flows associated with a critical point, the angle of crosses, or the closeness of critical points to the sector's boundary are the important factors that can be considered for inclusion in future classification schemes. These factors are not yet directly incorporated in the holistic classification method but should be researched further to be incorporated into the current classification scheme to identify similar classes that support minimal differences training. However, care must be taken that combining or adding additional factors can dilute the interpretability of the resulting classification scheme. There are also a finite number of sectors, and developing schemes that incorporate an excessive number of factors will limit the size (and therefore the value and the practicality) of a class of generic sectors.

# Chapter 6

# Validating the Identified Factors Affecting Sector Transitions

The literature review in Chapter 2 of this thesis identified that there appears to be little to no previous work identifying the most important factors affecting a controller's ability to transition between different sectors. As such, a list of factors that contribute to the similarities of sectors affecting the amount of training in transitions was identified in Chapter 3 in order to support identifying classes of sectors expected to have fewer transition barriers.

In this chapter through an online survey, the factors identified to be important in determining airspace similarities are assessed again through a broader group of controllers to verify the factors' significance as well as to measure their relative importance. Therefore, the objective of this chapter is as stated below.

Chapter Objective: *Verify and assess the relative importance of the key factors relevant to controller sector transitions as cited in controller interviews reported in Chapter 3.*

Results show that there are significant groups of factors, some groups being deemed more important than others.

## 6.1 Survey Design

The second part of the survey was designed to determine the relative importance of the factors affecting the similarity of airspace sectors, as determined from the semi-structured interviews reported in Chapter 3 through 6-point Likert scale rating questions. Each factor represents a characteristic or property of a sector. Participants were asked to assess how important it was for sectors to share the factor in order for controllers to be able to learn the new sector with less effort than traditionally required. A key goal was to assess the perceived importance of the factors across a larger number of subject matter experts. Based on each factor's importance and its applicable relevance to minimal difference training approach, the results will be used to direct future efforts on enhancements to sector classification schemes.

***The Factors Examined in the Survey***

This survey was designed to validate the significance of the factors hypothesized to be important in determining similarity of airspaces when it comes to transition training. Two new factors, *Traffic Volume* and *Altitude*, were added to the list in the survey as these two factors were repeatedly indicated as important ATC complexity factors in the previous research.

The importance of eight of the ten factors identified in Chapter 3 was determined in this survey. Two of the factors, *Hotspots* and S*pecial Areas* were inadvertently not included in the survey due to technical challenges experienced while setting up the survey. As such, the 10 factors validated for their relative importance in this survey are listed in alphabetical order in Table 6-1; descriptions of these factors can be found in Section 3.2.1.

**Table 6-1. List of 10 factors validated for their relative importance in survey – Part II**

| | **Factors** |
|---|---|
| 1 | Aircraft Types |
| 2 | Altitude |
| 3 | Coastal Area |
| 4 | Traffic Complexity |
| 5 | Knowing the Neighbor Sectors |
| 6 | Sector Area Shape and Size |
| 7 | Traffic Pattern |
| 8 | Types of Flows |
| 9 | Traffic Volume |
| 10 | Weather Condition |

***Question Design***

The survey questions are designed to probe participants' perception on the importance of each factor when learning a new sector. The ten questions are constructed as below in Table 6-2. Each question was asked with a beginning sentence "*When you make a transition to another sector and are about to operate it for the first time...*".

**Table 6-2. List of Questions Asked for Survey – Part II**

| Factor | Question as Presented in the Survey |
|---|---|
| Aircraft Types | *... it helps to have the experience of controlling similar aircraft types in the past.* |
| Altitude | *... it helps to have controlled similar altitude range of the new sector in the past.* |
| Coastal Area | *... it helps to be transferred to within the same coastal area (e.g., from a sector in the West coast to another sector in the West coast)* |
| Traffic Complexity | *... it helps to have the experience of dealing with a similar level of traffic complexity of the new sector.* |
| Knowing the Neighbor Sectors | *... it helps to have the experience of controlling in the past, or having the extensive knowledge of the new sector's neighbor sectors?* |
| Sector Area Shape and Size | *... it helps that sector shape and area size (allowed maneuvering space) are similar to the one you've controlled before.* |
| Traffic Pattern | *... it helps to have the experience of controlling a similar traffic flow pattern in the past. (e.g. crossing traffic vs. merging traffic)* |
| Types of Flows | *... it helps to have controlled the same types of flows (arrival, departure, and/or over-flight) in the past. (e.g. if the new sector's primary flows consists of arrival flows, having the experience of controlling arrival flows in the past)* |
| Traffic Volume | *... it helps to have the experience of operating a sector with a similar traffic volume in the past.* |
| Weather Condition | *... it helps that the new sector's weather condition are similar to the one you've controlled in the past.* |

Participants responded using a 6-point Likert scale, ranging from "*strongly disagree*" to "*strongly agree*" (Table 6-3). A six point scale excluding the neutral category was used in order to encourage the indifferent respondents to make a choice. Participants who do not wish to answer the question had a choice to leave any questions unanswered.

**Table 6-3. The Likert Scale Used for Participants to Rate Questions in Survey – Part II**

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Strongly disagree | Mostly disagree | Somewhat disagree | Somewhat agree | Mostly agree | Strongly agree |

## 6.2 Survey Procedure

The survey in Chapter 5 and Chapter 6 were conducted together, although each part was presented and analyzed separately. As such, the survey procedure details are applicable for both surveys and were explained in section 5.2 of this thesis.

## 6.3 Results

In order to verify and measure the relative importance of the ten factors, participants expressed their opinion on how important each factor is through the Likert scale rating system. In order to determine if there were statistically significant differences in the relative ranking of the factors, the Friedman Rank Test (Friedman et. al., 2007), a non-parametric statistical test, was used. This statistical method is further explained in the next sub-section.

While the values obtained in Table 6-4 cannot be used to verify the ranking order of the factors, some observations still can be made from these values. It can be observed that the mean values for all factors were above 3.5 and mode values for all factors equal to 4 or higher, indicating that all factors had a mean and mode ranking value to be "(strongly) agree that the factor is important to be similar between two sectors to minimize transition barriers".

Another valuable observation is that the factors with higher average rankings such as *Traffic Complexity*, *Traffic Volume*, and *Traffic Pattern*, their distribution was much tighter than other factors (i.e., the smaller standard deviation values). This means more participants agreed that these factors are important and there were very little variations in their answers. In contrast, the factors with lower ranking values such as *Size* and *Coastal Area* had broader distribution (i.e., the bigger standard deviation values) meaning that there were higher variations in their answers and not all participants agreed that these factors are important or not important.

**Table 6-4. Basic Statistical Measures of the 10 Factors**

| Testing Factor | Mean | SD | MODE |
|---|---|---|---|
| Traffic Complexity | 5.46 | 0.60 | 6 |
| Traffic Volume | 5.25 | 0.69 | 5 |
| Knowing the Neighbor Sectors | 5.20 | 1.07 | 6 |
| Traffic Pattern | 5.18 | 0.72 | 5 |
| Types of Flows | 5.04 | 0.87 | 5 |
| Altitude | 4.86 | 0.86 | 5 |
| Aircraft Types | 4.50 | 0.93 | 5 |
| Weather Condition | 4.11 | 1.14 | 4 |
| Sector Area Shape and Size | 3.79 | 1.14 | 4 |
| Coastal Area | 3.79 | 1.41 | 4 |

### 6.3.1 Statistical Significance Validation

Participant Likert scale rankings for each of the ten factors were used to measure their relative importance using the Friedman Rank Test. The Friedman Rank Test is a non-parametric test used to test for differences between groups; it was used in place of parametric repeated measures test such as ANOVA to avoid assuming equal measurement difference between the 6 ranking choices identified in Table 6-3. SPSS was used to conduct the analysis. Each participant's response was used to calculate each factor's mean rank across participants. Figure 6-1 shows a detailed illustration of how mean rank across participants for each factor is calculated. These ranked lists then formed the basis for subsequent analysis.

The left table of Figure 6-1 shows the list of Likert scale rating from participants, on a scale of 1 to 6. The right table of Figure 6-1 illustrates the process of calculating Friedman mean ranks. First, for each participant, each factor is ranked relative to each other (in this case, there are 10 factors so each factor is ranked from 1 to 10) depending on participant's Likert scale response value. In the cases where more than one factor had the same response value (e.g. a tie), the mean rank is averaged amongst these factors. After these rankings are established for all participants, Friedman mean rank values are calculated by averaging relative ranking values across all participants for each factor.

| **Likert Scale Rating from Participants (1~6)** | | | |
|---|---|---|---|
| | Participant #1 | | Participant #56 |
| Traffic Complexity | 6 | | 5 |
| Traffic Volume | 4 | | 5 |
| Knowing the Neighbor Sectors | 6 | | 5 |
| Traffic Pattern | 5 | | 6 |
| Types of Flows | 6 | ... | 2 |
| Altitude | 6 | | 4 |
| Aircraft Types | 4 | | 3 |
| Weather Condition | 4 | | 2 |
| Sector Area Shape and Size | 3 | | 2 |
| Coastal Area | 1 | | 1 |

| **Relative Ranking (1~10)** | | | | Mean Rank across participants |
|---|---|---|---|---|
| | Participant #1 | | Participant #56 | |
| Traffic Complexity | 8.5 | | 8 | 7.64 |
| Traffic Volume | 4 | | 8 | 6.91 |
| Knowing the Neighbor Sectors | 8.5 | | 8 | 6.86 |
| Traffic Pattern | 6 | ... | 10 | 6.70 |
| Types of Flows | 8.5 | | 3 | 6.26 |
| Altitude | 8.5 | | 6 | 5.79 |
| Aircraft Types | 4 | | 5 | 4.55 |
| Weather Condition | 4 | | 3 | 3.76 |
| Sector Area Shape and Size | 1 | | 1 | 3.49 |
| Coastal Area | 2 | | 3 | 3.04 |

**Figure 6-1. The Process of Calculating Friedman Mean Ranks**

From the graph it is evident that some factors such as *Complexity*, *Traffic Volume*, *Knowing the Neighbor Sectors*, *Traffic Pattern*, *Types of Flows*, and *Altitude* are considered more important by the participants than other factors. Analysis showed that there was a statistically significant difference in the perceived importance of different factors, $\chi^2(9) = 181.014$, $\underline{p} = 0.000$. This significance indicates that some factors were considered more important than other factors and the result is statistically reliable and very unlikely the result due to random chance.

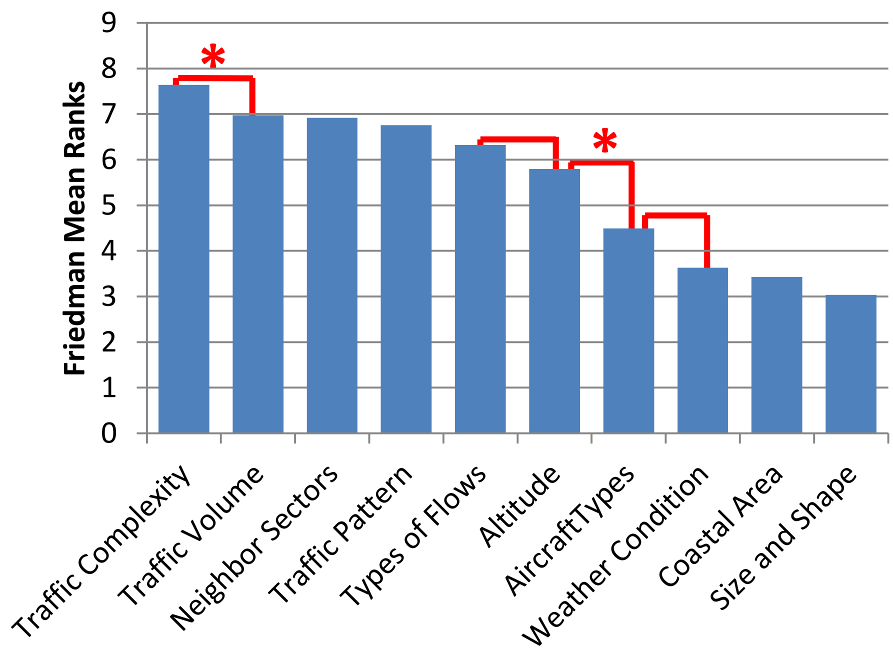



**Figure 6-2. Mean Ranks for 10 Key Factors**
**(square brackets representing comparisons used in follow up analysis, square bracket with an asterisk indicates significant difference)**

In order to examine which factors specifically are considered more important than others, some selected post-hoc analyses were performed. In order to avoid an excessive number of post-hoc analyses (i.e., run post-hoc analysis for every combination of the factors), Figure 6-2 was used to determine which pairs of factors would be reviewed for further analysis. As a result of reviewing which pairs of adjacent factors had the largest difference between them, the four pairs from the graph were selected for further comparisons, as indicated with square brackets in Figure 6-2. The selected four comparisons are *Traffic Complexity* and *Traffic Volume*, *Types of Flows* and *Altitude*, *Altitude* and *Aircraft Types*, and *Aircraft Types* and *Weather Condition*.

Four post-hoc analyses with Wilcoxon Signed-Rank Tests were conducted with a Bonefrroni correction applied, resulting in significance level set at $p < 0.013$. The results of the follow up analyses showed that there was a significant increase in perceived importance in *Complexity* compared against *Traffic Volume* (Z = -2.668, $p = .008$) as well as in *Altitude* compared against *Aircraft Types* (Z = -2.545, $p = -.011$). The significant pairs are indicated with an asterisk above its square bracket in Figure 6-2. However, there were no significant differences between factors *Types of Flows* and *Altitude* (Z = -1.099, $p = 0.272$) or *Aircraft Types* and *Weather Condition* (Z = -2.376, $p = 0.017$). As a result, three distinct groups of factors are identified with decreasing relative importance for controller transitions. The three groups are presented in different shades and patterns in Figure 6-3. The implications of these results are discussed in the Discussion section of this chapter in 6.4.

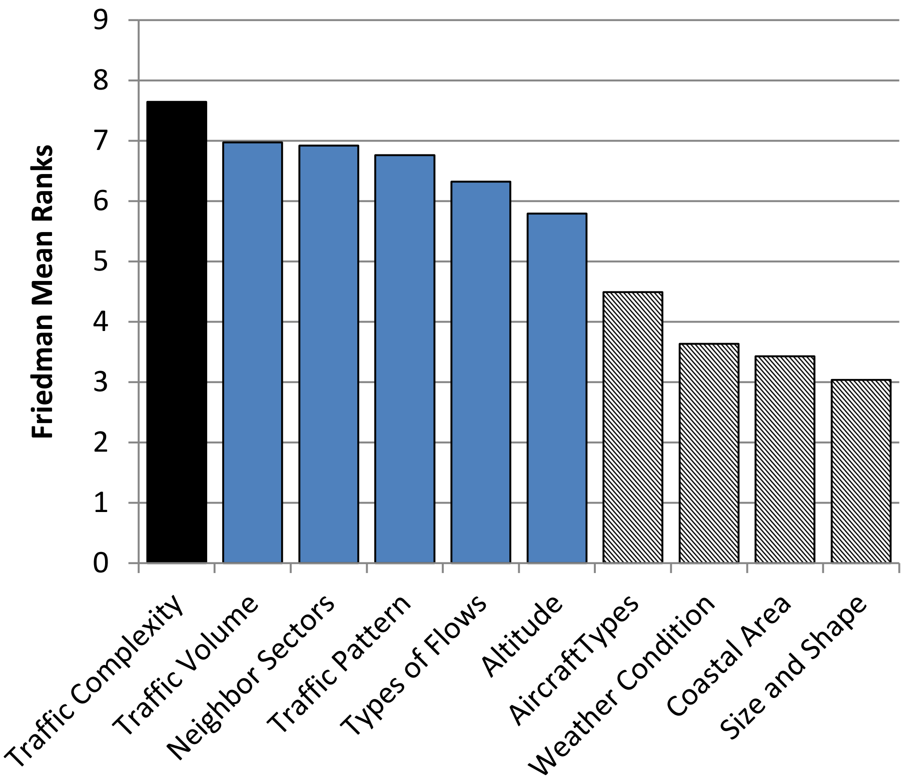



**Figure 6-3. Friedman Mean Ranks for 10 Key Factors**
**(shades indicate significantly distinct classes)**

The relative perceived importance data was also examined for differences between different groups of countries as well as in different groups of level of experience in ATC. The results showed that there was some difference in mean ranking between U.S. controllers versus Non-U.S. controllers (Figure 6-4a). However, there is hardly any difference in mean ranking between controllers with more experience versus less experience (Figure 6-4b).

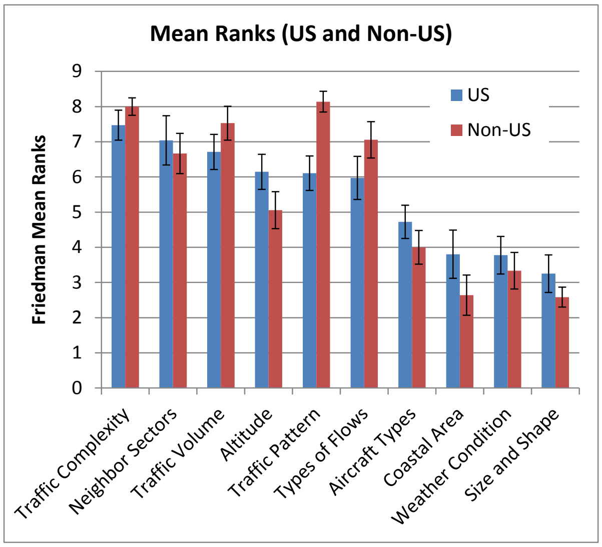



**Figure 6-4a. Mean Ranks comparison between US controllers vs. Non-US controllers,**

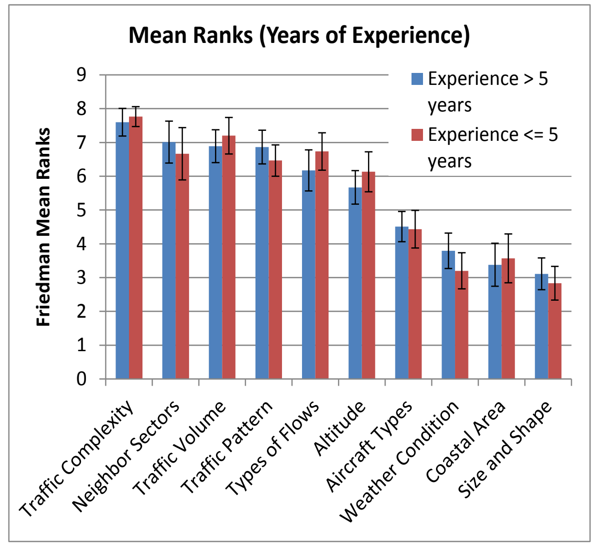



**Figure 6-4b. Mean Ranks comparison between controllers with over 5 years of experience vs. controllers with less than 5 years of experience)**

***error bars indicate 95% confidence intervals**

The difference in nationality seemed to produce some difference in their perspective of importance of factors. Overall, all controllers regardless of nationality agreed that *Aircraft Types*, *Coastal Area*, *Weather Condition*, and *Size of a Sector Area* is relatively less important than other factors tested in the survey. Interestingly, controllers from US indicated *Traffic Complexity* factors as relatively the most important factor whereas controllers from other countries indicated *Traffic Pattern* as relatively the most important factor. Often, the meaning of traffic complexity can encompass other factors. This was discussed previously in section 3.2.1.

However, the difference in years of experience does not differentiate in their perspective of importance of factors.

## 6.4 Discussion

Overall, the quantifiable results from Part II of the survey indicated that there were three significant groups of factors, as determined by controller perceptions of the relative importance of the factors. The first significant grouping has one factor, the traffic complexity. This perhaps means that in order for a controller to be able to easily transfer most knowledge, skills, and abilities to another sector when transitioning, it is essential that the level of complexity be the same between the old sector and the new sector. However, this is mostly directional, meaning that having the experience of dealing with a very complex sector, such as a sector with many critical points or a very narrow area, will most likely allow the controller to be able to easily learn a broader range of sectors. Conversely, a controller with only the experience of an "easy" sector, such as a large sector with minimal confliction points and low traffic level, will most likely be able to easily move to only a very limited range of sectors. These controllers will require significantly more time learning a new sector if the new sector is more “complex” than the one they have controlled in the past.

The second significant grouping consists of *Traffic Volume*, *Knowing the Neighbor Sectors*, *Traffic Pattern*, *Types of Flows*, as well as *Altitude* factors. *Traffic Pattern*, which was the factor most frequently cited in the controller interviews in Chapter 3, was identified to be still very important as identified in this survey, though not the most important.

The result of the ranking of these factors in this survey provides insight into the effectiveness of the current holistic classification scheme. The holistic classification scheme uses a structure-based classification technique which mainly relies on the traffic pattern of a sector. The important factors identified however are highly interrelated to one another. For example, the general complexity and volume of a sector can usually be determined by a sector’s traffic pattern. This indicates that the current classification scheme is approaching the "right direction" in developing an effective classification scheme to support minimal differences training.

However, the classification scheme can be refined further to consider other important factors identified through this survey, such as the *Knowing the Neighbor Sectors* and T*ypes of Flows. Knowing the Neighbor Sectors* factor is somewhat already practiced in current FAA's ATC operations, as a controller is usually free to move within the area of specialization which is composed of a few adjacent neighbor sectors. This can be investigated further to look for opportunities to group larger number of sectors together that a controller can easily move to within the neighbor area. Factors such as *Knowing the Neighbor Sectors* have an intuitive common sense appeal that belies the difficulty in developing a repeatable, consistent metric. There is also the challenge of determining which neighboring sectors (vertical, horizontal, sharing a lengthy boundary) are relevant, and how different neighboring sectors are combined. The *Types of Flows* factor can be addressed by examining traffic patterns that show directionality and classifying further depending on this additional information. An additional challenge requiring further research is assessing how each factor could be operationalized as part of a classification scheme.

Observing some difference in controllers' perceived importance of factors when compared between US and other countries indicates that controllers from different countries might develop slightly different perceived importance of factors. The results from controllers from other countries showing that traffic pattern is the most important factor indicates that a structure-based classification scheme can be promising in some other countries as well. However, overall, all countries regardless of their nationality agreed that *Aircraft Types*, *Coastal*

*Area*, *Weather Condition*, and *Size of a Sector Area* were factors relatively less important compared to other factors. This perhaps indicates that these factors should be considered secondary when developing an effective classification scheme supporting minimal differences training approach. Observing no difference in controllers' perceived importance of factors when compared by their years of experience indicates that the years of experience does not dictate controller's perceived importance of factors relevant to airspace similarities.

### *Other Important Factors Identified through Comments*

Participants were allowed to comment additional factors they think are important to be similar between moving-from and moving-to sectors by responding to the question "Are there any other factors that need to be similar to help learning a new sector easier/faster?" Eight of 56 participants indicated a few additional factors such as similar range of scope, similar equipment, same rules, and individual differences as factors that would affect the transferability of a controller. While the number of comments provided by the participants is of limited quantity, the detailed description on these extra factors they think are important provided insight into the factors that may be worthwhile considering in the future in order to enhance the current classification scheme.

The additional factors participants indicated to be important are factors such as similar range of scope (e.g. 50 mile range in low altitude sector vs. 200 mile range in high altitude sector), equipment similarity, angle of conflictions, number of confliction points, direction of traffic flow, quality of trainers, individual (controller's) differences, and magnetic direction of the flows. Several factors cited were judged to be already captured by existing factors. Specifically, participants cited angle of conflictions, number of confliction points, as well as direction of traffic flow are the factors that are judged to be encapsulated in the traffic pattern factor.

## 6.5 Chapter Summary

In summary, the overall result of the survey indicates that the structure-based classification technique is an effective way to determine classes that support minimal differences training determined through the survey.

The objective stated earlier in the chapter was successfully achieved. The objective statement is re-stated below.

Chapter Objective: *Assess the relative importance of range of key factors relevant in transitions cited in controller interviews.*

The second part of the survey addressed the objective #1 by verifying that the ten factors evaluated are important and three distinct groupings were identified depending on their relative importance. The factors' relative importance and transferability as identified through the survey results provide a useful insight into directing future efforts on enhancements to sector classification schemes.

# Chapter 7

# Conclusions

Air traffic control is a challenging profession involving complicated time-critical and life-critical tasks and operations. This results in significant time to train one individual to become a certified controller. The lengthy training extends even for fully certified controllers if they are relocated and must learn new pieces of airspaces. This causes significant staffing inflexibility and inefficient air traffic management. Motivated by the opportunity to combat this challenge, the thesis examined ways to support generic airspace concept by identifying classes of existing airspaces that a controller can move with easier mobility than the current ATC system.

## 7.1 Research Objectives and Key Findings

The general research question of the thesis stated at the beginning of the thesis in Chapter 1 was "*How can we identify groups of airspace sectors that will have fewer barriers to the transition of controllers between different sectors (in order to support minimal differences training approach)?*".

The resulting three objectives of the thesis to answer the general research question above are restated and discussed how they were achieved below.

Objective 1 – *Identify key factors that affect the transferability of a controller's existing knowledge skills and abilities to a new airspace sector.*

The first research objective was addressed by reviewing the literature (as detailed in Chapter 2) and conducting the semi-structured interviews with subject-matter-experts (as described in Chapter 3). The literature review in Chapter 2 of this thesis identified that there appears to be little to no previous work identifying the most important factors affecting a controller's ability to transition between different sectors. A key contribution of this work is identifying a list of factors that contribute to the similarities of sectors affecting the amount of training in transitions (Chapter 3). This list supports the development of methods classifying sectors expected to have fewer transition barriers. Through controller interviews, some techniques that are easily transferable were identified as well. Such techniques are flow control, sequencing technique, and speed control that are typically used in merging traffics.

Objective 2 – *Develop a method, based on a few of the most important factors identified from Objective 1, for determining classes of sectors expected to have fewer transition barriers.*

The second objective was addressed by developing the two classification methods presented in Chapter 4. From the literature review, as well as the interviews conducted for Objective 1, traffic patterns were identified as a valuable and appropriate initial basis for identifying classes of generic sectors. Consequently, commonly occurring traffic patterns were identified and two distinct classification methods were developed and explored, the holistic classification approach and the decompositional classification approach. The holistic classification approach produced 17 classes of the current 404 high-altitude NAS sectors and these classes were used later in Chapter 5 in order to measure the effectiveness of the structure-based classification method. Analyses done as part of the decompositional classification emphasized the importance of narrowing down the features that are most important for transitions in order to produce more effective classes.

Objective 3 – *Evaluate the developed classification method and validate the key factors identified in Objective 1 through subject-matter-experts.*

Finally, the third objective of thesis was addressed by conducting an online survey with 56 certified air traffic controllers. The effectiveness of structure-based classification techniques was measured against perceptions of subject-matter-experts in Chapter 5 and the relative importance of the key factors relevant to controller sector transitions were verified to be indeed important and their relative importance was also assessed in Chapter 6. The findings affirmed that structure-based classification is a valid step worth assessing for its effectiveness more in the future. Additional factors were identified that are not yet incorporated into the classification methods. Some of these factors, such as the location of critical points or hot spots, may be infeasible to be incorporated, as the locations of multiple critical points cannot be exactly the same in two sectors. Some factors, however, should be analyzed further in order to assess their feasibility to be incorporated into classification schemes. Notable such factors are the number of critical points, the number of flows associated with a critical point, the angle of crosses, and the closeness of critical points to the sector's boundary.

### 7.2 Summary

The major finding of this thesis is that through the development and validation process of the studies performed in this thesis, a structure-based classification scheme was found to be an effective way to classify sectors in order to support minimal differences training. The resulting classes of sectors are expected to have less transition barriers. This is because the traffic patterns in a sector reflect various operations that require certain cognitive abilities of controllers. The skills, abilities, and knowledge associated with these specific operation details, can be transferred more efficiently amongst sectors with similar traffic patterns.

This finding is promising implication that there is a lot of potential for existing airspaces to be categorized, without altering any physical properties of airspaces, so that air traffic management and controllers can easily recognize which airspaces current controllers can simply move to with less training.

However, this does not mean the classification scheme developed in this thesis captures the most effective way of classifying current airspace system. The following section discusses some recommendations and future work suggested to enhance the work done in this thesis.

### 7.3 Recommendations and Future Work

The identification of classes of sectors with similar structure provides a basis for assessing the potential of near-term deployment of generic airspace. Having identified classes of sectors, future work should further refine the classes, and use human-in-the-loop experiments to verify the relevance of the identified differences. Through these exercises of refining the classes and human-in-the-loop experiments, the classification scheme can be polished to the state it can be applicable to the ATC system and yield effective results.

It is recommended that further research be performed to assess how each factor could be operationalized as part of a classification scheme. However, care must be taken in determining which factors to be incorporated into the classification scheme, as there are a finite number of sectors and developing classification methods that integrate an excessive number of factors will limit the size (and therefore the value and the practicality) of a class of generic sectors.

Moreover, the results from this study also discovered that there exist factors beyond ATC operational factors, the cultural factors, which are important considerations in support of the minimal differences approach to generic airspace. Factors such as individual differences and motivational factors are a couple of representative cultural factors identified. Significant amount of research has been done in the "Organizational Behavior" research area in order to look into how cultural differences between different organizations affect employees' and companies' performance.

In the future, various factors beyond ATC operational factors can be researched further in order to develop more effective air traffic management system. Suggested factors to be researched are decision support tool usage, procedures, collaboration requirements, and other organizational and motivational factors that influence controllers' transition barriers. These factors can be investigated further to examine how they affect decision-making and learning processes when controllers transition between different facilities. Based on these findings, the current ATC training model can be extended in order to capture the impact of differences between facilities. These models then can be used to develop methods to minimize these differences in order to increase staffing flexibility.

Understanding how these organizational and operational differences and factors can be addressed will have practical contribution to different air traffic control organizations by providing ways to increase the efficiency of air traffic controller training and staffing. The challenge of moving workforce around is not only specific to ATC organizations. The results will also be of interest to other organizations that involve complex systems; knowledge of the success (or failure) of ways to bridge cultural differences will help other related application areas such as healthcare and military.

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# Appendix A

## Sector Grouping Results based on Holistic Classification

**Legend:**
Moderately Concentrated flows = Column #**(1)**
Heavily concentrated flows = Column #**(2)**
Heavily concentrated flows with densely distributed traffic in the background = Column #**(3)**

| Single Flow | | Cross Flow | | Merge Flow | | Fan Flow | |
|---|---|---|---|---|---|---|---|
| **(1)** | **(2)** | **(2)** | **(3)** | **(2)** | **(3)** | **(2)** | **(3)** |
| ZAB37 | ZAU36 | ZDC42 | ZAU95 | ZBW24 | ZLA26 | ZHU46 | ZLA38 |
| ZFW92 | ZAU24 | ZAU94 | ZAB50 | ZAU25 | ZAU23 | ZAB91 | ZAB78 |
| ZNY27 | ZAU35 | ZDC52 | ZAB70 | ZAU89 | ZBW48 | ZBW19 | ZAB89 |
| ZNY83 | ZAU45 | ZFW26 | ZAB72 | ZBW09 | ZDC12 | ZBW31 | ZBW46 |
| ZOB74 | ZAU52 | ZFW49 | ZAB87 | ZBW33 | ZDC19 | ZBW38 | ZDC39 |
| | ZFW28 | ZFW50 | ZAB96 | ZDC07 | ZDC58 | ZBW49 | ZDV24 |
| | ZFW71 | ZFW52 | ZAU33 | ZDC18 | ZDC59 | ZBW59 | ZDV35 |
| | ZJX87 | ZFW98 | ZAU71 | ZDV28 | ZDV04 | ZDC10 | ZFW47 |
| | ZMA19 | ZID76 | ZAU91 | ZFW89 | ZFW42 | ZDC72 | ZHU81 |
| | ZOB68 | ZID77 | ZBW10 | ZHU65 | ZLC34 | ZDV64 | ZJX34 |
| | | ZID83 | ZDC36 | ZID96 | | ZFW39 | ZLA36 |
| | | ZID89 | ZDC38 | ZJX47 | | ZFW97 | ZLA37 |
| | | ZID94 | ZDV05 | ZJX75 | | ZHU63 | ZMA65 |
| | | ZMA17 | ZDV23 | ZJX95 | | ZJX58 | ZOA13 |
| | | ZOB37 | ZDV46 | ZLA34 | | ZJX78 | ZOA32 |
| | | ZOB64 | ZFW43 | ZLA53 | | ZJX86 | ZOA36 |
| | | ZOB77 | ZFW51 | ZME63 | | ZLA40 | ZSE46 |
| | | ZTL34 | ZFW93 | ZMP22 | | ZMA01 | ZSE47 |
| | | ZTL50 | ZHU74 | ZNY34 | | ZMA64 | |
| | | | ZID99 | ZNY56 | | ZMA68 | |
| | | | ZJX11 | ZNY73 | | ZMP16 | |
| | | | ZJX51 | ZOB29 | | ZNY39 | |
| | | | ZJX65 | ZTL36 | | ZNY49 | |
| | | | ZKC06 | | | ZNY55 | |
| | | | ZKC07 | | | ZOA34 | |
| | | | ZKC20 | | | ZTL10 | |

| Parallel Flow | | | Star Cross Flow | Almost no traffic | Complex traffic | | | |
|---|---|---|---|---|---|---|---|---|
| **(1)** | **(2)** | **(3)** | **(3)** | | | | | |
| ZBW20 | ZDC04 | ZAB90 | ZME28 | ZAU34 | ZBW01 | ZHU59 | ZLC42 | ZSE13 |
| ZAU88 | ZAB79 | ZAB80 | ZAB58 | ZAU41 | ZAB65 | ZID88 | ZLC45 | ZSE14 |
| ZFW65 | ZDC37 | ZDV09 | ZAB93 | ZAU46 | ZAB67 | ZID93 | ZMA40 | ZSE15 |
| ZHU68 | ZFW24 | ZHU70 | ZAB98 | ZFW86 | ZAB68 | ZID97 | ZME19 | ZSE16 |
| ZID75 | ZFW61 | ZHU95 | ZAU61 | ZHU76 | ZAB92 | ZJX15 | ZME22 | ZSE42 |
| ZJX14 | ZFW82 | ZHU97 | ZAU84 | ZHU82 | ZAU90 | ZJX44 | ZME25 | ZSE48 |
| ZMP15 | ZFW90 | ZJX35 | ZDV18 | ZID14 | ZBW02 | ZJX48 | ZME27 | ZTL15 |
| ZOB07 | ZFW94 | ZOA30 | ZDV33 | ZID80 | ZBW39 | ZJX49 | ZME32 | ZTL20 |
| | ZHU23 | | ZDV37 | ZLA60 | ZBW53 | ZJX67 | ZME33 | ZTL28 |
| | ZHU26 | | ZDV38 | ZLA72 | ZDC09 | ZJX68 | ZME35 | ZTL33 |
| | ZHU78 | | ZDV61 | ZOA29 | ZDC11 | ZJX76 | ZME43 | ZTL42 |
| | ZID87 | | ZDV65 | ZOB51 | ZDC16 | ZKC03 | ZME45 | |
| | ZJX33 | | ZID70 | | ZDC20 | ZKC14 | ZMP11 | |
| | ZKC33 | | ZID78 | | ZDC32 | ZKC27 | ZMP12 | |
| | ZMA25 | | ZID81 | | ZDC50 | ZKC28 | ZMP13 | |
| | ZME26 | | ZID91 | | ZDC60 | ZKC29 | ZMP17 | |
| | ZME30 | | ZID95 | | ZDV03 | ZKC31 | ZMP18 | |
| | ZME31 | | ZID98 | | ZDV14 | ZKC47 | ZMP19 | |
| | ZME44 | | ZKC21 | | ZDV34 | ZKC90 | ZMP20 | |
| | ZNY07 | | ZKC41 | | ZDV67 | ZKC92 | ZMP30 | |
| | ZNY08 | | ZME20 | | ZFW25 | ZKC94 | ZMP38 | |
| | ZNY09 | | ZME34 | | ZFW46 | ZKC97 | ZMP40 | |
| | ZNY72 | | ZME61 | | ZFW48 | ZKC98 | ZMP42 | |
| | ZNY75 | | ZME62 | | ZHU24 | ZLA27 | ZMP43 | |
| | ZNY82 | | ZMP28 | | ZHU37 | ZLA30 | ZNY42 | |
| | ZOA46 | | ZMP29 | | ZHU42 | ZLA31 | ZOA14 | |
| | ZOB26 | | ZOB19 | | | ZLA32 | ZOA15 | |
| | ZOB36 | | ZOB39 | | | ZLA33 | ZOA31 | |
| | ZOB38 | | ZOB49 | | | ZLA35 | ZOA33 | |
| | ZOB47 | | ZTL02 | | | ZLA39 | ZOA43 | |
| | ZOB57 | | ZTL03 | | | ZLA99 | ZOB45 | |
| | ZOB59 | | ZTL08 | | | ZLC20 | ZOB67 | |
| | ZTL11 | | ZTL27 | | | ZLC29 | ZOB79 | |
| | ZTL23 | | ZTL39 | | | ZLC33 | ZSE07 | |
| | | | ZTL40 | | | ZLC41 | ZSE11 | |

# Appendix B

# Sector Grouping Results based on Decompositional Classification

Note: The decompositional classification method is applied only on 75 sectors

| Center | Sector | Major flows | Cross | Merge | Vertical Handoffs | Trajectory Changes | Holding |
|---|---|---|---|---|---|---|---|
| ZAB | 37 | 5 | 6 | 1 | 0 | 0 | 0 |
| ZAB | 39 | 3 | 1 | 0 | 0 | 0 | 0 |
| ZAB | 38 | 6 | 9 | 0 | 0 | 2 | 0 |
| ZAB | 41 | 5 | 5 | 1 | 0 | 1 | 0 |
| ZAB | 45 | 4 | 0 | 1 | 0 | 1 | 0 |
| ZAB | 36 | 3 | 2 | 2 | 0 | 1 | 0 |
| ZAB | 46 | 2 | 0 | 1 | 0 | 0 | 0 |
| ZAB | 48 | 3 | 0 | 1 | 0 | 1 | 0 |
| ZAB | 51 | 2 | 1 | 0 | 0 | 0 | 0 |
| ZAB | 52 | 5 | 3 | 1 | 0 | 0 | 0 |
| ZAB | 53 | 3 | 0 | 1 | 0 | 2 | 0 |
| ZAB | 55 | 4 | 3 | 2 | 0 | 0 | 0 |
| ZAB | 57 | 3 | 1 | 1 | 0 | 1 | 0 |
| ZAB | 42 | 4 | 0 | 2 | 0 | 1 | 0 |
| ZAB | 43 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAB | 44 | 3 | 1 | 0 | 0 | 0 | 0 |
| ZAB | 14 | 2 | 1 | 1 | 0 | 1 | 0 |
| ZAB | 20 | 4 | 2 | 1 | 2 | 1 | 0 |
| ZAB | 22 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZAN | 2 | 9 | 0 | 3 | 6 | 1 | 0 |
| ZAN | 4 | 5 | 0 | 0 | 5 | 1 | 0 |
| ZAN | 6 | 6 | 1 | 1 | 5 | 1 | 0 |
| ZAN | 8 | 6 | 2 | 0 | 4 | 0 | 0 |
| ZAN | 10 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 53 | 5 | 5 | 1 | 0 | 1 | 0 |
| ZAU | 54 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 56 | 3 | 2 | 0 | 0 | 0 | 0 |
| ZAU | 57 | 2 | 1 | 0 | 0 | 0 | 0 |
| ZAU | 59 | 2 | 1 | 0 | 0 | 0 | 0 |
| ZAU | 60 | 2 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 61 | 2 | 1 | 1 | 0 | 0 | 0 |
| ZAU | 62 | 2 | 1 | 0 | 0 | 0 | 0 |
| ZAU | 3 | 2 | 0 | 1 | 0 | 0 | 0 |
| ZAU | 4 | 4 | 1 | 1 | 0 | 0 | 0 |
| ZAU | 11 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 12 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 24 | 1 | 0 | 0 | 0 | 1 | 0 |
| ZAU | 26 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 36 | 7 | 1 | 2 | 0 | 1 | 0 |
| ZAU | 45 | 1 | 0 | 0 | 0 | 0 | 0 |
| ZAU | 46 | 4 | 1 | 1 | 0 | 0 | 0 |
| ZBW | 1 | 10 | 14 | 3 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ZBW | 2 | 5 | 6 | 3 | 0 | 1 | 0 |
| ZBW | 6 | 2 | 0 | 0 | 0 | 1 | 0 |
| ZBW | 8 | 2 | 0 | 1 | 0 | 1 | 0 |
| ZBW | 9 | 4 | 1 | 0 | 0 | 1 | 0 |
| ZBW | 15 | 2 | 0 | 0 | 0 | 0 | 1 |
| ZBW | 20 | 2 | 1 | 0 | 0 | 1 | 0 |
| ZBW | 26 | 2 | 0 | 0 | 1 | 0 | 0 |
| ZBW | 27 | 1 | 0 | 0 | 1 | 1 | 0 |
| ZBW | 28 | 6 | 2 | 4 | 0 | 5 | 0 |
| ZBW | 32 | 2 | 1 | 0 | 0 | 1 | 0 |
| ZDC | 3 | 3 | 2 | 0 | 0 | 1 | 0 |
| ZDC | 4 | 4 | 1 | 1 | 0 | 3 | 0 |
| ZDC | 9 | 6 | 2 | 2 | 0 | 3 | 1 |
| ZDC | 11 | 3 | 1 | 1 | 0 | 0 | 1 |
| ZDC | 12 | 3 | 0 | 2 | 0 | 3 | 1 |
| ZDC | 15 | 5 | 3 | 2 | 0 | 3 | 2 |
| ZDC | 17 | 3 | 0 | 2 | 0 | 2 | 1 |
| ZDC | 18 | 6 | 2 | 4 | 0 | 4 | 2 |
| ZDC | 36 | 4 | 3 | 0 | 0 | 0 | 0 |
| ZDC | 37 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZDC | 39 | 3 | 1 | 0 | 0 | 1 | 0 |
| ZDC | 42 | 4 | 1 | 2 | 0 | 3 | 0 |
| ZDC | 43 | 8 | 4 | 1 | 0 | 2 | 1 |
| ZDC | 48 | 2 | 0 | 1 | 0 | 2 | 0 |
| ZDC | 49 | 3 | 0 | 1 | 0 | 2 | 1 |
| ZDC | 51 | 3 | 0 | 2 | 1 | 2 | 0 |
| ZDC | 52 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZDC | 53 | 2 | 1 | 1 | 0 | 0 | 0 |
| ZDC | 66 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZDC | 88 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZDC | 89 | 0 | 0 | 0 | 0 | 0 | 1 |
| ZDC | 90 | 0 | 0 | 0 | 0 | 0 | 0 |
| ZDC | 91 | 0 | 0 | 0 | 0 | 0 | 0 |

# Appendix C

## Sector Selection for Survey in Chapter 5

| Test Number | Sector A | Sector B | Sector C |
|---|---|---|---|
| 111 | ZAU36 | ZJX87 | ZME34 |
| 112 | ZAU36 | ZMA19 | ZTL02 |
| 113 | ZAU36 | ZAU45 | ZMP28 |
| 121 | ZAU52 | ZAU24 | ZID91 |
| 122 | ZAU52 | ZAU45 | ZDV33 |
| 123 | ZAU52 | ZAU36 | ZDV18 |
| 131 | ZFW71 | ZFW28 | ZTL27 |
| 132 | ZFW71 | ZAU52 | ZDV38 |
| 133 | ZFW71 | ZJX87 | ZME61 |
| 211 | ZDC52 | ZAU94 | ZNY68 |
| 212 | ZDC52 | ZID89 | ZTL06 |
| 213 | ZDC52 | ZFW49 | ZAU47 |
| 221 | ZFW52 | ZID76 | ZID66 |
| 222 | ZFW52 | ZID83 | ZDV47 |
| 223 | ZFW52 | ZOB77 | ZLC18 |
| 231 | ZID76 | ZFW50 | ZAU47 |
| 232 | ZID76 | ZTL34 | ZFW20 |
| 233 | ZID76 | ZID77 | ZID92 |
| 311 | ZFW98 | ZOB64 | ZAB70 |
| 312 | ZFW98 | ZOB37 | ZDC36 |
| 313 | ZFW98 | ZID83 | ZDC38 |
| 321 | ZID89 | ZID76 | ZAB72 |
| 322 | ZID89 | ZID77 | ZDV23 |
| 323 | ZID89 | ZFW52 | ZKC06 |
| 331 | ZID83 | ZOB77 | ZID99 |
| 332 | ZID83 | ZID76 | ZFW43 |
| 333 | ZID83 | ZFW98 | ZDC36 |
| 411 | ZID89 | ZDC42 | ZBW33 |
| 412 | ZID89 | ZDC52 | ZOB29 |
| 413 | ZID89 | ZID83 | ZNY73 |
| 421 | ZID94 | ZID77 | ZDC07 |
| 422 | ZID94 | ZFW98 | ZNY34 |
| 423 | ZID94 | ZID98 | ZJX75 |
| 431 | ZFW49 | ZAU94 | ZOB29 |
| 432 | ZFW49 | ZOB77 | ZJX85 |
| 433 | ZFW49 | ZOB37 | ZID96 |
| 511 | ZME34 | ZID98 | ZFW52 |
| 512 | ZME34 | ZID81 | ZAU94 |
| 513 | ZME34 | ZTL40 | ZTL50 |
| 521 | ZAB98 | ZAU84 | ZTL34 |
| 522 | ZAB98 | ZME62 | ZMA17 |
| 523 | ZAB98 | ZDV18 | ZID77 |
| 531 | ZID91 | ZME28 | ZOB77 |
| 532 | ZID91 | ZAU61 | ZDC52 |
| 533 | ZID91 | ZOB19 | ZFW98 |

| | | | |
|---|---|---|---|
| 611 | ZBW33 | ZNY34 | ZHU46 |
| 612 | ZBW33 | ZHU65 | ZNY49 |
| 613 | ZBW33 | ZOB29 | ZNY55 |
| 621 | ZME63 | ZLA34 | ZDV64 |
| 622 | ZME63 | ZBW33 | ZBW38 |
| 623 | ZME63 | ZNY56 | ZNY39 |
| 631 | ZJX75 | ZAU25 | ZFW97 |
| 632 | ZJX75 | ZDC07 | ZLA40 |
| 633 | ZJX75 | ZOB29 | ZBW31 |