



**EXPERIMENTAL STUDIES OF COGNITIVELY BASED AIR
TRAFFIC CONTROL COMPLEXITY METRICS
FOR FUTURE OPERATIONAL CONCEPTS**

Lishuai Li and R. John Hansman

*This report is based on the S.M. Thesis of Lishuai Li submitted to
the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degree of
Master of Science in Aeronautics and Astronautics
at the Massachusetts Institute of Technology.*

Report No. ICAT-2009-03
September 2009

MIT International Center for Air Transportation (ICAT)
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

EXPERIMENTAL STUDIES OF COGNITIVELY BASED AIR TRAFFIC CONTROL COMPLEXITY METRICS FOR FUTURE OPERATIONAL CONCEPTS

by

Lishuai Li and Prof. R. John Hansman

ABSTRACT

New procedures and technologies of Air Traffic Control (ATC) under development in Next Generation Air Transportation System (NextGen) will change controllers' tasks, roles, and responsibilities. However, cognitive complexity will remain one of the limiting factors in future system's capacity and none of existing complexity metrics can be directly extended to evaluate cognitive complexity under future operational concepts. Therefore, complexity metrics, applicable to future operational concepts, need to be developed.

This thesis developed the structure for a cognitively based complexity metric, Modified Aircraft Count (MAC). Cognitive complexity is decomposed based on individual aircraft complexity factors and sector specific factors. The complexity contribution of each aircraft is summed and adjusted by sector level complexity factors. Cognitive principles, such as controller strategies, may be incorporated in aircraft specific complexity factors and sector level complexity factors.

To investigate complexity factors in Modified Aircraft Count, two simulations were developed to explore two proposed NextGen operational concepts, including Time-Based Control at a Metering Fix and Dynamic Route Structure Control. Two experiments were designed to evaluate controller performance and subjective workload under the simulated operational concepts. The Time-Based Control at a Metering Fix was found to have enhanced schedule conformance, reduced operational errors and lower perceived complexity. The Dynamic Route Structure Control introduced longer hand-off acceptance times, however, no other significant changes of controller performance and subjective workload were found.

A new complexity probe technique was developed and applied in the two experiments to explore individual aircraft complexity factors in Modified Aircraft Count. In the new complexity probe, participants were asked to identify high complexity aircraft from the screen shot of a traffic situation they had experienced. It was shown to be an effective tool to assess aircraft specific complexity factors. Four complexity factors (proximity to other aircraft, membership of a standard flow, proximity to weather, and projected proximity to other aircraft) were examined by the relationship between their corresponding observable factors and high complexity aircraft percentage. The chance of an aircraft being considered as of high complexity increased if the aircraft was closer to another aircraft, off the standard route structure, closer to the area impacted by weather, or more likely to be in a conflict in the future.

ACKNOWLEDGEMENTS

This work was supported by the National Aeronautics and Space Administration (NASA) under grant NNA06CN23A. Dr. Parimal Kopardekar acted as the technical monitor and provided valuable feedback and assistance.

The authors wish to thank Prof. Greg M. Thibeault at Daniel Webster College who provided supports to conduct the experiments for this work. Thanks to all the student controllers at Daniel Webster College who participated in the experiments.

The authors would also like to thank Paul U. Lee, Nancy M. Smith, Thomas Prevot, and other researchers in the Airspace Operations Laboratory at NASA Ames Research Center for intellectual feedback and collaborations throughout this research and the air traffic controllers who provided insights in formal and informal meetings during the course of this research.

Contents

1	Introduction	11
1.1	Motivation	11
1.2	Research Questions	12
1.3	Study Overview	13
2	Background and Literature Review	15
2.1	Complexity Definition	15
2.1.1	Complexity in General	15
2.1.2	Complexity in Air Traffic Control	17
2.2	Complexity Factors and Metrics in Air Traffic Control	17
2.2.1	Complexity Factors	17
2.2.2	Complexity Metrics	19
2.3	Four Dimensional Trajectory and Other Transitions in NextGen	23
2.4	Summary	25
3	A Preliminary Structure for Cognitively Based Complexity Metrics	26
3.1	Structures of Existing Complexity Metrics	26
3.2	Modified Aircraft Count	28
3.3	Investigation of Aircraft Complexity Factors in MAC	32
3.3.1	Aircraft Complexity Assessment Method	33
3.4	Summary	35
4	Simulation Studies of Two Simplified Future Operational Concepts	37

4.1	Experiment 1: Time-Based Control at a Metering Fix	38
4.1.1	Independent Variables	40
4.1.2	Dependent Variables	42
4.1.3	Apparatus, Participants, and Procedure	43
4.1.4	Results and Discussion	44
4.1.5	Conclusion of Experiment 1	48
4.2	Experiment 2: Dynamic Route Structure Control	48
4.2.1	Independent Variables	49
4.2.2	Dependent Variables	52
4.2.3	Apparatus, Participants, and Procedure	52
4.2.4	Results and Discussion	53
4.2.5	Conclusion of Experiment 2	58
4.3	Summary	59
5	Empirical Findings on Aircraft Complexity Factors from Aircraft Complexity Assessment	61
5.1	Complexity Factor: Proximity to Other Aircraft	61
5.2	Complexity Factor: Membership of a Standard Flow	67
5.3	Complexity Factor: Weather Impacting Area Encounters	72
5.4	Complexity Factor: Projected Proximity to Other Aircraft	75
5.5	Summary	81
6	Conclusion	82
6.1	Thesis Summary	82
6.2	Conclusion	84

List of Figures

2-1	Mental and Physical Processes Required in Air Traffic Control (Pawlak et al., 1996)	18
3-1	An Example of Aircraft Complexity Assessment Result	34
4-1	Example of Strategy Difference between Current Operation and 4DT Operation	39
4-2	Design Matrix of Experiment 1: Time-Based Control at a Metering Fix	40
4-3	Main Display in Experiment 1 (Position-Based Control)	41
4-4	Main Display in Experiment 1 (Time-Based Control)	41
4-5	Schedule Conformance in Experiment 1	45
4-6	Operational Errors in Experiment 1	46
4-7	Subjective Workload Ratings in Experiment 1	47
4-8	Example of Strategy Difference between Static Route Structure and Dynamic Route Structure	49
4-9	Design Matrix of Experiment 2: Dynamic Route Structure	50
4-10	Main Display in Experiment 2	51
4-11	Dynamic Route Structure Control Example	51
4-12	Hand-Off Acceptance Time in Experiment 2	55
4-13	Delivery Performance in Experiment 2	56
4-14	Operational Errors in Experiment 2	57
4-15	Subjective Workload Ratings in Experiment 2	58

5-1	High Complexity Aircraft Percentage by Horizontal Distance to Other Aircraft by Different Operational Concepts in Two Experiments . . .	63
5-2	The Impact of Horizontal Proximity on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix	65
5-3	The Impact of Horizontal Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control	66
5-4	High Complexity Aircraft Percentage by Relative Position to Route Structure by Different Operational Concepts in Two Experiments . .	68
5-5	The Impact of Route Structure on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix	70
5-6	The Impact of Route Structure on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control	71
5-7	High Complexity Aircraft Percentage by Distance to Weather by Different Operational Concepts in Experiment 2	73
5-8	The Impact of Weather Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control	74
5-9	The Impact of Projected Distance and Projected Time on High Complexity Aircraft Percentage by Different Operational Concepts in Experiment 1: Time-based Control at a Metering Fix	76
5-10	The Impact of Projected Distance and Projected Time on High Complexity Aircraft Percentage by Different Operational Concepts in Experiment 2: Dynamic Route Structure Control	77
5-11	The Impact of Projected Proximity on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix	79

5-12 The Impact of Projected Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Rout Structure Control	80
---	----

List of Tables

2.1	MAP Values	20
3.1	Example Aircraft Complexity Factors	30
3.2	Example Sector Complexity Factors	31
3.3	Example Measures Used to Validate Complexity Metrics	33

Chapter 1

Introduction

1.1 Motivation

Cognitive complexity, which is directly related to controller workload, is likely to remain one of the functional limitations on the capacity of the air traffic control (ATC) system (Majumdar and Polak, 2001; Hilburn, 2004). New ATC procedures and technologies under development will affect cognitive complexity since controller roles and tasks will be altered. The current complexity metrics, such as the monitor alter parameter (MAP), may not be applicable to future operations. Well grounded complexity metrics that are robust to be used in future operational concepts are needed to evaluate trade-offs of new operational concepts and also to be used in the ATC operational management of future system.

The Next Generation Air Transportation System (NextGen) has been proposed as a wide-ranging initiative to modernize the air traffic control system. New capabilities and operational concepts have been proposed in NextGen. As a result, the tasks, roles and responsibilities of controllers will be changed. In order to develop metrics which reflect the cognitive complexity of future operational concepts, it will be important to identify and understand the changes in cognitive complexity and controller strategies introduced by new operational concepts in NextGen systems. Many new operational concepts have been proposed in NextGen. Four-dimensional trajectory (4DT) is one of them. In 4DT systems, flight path and time information along the

path helps controllers to manage flights more effectively and precisely (JPDO, 2007). Moreover, flexible route definitions enabled by 4DT allow traffic flows to be shifted as necessary to enable more effective weather avoidance. Some other 4DT capabilities are also envisioned in NextGen, such as aggregated and individual 4DTs can tailored to individual flight preferences. These changes are expected to significantly alter the controllers' tasks and cognitive strategies. There is a clear need to understand how the new ATC procedures and technologies affect cognitive complexity, what the factors that drive cognitive complexity are, and how to identify the "safe" limits of controller workload ultimately.

None of the complexity metrics to date have been accepted to fully capture the notion of complexity as it is perceived by the controller. Moreover, current complexity metrics require calibrations and testings in the actual sector and under the actual procedures. Thus, current metrics are difficult to project cognitive complexity under future operational concepts. In addition, many complexity factors used in these metrics have not been explicitly validated. Well grounded complexity metrics would help to assess the cognitive complexity under future operational concepts, and also be helpful in managing cognitive complexity in future air traffic control systems where complexity may be one of the target or limiting parameters in the control strategies.

1.2 Research Questions

The research questions of this thesis are

- What are possible structures of complexity metrics that would be applicable to future operational concepts?
- What is the impact of some complexity factors on cognitive complexity under current operation and future operational concepts?

The research of this thesis is focusing on the development of cognitively based complexity metrics and the cognitive principles of the complexity factors incorporated in the metrics. Controller cognitive complexity is the object of the study. The

term, complexity, has been used frequently in ATC literature. The consensus view among the ATC research is that complexity drives controller workload. However, the concepts and definitions of ATC complexity presumed in ATC studies differ and can be grouped into three categories: situation complexity, perceived complexity, and cognitive complexity (Histon and Hansman, 2008). Situation complexity is an intrinsic property of the configuration of the traffic situation; Perceived complexity is a subjective experience of the controller; Cognitive complexity is the complexity of the working mental model(s) used by a controller to control an air traffic situation, a property of the process being used to perform the ATC task (Histon and Hansman, 2002). The cognitive complexity of a controller can be affected by the geometrical complexity of the traffic, the controller's task, their mental models and strategies, and other factors such as fatigue and stress (Histon and Hansman, 2008).

1.3 Study Overview

In order to address the proposed research questions, a structure for cognitively based complexity metrics, Modified Aircraft Count (MAC), was developed based on the assumption of aircraft based decomposition of cognitive complexity and cognitive principles in different operational concepts. Two experiments were designed to explore the validity of MAC in two simplified future operational concepts. Controller performance and subjective workload in the simulated operational concepts were examined. Furthermore, the impact on controller cognitive complexity of two future operational concepts was investigated through a new complexity probe, Aircraft Complexity Assessment.

In Chapter 2, a literature review was performed focusing on the definition of complexity, common complexity metrics, and current studies on 4DT related controller cognitive complexity.

In Chapter 3, a structure for cognitive complexity metrics was developed based on the modified aircraft count method proposed by Histon et al. (2002b). The basic idea of the Modified Aircraft Count (MAC) structure was to measure the cognitive

complexity of a traffic situation by the sum of each aircraft's complexity contribution and then adjusted by sector level complexity factors. Simulation methods and a special complexity probe technique were proposed to investigate complexity factors the Modified Aircraft Count structure. The new complexity probe technique, Aircraft Complexity Assessment, allowed high complexity aircraft to be identified on a screen shot of a traffic situation. Complexity factors associated with individual aircraft were able to be assessed through this complexity probe method.

In Chapter 4, two part task simulations were designed to represent key elements of the two future operational concepts. Experiment 1: Time-Based Control at a Metering Fix was designed to investigate the potential impact on controller cognitive complexity of a simple version of 4DT operations. Experiment 2: Dynamic Route Structure Control was designed to explore the proposed operational concepts of flexible route definition and dynamic flow management in NextGen. Cognitive complexity of air traffic controllers cannot be measured directly. Controller performance and subjective report of workload or perceived complexity were analyzed in each experiment.

In Chapter 5, efforts were made to quantify the cognitive complexity impact of aircraft complexity factors. Aircraft-specific complexity was assessed through the results of Aircraft Complexity Assessment. Four aircraft complexity factors were validated, including proximity to other aircraft, membership of a standard flow, proximity to weather, and projected proximity to other aircraft. These complexity factors were evaluated based on the values of associated observable factors and the results of identified high complexity aircraft. Statistical relationships between these observable factors and high complexity aircraft were given. Various controller strategies in different traffic situations were also indicated by the empirical results.

Chapter 2

Background and Literature Review

This chapter reviews definitions of complexity in air traffic control, methods to measure complexity, and studies to explore new operational concepts in NextGen, especially the four-dimensional trajectory operational concept. This section is organized into three parts. First, concepts and definitions of complexity are discussed in order to provide a basic understanding of what complexity is. Then, the proposed complexity factors and methods to measure complexity are introduced. At the end, the impact of future operational concepts on controller cognitive complexity is discussed.

2.1 Complexity Definition

2.1.1 Complexity in General

The term "complexity" is difficult to define precisely. Nonetheless, many attempts can be found in the literature and they share several common characteristics to the concepts and definitions of complexity. Cilliers (1998) describes a list of complex system characteristics which can be applied to many human-machine complex systems. These characteristics (Cilliers, 1998; Hilburn, 2004) are:

- A large number of elements whose interaction defies analysis by traditional mathematical means

- Dynamic interaction between elements, that involves transfer of energy and/or information
- Redundancy that permits some subset of the system to carry out the function of the whole
- Localized autonomy and lack of information sharing between all elements
- Non-linear interactions between elements, which makes it possible for small perturbations to have large effects

The list covers several key characteristics of the concept of complexity that are prevalent in previous definitions of complexity, such as numeric size and variety of basic elements, internal structure, and how the object or problem is represented (Edmonds, 1999; Xing and Manning, 2005; Cummings and Tsonis, 2006; Histon and Hansman, 2008).

Complexity has been associated with “size”, “count”, “number of items in an object”, or “variety” (Edmonds, 1999). To some extent a larger numeric size corresponds to a higher degree of complexity. In addition to size, variety has also been used in various applications as the measure of complexity.

However, Edmonds (1999) pointed out that size or variety alone is not a sufficient definition of complexity as the full richness of what is meant by complexity can not be captured. Indeed, a system with many components that are not interacting may still be viewed as less complex than a system with few but strongly interacting components. Hence, the internal structure of a system is also a key characteristic of complexity.

The third key characteristic, argued by Edmonds (1999); Xing and Manning (2005); Cummings and Tsonis (2006); Histon and Hansman (2008), is that complexity depends on how the object or problem is represented. Recall that “complexity only makes sense when considered relative to a given observer” (Edmonds, 1999). The complexity of a system depends on which aspects the observer is concerned with and how the observer processes information (Xing and Manning, 2005).

2.1.2 Complexity in Air Traffic Control

Among ATC research, few definitions of “complexity” can be found, however, the key characteristics of complexity are consistent with typical uses of the term. The consensus view among ATC research is that complexity drives controller workload (Christien et al., 2002; Majumdar and Ochieng, 2002; Hilburn, 2004). Mogford et al. (1995) refer the term “ATC complexity” as the effect on the controller by the complexity of the airspace and the air traffic flying within it. Athenes et al. (2002) describe ATC complexity as “a way to characterize air traffic situations”, which accounts for a large proportion of controller workload. Similarly, Histon and Hansman (2008) suggests “cognitive complexity” to relate to the cognitive difficulty of controlling an air traffic situation.

Although there is a common view about the link between complexity and workload, the concepts and definitions of ATC complexity presumed in ATC studies differ and can be grouped into three major categories: situation complexity, perceived complexity, and cognitive complexity (Histon and Hansman, 2008). Situation complexity is an intrinsic property of the configuration of traffic; perceived complexity is a subjective experience of the controller; cognitive complexity is a property of the process being used to perform the ATC task (Histon and Hansman, 2008).

2.2 Complexity Factors and Metrics in Air Traffic Control

2.2.1 Complexity Factors

There is a large amount of work in ATC complexity focusing on the identification of factors and influences that appear to make an air traffic situation more or less complex. Summaries of these studies can be found in the review papers (Mogford et al., 1995; Majumdar and Ochieng, 2002; Hilburn, 2004; Loft et al., 2007).

At the beginning of ATC complexity studies, traffic density has been the factor that most closely associated with complexity. However, it is increasingly clear that

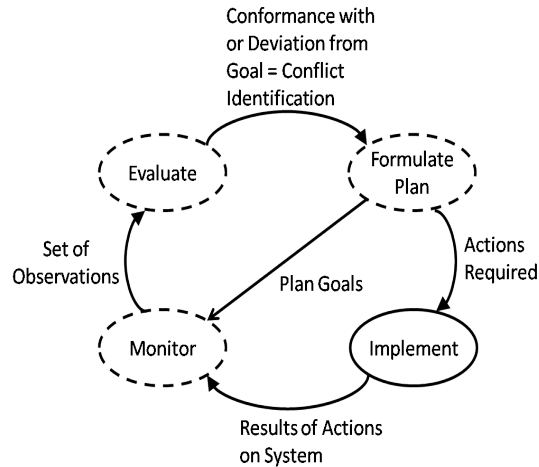


Figure 2-1: Mental and Physical Processes Required in Air Traffic Control (Pawlak et al., 1996)

density by itself is an insufficient indicator of the difficulty a controller faces (Hilburn, 2004), since traffic density itself does not capture the richness of the associated traffic complexity (Mogford et al., 1995; Kirwan et al., 2001; Athenes et al., 2002).

Up until now, various complexity factors have been identified. Most of them can be grouped into two categories: the distribution of aircraft in the air traffic situation and properties of the underlying structure in a sector (Histon and Hansman, 2002). Indicators for the distribution of aircraft in the air traffic situation include traffic density, the proportion of aircraft changing altitudes, and number of conflicts, etc. Indicators for the properties of the underlying structure in a sector include sector size, sector shape, the configuration of airways, the location of airway intersections relative to sector boundaries, and the impact of restricted areas of airspace (Histon and Hansman, 2002).

In addition to the observable indicators mentioned above, due to the cognitive nature of the ATC task, there are other complexity factors that are not directly observable. Pawlak et al. (1996) define four types of general tasks that controllers must perform as shown in Figure 2-1. Of these, only the implementation processes are observable. The other three processes, planning, monitoring, and evaluating, are not directly observable. The four processes combine to determine the level of mental effort required for air traffic control (Pawlak et al., 1996).

The cognitive nature of the ATC task may be the main reasons for the nonlinear interactions between complexity factors (Majumdar and Ochieng, 2002; Athenes et al., 2002) and the different responses by different controllers to the same constellation of complexity factors (Mogford et al., 1994; Loft et al., 2007). Correspondingly, the controller cognitive processes are analyzed and incorporated in the development of complexity model in some work (Seamster et al., 1993; Pawlak et al., 1996; Histon et al., 2002a). It is common view that cognitive complexity in ATC relies heavily on controllers' perception and recognition of the traffic situation.

Identified complexity factors have been elicited using several techniques in the past studies. Verbal reports, questionnaires, and interviews have been used to elicit complexity factors directly from air traffic controllers (Mogford et al., 1994; Wyndemere, 1996). Statistical methods have also been applied to indirectly determine potential complexity factors using controller subjective workload ratings of different air traffic situations (Mogford et al., 1994; Kopardekar and Magyarits, 2003; Kopardekar et al., 2007). However, few techniques used can give in-depth information of the quantitative relationship between each of the factors and controller cognitive complexity.

2.2.2 Complexity Metrics

The current ATC system uses the monitor alert parameter (MAP) of the Enhanced Traffic Management System (ETMS) to measure sector level activity and the corresponding air traffic controller taskload. The MAP value is designed to be the number of aircraft that a sector/airport can accommodate without degraded efficiency during specific periods of time (FAA, 2007). The MAP value is set based on average sector flight time. Table 2.1 shows the MAP values established in (FAA, 2007). However, it is widely recognized, however, that the monitor alert parameter has significant shortcomings in its ability to accurately measure and predict sector level complexity (Chatterji and Sridhar, 2001).

Researchers have invested substantial effort in formulating quantifiable metrics to describe air traffic complexity or the limit of controller workload. The earliest such work is done by Davis et al. (1963) and Arad (1964) (as cited in Mogford et al., 1995;

Table 2.1: MAP Values

Average Sector Flight Time	MAP Value
3 min.	5
4 min.	7
5 min.	8
6 min.	10
7 min.	12
8 min.	13
9 min.	15
10 min.	17
11 min.	18
12 min. or greater	18

Majumdar and Ochieng, 2002; Hilburn, 2004). Davis et al. (1963) find that workload (defined as total task time) responded to both traffic density and complexity (defined as proportion of arrival and departure traffic to overflight traffic). Arad (1964) focuses on the impact of airspace factors on controller workload, and Jolitz (1965) finds that the number of aircraft handled can predict controllers' rated workload better than the workload formula in (Arad, 1964). A number of research groups have also developed metrics based on basic aircraft count approach. Schmidt (1976) proposes a controller workload model which calculates the Control Difficulty Index (CDI) based on the execution time and frequency of observable tasks. The average flight time for an aircraft through a sector has been included to improve the basic aircraft count method in some studies (Buckley et al., 1969; Mills, 1998). Stein (1985) uses simulation to investigate the effect on controller workload of several factors, including total amount of traffic, number of handoffs, localised traffic density, number of handoffs inbound, and number of handoffs outbound.

Since the 1990s, research in ATC complexity has been motivated by the concept of Free Flight (RTCA, 1995), which is a concept of transferring route selection and separation assurance authority from ground to air (flight deck). Dynamic Density is intended as an objective measure to identify situations that are complex enough such that centralized control would still be required (RTCA, 1995). It is defined as the

collective effect of all factors, or variables, that contribute to sector level air traffic control complexity or difficulty at any given time (Kopardekar et al., 2007).

Multiple metrics of Dynamic Density have been proposed using a number of variables representing complexity factors to describe the complexity level in a sector (Wyndemere, 1996; Laudeman et al., 1998; Kopardekar et al., 2002; Chatterji and Sridhar, 2001; Masalonis et al., 2003). Most of these metrics have been developed and validated using large data sets from real operations or human-in-the-loop simulations. The weighting of the contributing complexity factors are obtained using regression models. Some typical factors include: the distribution of aircraft in the air traffic situation, sector size and shape, the location of airway intersections relative to sector boundaries, aircraft changing altitudes, and the impact of restricted areas of airspace. For instance, Laudeman et al. (1998) calculate dynamic density as the sum of the density of traffic weighted by the number of changes in speed, heading, and altitude; the proximity of aircraft; and the time until predicted conflicts. Four popular dynamic density metrics are examined by Kopardekar and Magyarits (2003). Twelve complexity factors with high weightings from the four metrics have been identified and incorporated into one single metric. Further study indicates that the Dynamic Density metric perform better than aircraft count (Kopardekar et al., 2007).

However, using Dynamic Density also has its shortcomings. Factor weightings are applicable only to the sector in which they are collected and validated (Hilburn, 2004). The current Dynamic Density models do not consider the complexity changes with increased levels of automation and the prediction of complexity (Kopardekar et al., 2007). Also, the models are not feasible for predictive air traffic management when traffic and weather forecast are used for dynamic airspace adjustments (Kopardekar et al., 2007).

Some complexity models also attempt to capture intrinsic complexity factors. For example, Delahaye and Puechmorel (2000) use factors derived directly from the location and speed of aircraft. They measure the level of complexity by Kolmogorov entropy for different geometric traffic situation. A high entropy value means significant disorder in the trajectories, which is interpreted as a high level of complexity in

the system. Kolmogorov Entropy has been evaluated for four types of traffic convergences.

The airspace structure is considered an important factor for understanding complexity (Wyndemere, 1996; Sridhar et al., 1998; Kirwan et al., 2001; Schaefer et al., 2001; Histon and Hansman, 2002). A small number of the complexity metrics have include some terms related to airspace structure. For example, Wyndemere (1996) includes a term “airspace structure” as one of the complexity factors in the proposed metric. The impact on complexity by airspace structure is measured by the difference between aircraft heading and an identified major axis of a sector. It assumes that the complexity increases if there are aircraft flying against the major flow of the sector. Histon and Hansman (2002) further suggests that the cognitive complexity is affected by controllers’ higher level organizations and conceptualization of the traffic pattern. Two air traffic situations may have an identical dynamic density value, but may not be of the same cognitive difficulty due to cognitive simplifications provided by the structure in one of the situations (Histon and Hansman, 2002). Abstractions of underlying structures that help controllers simplify and understand traffic patterns are identified Histon et al. (2002a,b); Histon and Hansman (2002, 2008).

To summarize, although numerous complexity metrics have been developed, no metric fully captures the notion of complexity as it is perceived by the controller (Hilburn, 2004; Loft et al., 2007). Most existing metrics will not be directly extended to evaluate complexity under future operational concepts. They are constructed and calibrated explicitly or implicitly based on the tasks controllers perform under current operational concepts. The basis of these metrics would be weakened because controller tasks and responsibilities, the information systems, as well as automation tools will be altered under future operational concepts. Furthermore, no metrics can fully capture the influence of controller strategy on cognitive complexity. Cognitive principles and controller strategies would be a robust basis for complexity metrics that will be applicable to future operational concepts. In addition, few statistical examination of the relationship between complexity and observable factors have been found in the literature.

2.3 Four Dimensional Trajectory and Other Transitions in NextGen

NextGen operational concepts (JPDO, 2007) are still in development. They will introduce significant changes in system architecture, technologies used in Communication, Navigation and Surveillance, decision support tools, operating procedures and controller-pilot roles and responsibilities. These changes are expected to significantly alter the controllers' tasks and cognitive strategies. However, cognitive complexity will continue to be a limiting factor on system capacity. The impact on controller cognitive complexity should be considered when evaluating trade-offs of new operational concepts. Several examples of likely changes are discussed below to illustrate aspects of controller cognitive impacts which will be considered in evaluating trade-offs in new operational concepts and the development of complexity metrics.

The shift to a 4DT based system is anticipated to be a key aspect of the NextGen Concepts of operation. 4DTs include information about expected flight path and time along the path (JPDO, 2007). Flights can be synchronized to access the airspace system assets. The management of aggregate 4DTs also enables flexible route definitions. Traffic flows can be shifted as necessary when the area is impacted by convective weather to enable more effective traffic flow management.

The operational concepts of 4DT are still under development. Erzberger (2004) proposes the Advanced Airspace Concept (AAC) in NextGen design, which is a computer logic on the ground that monitors aircraft separations and uplinks modified trajectories when potential conflicts develop. 4DTs are basic elements required in the Advanced Airspace Concept proposed by Erzberger (2004). Wichman et al. (2004) propose an operational concept of 4DT based air traffic management, which is a heavily integrated air-ground system that requires compatible bandwidth data link capabilities for maintaining the common data base for traffic management and control. Several simulation studies using varied 4DT concepts have been conducted with different research focuses. Williams (1991) has conducted a simulation experiment to explore integration of a 4D-equipped aircraft into a 4D ATC system. He finds the

dissimilarities between airborne and ATC generated speed strategies to be a problem. A number of human-in-the-loop simulation studies performed by Prevot et al. (2003a,b) examine a concept of trajectory-oriented time-based arrival management. Data gathered in these experiments reflect the potential benefits envisioned for the concept, such as reduced inter-arrival time variability, reduced controller workload, and increased energy-efficient descents. The obstacles to and requirements for the implementation of a 4DT concept are studied by Mueller (2004). Mueller (2004) uses computer simulations and Unmanned Aerial Vehicle (UAV) flight tests to analyze the navigation requirements for the 4DT concept, individual flight corridor.

In addition, the expected increase in airborne separation authority and potential changes in controller-pilot roles and responsibilities has been studied extensively after the concept of free flight is proposed (Hilburn et al., 1997; Corker et al., 2000; Metzger and Parasuraman, 2001; Galster et al., 2001; Lee et al., 2003; McAnulty and Zingale, 2005). Controllers are expected to transit from a tactical control role to a strategic planning role, creating new monitoring tasks for controllers, which are cognitively different from current control tasks. McAnulty and Zingale (2005) summarize the existing literature on workload and performance issues related to pilot-based spacing and separation. Multiple variations of pilot self-spacing are under development. McAnulty and Zingale (2005) point out that the advanced concepts of pilot self-separation are not mature and require further development before they become operationally feasible.

NextGen implementation will also involve transition periods of mixed equipage, where aircraft with different levels of onboard equipage will coexist and controllers will apply equipment-conditional procedures. Prior studies indicate that mixed equipage appears to interfere with air traffic controllers' cognitive processes at multiple levels and lead to degradation of human performance (Grossberg, 1989; Christien et al., 2002; Major and Hansman, 2004; Pina, 2007). However, Pfeleiderer (2005) suggests that although aircraft mix appears to be associated with traffic complexity, it may not be as influential as other complexity factors in the en route environment.

2.4 Summary

This chapter has reviewed definitions of complexity, identified complexity factors and major complexity metrics. Cognitive complexity directly related to controller workload which is likely to remain one of the functional limitations on the capacity of the air traffic control system. The traffic density (also known as traffic count, density, or traffic load) is almost universally identified as a key complexity factor. Most of the factors used in the current metrics are “geometric factors”; they have the ability to measure a current air traffic situation in a calibrated and validated airspace. However, controllers may have different cognitive complexity for the same geometric complexity, because the geometric complexity factors do not capture the effects of the underlying structure and its impacts on the cognitive complexity of managing that situation. Further investigations designed to define, quantify, and assess the validity of proposed factors as contributors to air traffic cognitive complexity are required.

New operational concepts proposed in NextGen will change the roles and tasks of air traffic controllers. Several examples of likely changes are discussed to illustrate aspects of controller cognitive impacts which are considered in evaluating trade-offs in new operational concepts and the development of complexity metrics. Several studies have explored 4DT operational concepts with various research interests. However, the impact of new operational concepts on controller cognitive complexity has numerous aspects that have not been explicitly investigated. Complexity metrics based on a cognitive understanding of future operational concepts would be an effective tool in evaluating design trades and operational considerations.

Chapter 3

A Preliminary Structure for Cognitively Based Complexity Metrics

3.1 Structures of Existing Complexity Metrics

Numerous efforts have been performed to identify complexity factors and to develop complexity metrics in the past to quantify the level of air traffic control complexity (for reviews, see Mogford et al., 1995; Hilburn, 2004; Loft et al., 2007). Various methods have been applied to categorize the identified complexity factors, such as methods based on events (Schmidt, 1976), geometric properties of the aircraft distribution (Wyndemere, 1996; Laudeman et al., 1998), controller activities (Manning et al., 2000; Manning and Pfeiderer, 2006), and the non linear form, Kologomorov complexity (Delahaye and Puechmorel, 2000). Among them, two structures are most frequently employed. One structure is through a linear sum of weighted complexity factors e.g. (Wyndemere, 1996; Laudeman et al., 1998; Kopardekar et al., 2002). Another structure is based on aircraft count approach e.g. (Davis et al., 1963; Schmidt, 1976; Buckley et al., 1969; Mills, 1998; Histon et al., 2002b).

The most recent complexity metrics based on a linear sum of weighted complex-

ity factors are the Dynamic Density metrics. Dynamic Density is designed as an objective measure to define the complexity limit of a situation that centralized control would still be required (RTCA, 1995). It is defined as the collective effect of all factors, or variables, that contribute to sector level air traffic control complexity at any given time (Kopardekar et al., 2007). Multiple metrics of Dynamic Density have been proposed using a number of variables that represent complexity factors to describe the complexity level in a sector (Wyndemere, 1996; Laudeman et al., 1998; Kopardekar et al., 2002; Chatterji and Sridhar, 2001; Masalonis et al., 2003). Most of these metrics have been developed and validated using large data sets from real operations or human-in-the-loop simulations. The weighting of the complexity factors that contribute to Dynamic Density are obtained using regression models. So the metric need to be calibrated every time it is applied to a new sector as well as in a new operational concept.

For the metrics based on aircraft count approach, the earliest work is performed by Davis et al. (1963) who finds the number of aircraft to be a good indicator of controller workload. Multiple studies have been performed to improve upon the basic aircraft count approach, for example a method using the CDI is proposed by Schmidt (1976) based on an analysis of event frequency and difficulty. Some other variations of the aircraft count approach modify the count by the average flight time for an aircraft though a sector (Buckley et al., 1969; Mills, 1998). Preliminary metrics based on the relative contribution to the complexity of individual aircraft have also been proposed (Histon et al., 2002b).

Although various complexity metrics have been developed, these complexity metrics are validated and calibrated in a particular airspace and under the actual operational procedures. These metrics are typically limited in the airspace on which it was calibrated, therefore, they are difficult to be applicable to future operational concepts without re-construction and re-calibration. The controllers' strategies for mitigating cognitive complexity have not been effectively modeled in existing complexity metrics, such as the controllers' use of structure-based abstractions to simplify cognitive complexity (Histon et al., 2002b). Furthermore, the relationship between

complexity and individual complexity factors have not been rigorously examined in the past. For example, the criteria for aircraft position proximity in these metrics are primarily based on anecdotal evidence with little attention focused on examining the values statistically. This chapter presents a preliminary structure of a complexity metric, and a new measurement to probe controller cognitive complexity to support the development of the proposed complexity metric.

3.2 Modified Aircraft Count

A structure for cognitive complexity metrics, Modified Aircraft Count (MAC), was developed based on the structure which was first proposed by Histon et al. (2002b). The structure included information of aircraft specific state, sector level state, as well as controller strategies. Controller’s cognitive strategies should be able to be decomposed into observable states and integrated into the complexity metric structure. Complexity metrics that are formed on this structure would be robust to work in different sectors and different operational concepts. Moreover, the metric structure can provide values that are intuitive to air traffic controllers and consistent with the current basis for limiting traffic level.

$$MAC = SM \times \sum_{i=0}^N (AM_i) \quad (3.1)$$

The Modified Aircraft Count represents the effective number of aircraft in a sector, which is the sum of each individual aircraft’s contribution to cognitive complexity and then adjusted by sector level complexity factors. In this approach, the cognitive complexity is computed from Equation 3.1. The cognitive complexity is decomposed by individual aircraft, and each aircraft’s complexity contribution is formulated based on an understanding of the cognitive strategies that the controllers use. The cognitive complexity level is determined by each Aircraft Multiplier (AM) and a Sector Multiplier (SM). An AM represents the relative complexity contribution of one aircraft. Its value is normalized to a standard aircraft. Each AM is affected by multiple

factors of aircraft specific complexity, and then adjusted by a SM. The value of SM is determined by sector level complexity factors, such as sector properties, sector procedure requirements, ATC automation level, and mixed equipage impact. Although the sector effects can be included in the individual AMs, the SM term is introduced in this structure to allow easy adjustment of sector effects when MAC is applied in different sectors or even different operational concepts.

Aircraft Multiplier

$$AM_i = f(ACF_1, ACF_2, \dots, ACF_n) \quad (3.2)$$

$$= f(ACF_1) \times f(ACF_2) \times \dots \times f(ACF_n) \quad (3.3)$$

The Aircraft Multiplier is defined in Equation 3.2. The AM captures the complexity contribution of each aircraft, which can be greater or smaller than the complexity of a standard aircraft(1) depending on the effects of multiple complexity factors ($f(ACF_1, ACF_2, \dots, ACF_n)$). If we chose a standard aircraft to be a normal aircraft in a sector that no additional attention is needed rather than being simply monitored, the cognitive complexity contribution of the standard aircraft is assumed to be equal to unity in this structure in order to be consistent with the basic aircraft count. The cognitive complexity contribution of each aircraft in the sector (AM_i) is compared to the standard aircraft (1). The relative level of cognitive complexity contribution is affected by many aircraft specific complexity factors, denoted by $ACF_1, ACF_2, \dots, ACF_n$.

A list of aircraft complexity factors were identified based on a literature review, preliminary cognitive analysis, and the expected elements of the NextGen operational concepts. The aircraft specific complexity factors included in the AM function need to be based on the cognitive principles that the controllers use. Although a small number of factors need be added or eliminated depending on the details of the operational concepts, this structure of AM function remains the same. The list of example aircraft specific complexity factors is given in Table 3.1.

Table 3.1: Example Aircraft Complexity Factors

Aircraft Complexity Factors (ACF_i)
Aircraft Proximity
Projected Aircraft Proximity
Sector Boundary Encounters
Restricted/Military Area Encounters
Weather Impacting Area Encounters
Aircraft in Transition (Descending/Climbing)
Membership of Standard Flow (Belong to a standard flow or not)
Location Relative to Critical Points
Pilots Preference of Weather Deviation
Level of Knowledge of Aircraft Intent
Separation Responsibility (Airborne, ground, or ground-based automation)
Pilots Preference of Weather Deviation
Communication Capability (Datalink capability and flight crew communication ability)
Level of Priority ATC service (Emergency, VFR, IFR)
Traffic Restrictions or Special Requests from TMU or Other Controllers
Level of Surveillance Capability

An appropriate mathematical structure is needed to combine the identified complexity factors. It is assumed that the contribution to cognitive complexity of each aircraft specific complexity factor can be normalized to a standard aircraft. One simple and effective solution is a product of each individual complexity factor functions, $f(ACF_i)$, as shown in Equation 3.3. The value of an AM is the combined effects of each complexity factor. For example, if an aircraft is in proximity with another aircraft and additional attention is needed, then it's contribution to complexity will be larger than the standard aircraft and the value of $f(ACF_{proximity})$ will be larger than 1. At the same time, if the aircraft is in a standard flow, the value of $f(ACF_{Membership\ of\ Standard\ Flow})$ will be less than 1. Finally, all the functions of aircraft complexity factors are combined multiplicatively and a value of this aircraft's AM is obtained. The contribution of this aircraft to cognitive complexity is represented by the value of AM.

The functions of aircraft complexity factors ($f(ACF_i)$) have not been fully devel-

oped. The output of the functions is the change in cognitive complexity relative to a standard aircraft, while the input(s) are the observable parameter(s) corresponding to the complexity factor in the function. For example, the function for proximity, $f(ACF_{proximity})$, might be a continuous function decreased with the horizontal distance between two aircraft at the same altitude.

Sector Multiplier

$$SM = f(SCF_1, SCF_2, \dots, SCF_m) \quad (3.4)$$

$$= f(SCF_1) \times f(SCF_2) \times \dots \times f(SCF_m) \quad (3.5)$$

As implied by Equation 3.4, the sector multiplier captures the impact of sector level complexity factors ($f(SCF_1, SCF_2, \dots, SCF_m)$), such as sector properties, sector procedure requirements, ATC automation level, and mixed equipage impact. When MAC is applied in different sectors or under different operational concepts, MAC can be adjusted by simply changing the SM function. Possible sector level complexity factors are listed in Table 3.2.

Table 3.2: Example Sector Complexity Factors

Sector Complexity Factors (SCF_i)
Available airspace
Number and position of standard ingress / egress points
Spatial distribution of airways / navigation aids
Distribution of closest points of approach
Traffic restrictions (eg. Metering)
Level of ATC automation
Level of mix equipage

Similar to AMs, SM is a multiplicative combination of sector level complexity factor functions as in Equation 3.5. The assumption is that each function of sector level complexity factors is able to be normalized to a baseline condition of a standard sector. For example, the total complexity in a sector can be defined as the sum of AMs, multiplied by the inverse of available airspace, the difficulty level of sector properties,

additional task difficulty due to traffic restrictions, level of ATC automation tools, and level of mix equipage. The level of mixed equipage during the transition to a new operational concept is expected to affect controller cognitive complexity on a sector level. Controller performance is degraded when the capability and performance of aircraft is at various levels (Grossberg, 1989; Christien et al., 2002; Major and Hansman, 2004; Pina, 2007). However, the function of the mix equipage, $SCF_{mix\ equipage}$, should be carefully calibrated since Pfeleiderer (2005) argues that aircraft mix may not be as influential as other complexity factors in the en route environment based on an experimental study result.

3.3 Investigation of Aircraft Complexity Factors in MAC

In order to investigate aircraft complexity factors in MAC, part task simulations were used to explore the impact on cognitive complexity of various future operational concepts. Through the simulation studies, likely controller cognitive strategies will be explored and identified. These strategies are the basis to examine whether the cognitive decomposition in MAC is appropriate and whether the complexity factors are consistent in different operational concepts. As an initial step, the work of this thesis was focused on the investigation of the aircraft complexity factors in the Aircraft Multipliers.

Two part task simulations were developed to support the analysis. Each simulation was designed to explore one simplified future operational concept. The simplified future operational concepts which would change system structures and controller cognitive strategies were selected. Two simulations were designed and conducted as two stand-alone experiments. The two experiments were, Experiment 1: Time-Based Control at a Metering Fix, and Experiment 2: Dynamic Route Structure Control. The details of the two experiments are presented in Chapter 4.

Furthermore, an Aircraft Complexity Assessment method has been especially de-

veloped and applied in the two experiments to inspect the two assumptions. The experimental results from this complexity probe method are presented in Chapter 5.

3.3.1 Aircraft Complexity Assessment Method

No complexity probe used in the past have the ability to explicitly assess each aircraft’s contribution to cognitive complexity. Most of the techniques used to quantify the impact of complexity factors are based on aggregated controller subjective complexity ratings on a sector level. However, the information of the complexity contributed by individual aircraft is not available through these subjective ratings.

Most common techniques and measures used to validate or calibrate complexity metrics have been summarized in Table 3.3. Among these measures, physiological measures and system performance can only indirectly reflect controller cognitive complexity level. Controller activities can indicate how busy a controller is, but not how complex the situation is. The measures of controller perceptions and reported workload are the subjective evaluations of the perceived complexity based on aggregated information of current traffic situation, which is always a combined effect of all the aircraft and various complexity factors.

Table 3.3: Example Measures Used to Validate Complexity Metrics

Measure Group	Measure Example	References
Physiological measures	Eye blink rate, pupil diameter, visual fixation frequency, EEG, EMG, EOG, heart rate measures, respiration, biochemical activity	(Hilburn et al., 1995; Athenes et al., 2002; Averty et al., 2002)
Controller perceptions and reported workload	ATWIT, NASA TLX, expert judgment/over the shoulder ratings (PACE), complexity factor rankings	(Stein, 1985; Wyndemere, 1996; Laudeman et al., 1998; Manning et al., 2000)
System performance	Operational errors, delays, fuel burn, efficiency	(Jolitz, 1965; Buckley et al., 1969; Grossberg, 1989; Pfeiderer et al., 2007)
Controller activities	Number and duration of communications, interface interactions, coordination events, handoffs	(Stein, 1985; Laudeman et al., 1998)

A new complexity probe method, Aircraft Complexity Assessment, was proposed in this work to assess aircraft specific complexity. In this method, experiment participants were asked to identify specific aircraft which contribute higher complexity load to the overall complexity situation than a standard aircraft on the screen shots of a traffic situation. The standard aircraft was selected as an aircraft on a standard route without any potential conflicts in the two experiments. An example result from the Aircraft Complexity Assessment method is shown in Figure 3-1. In Experiment 1 of the study, the Aircraft Complexity Assessment was conducted during the simulation for five times when the simulation was paused. Since the temporary stops during the simulation had the potential to invade ongoing controller tasks, the procedure of the Aircraft Complexity Assessment was modified to avoid the need to pause the simulation. The assessment was conducted after each simulation run in Experiment 2. A simulation replay capability was used to help the controller to recall the traffic situation. The replay was paused for five times and participants were asked to identify high complexity aircraft in each traffic situation shown in the replay after each simulation run.

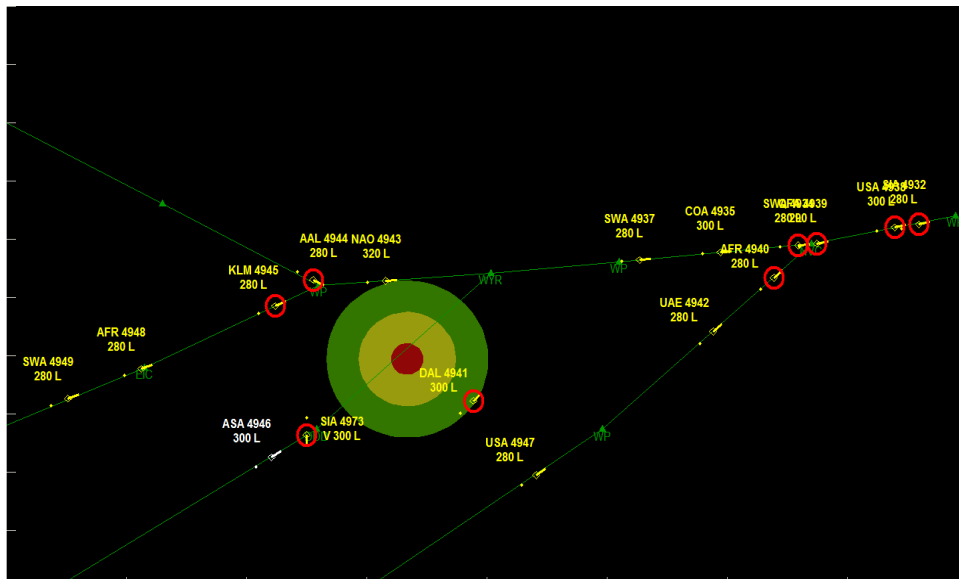


Figure 3-1: An Example of Aircraft Complexity Assessment Result

High complexity aircraft were identified by experiment participants. Observable factors which are hypothesized to drive complexity were tested based on the results of identified high complexity aircraft. Cognitive complexity was quantitatively evaluated by measuring relationships statistically between observable factors and controller subjective reports of cognitive complexity. The probability of an individual aircraft being considered as of high complexity was found to be affected by several observable factors, including proximity to other aircraft, proximity to convective weather, projected proximity and time, and whether the aircraft was on the standard route structure. Each of these factors, together with the detailed results, was discussed in Chapter 5.

3.4 Summary

The structures used in ATC complexity metrics have been reviewed. The two most commonly used structures are a linear sum of weighted complexity factors and a modification of aircraft count. However, the past complexity metrics are developed and calibrated based on current operations. A complexity metric that can be applicable to future operational concepts is needed. In order to be applicable to various operational concepts, the complexity metric should be based on controller cognitive principles that are consistent in different operations. A complexity metric structure, Modified Aircraft Count, was proposed to incorporate controller strategies in the structure of the metric. The basic idea of MAC was that the overall cognitive complexity level was determined by each aircraft's complexity contribution which was captured by Aircraft Multipliers and adjusted by a Sector Multiplier. Each AM was affected by multiple aircraft specific complexity factors. The SM was determined by sector level complexity factors, such as sector properties, sector procedure requirements, ATC automation level, and mixed equipage impact. Functions of both AM and SM were designed based on a understanding of controller strategies in various operational concepts. This structure were hypothesized to allow easy adjustment and to give comparable results when MAC is applied in different sectors or different

operational concepts.

Methods to investigate aircraft complexity factors in the MAC structure were proposed, including part task simulations representing future operational concepts and a new complexity probe method, Aircraft Complexity Assessment method. The simulation studies are presented in Chapter 4. The design and procedure of the Aircraft Complexity Assessment method is presented in this chapter. The Aircraft Complexity Assessment method allowed aircraft specific complexity to be assessed through controller subjective report. In this method, experiment participants were asked to identify specific aircraft which contribute high complexity load to the overall complexity situation on the screen shots of a traffic situation. Observable factors which were hypothesized to drive complexity can be tested based on the traffic situation information of identified high complexity aircraft.

Chapter 4

Simulation Studies of Two Simplified Future Operational Concepts

New operational concepts have been proposed in NextGen. Significant changes in system architecture, operating procedures, and decision support tools, will be introduced. These changes are expected to significantly alter the controllers tasks and cognitive strategies. However, cognitive complexity will continue to be a limiting factor on system capacity. Simulation studies of two simplified future operational concepts were designed to explore controller strategies, complexity factors in MAC, and to evaluate the trade-offs of the two simplified future operational concepts.

The shift to a 4DT based system is anticipated to be a key aspect of the NextGen concepts of operation. The specificity of expected flight path and time information helps controllers to synchronize access to airspace system assets (or to restrict access, as required) and to ensure separation (JPDO, 2007). The management of aggregate 4DTs also allows flexible route definitions in which traffic flows can be shifted as necessary to enable more effective weather avoidance. There are some other 4DT capabilities envisioned in NextGen, such as individual 4DTs tailored to individual flight preferences.

Simulation studies were performed to evaluate the impact of possible future 4DT

operational concepts on controller cognitive complexity and to investigate the most important complexity factors driving cognitive complexity in current operation and further operational concepts. Two experiments were designed to address the proposed questions. Experiment 1, Time-Based Control at a Metering Fix, was designed to investigate the potential impact on controller cognitive complexity from a simple version of 4DT operation. Experiment 2, Dynamic Route Structure Control, was designed to explore the proposed operational concepts of flexible route definition and dynamic flow management in NextGen.

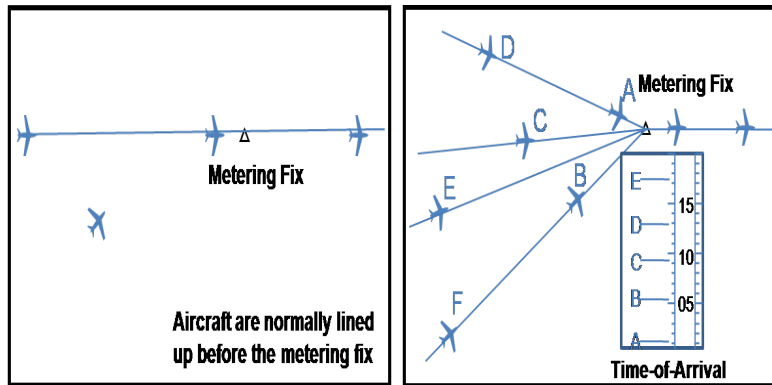
This chapter presents the two experiments, focusing on the experiment set-up and the evaluation of the trade-offs of the two simplified future operational concepts measured through controller performance and subjective workload metrics. In Chapter 5, aircraft complexity factors in MAC are investigated using a complexity probe technique within the experiments presented in Chapter 3.

4.1 Experiment 1: Time-Based Control at a Metering Fix

The shift to a 4DT based system is anticipated to be a key aspect of NextGen. The definition of 4DT by JPDO (2007) is a precise description of an aircraft path in space and time: the “centerline” of a path plus the position uncertainty, using waypoints to describe specific steps along the path. The specificity of 4DT enables precise management of an aircraft’s current and future position. A major expected benefit of 4DT is in allowing both service providers and operators to assess the effects of proposed trajectories and resource allocation plans (JPDO, 2007). Another benefit of 4DT is that by using conflict-free 4DT plan, controllers can focus on overall flow management instead of individual flight management.

In the 4DT operational environment, the roles and tasks of controllers might be different from the roles and tasks in current operational environment. As the development of 4DT operational concepts is still ongoing, there is still lack of detail

clarification, such as how many Controlled Time of Arrivals (CTA) should be specified along the path, who wield the authority to change CTAs, and what happens to the non-conformance aircraft. Since controllers will probably retain the final responsibility for aircraft separation, it is very likely that controllers will be able to give CTA commands in addition to the current commands that they can give to aircraft. When controllers have the ability to give CTA commands, the strategies controllers use to control the traffic might alter significantly. Figure 4-1 demonstrates an example of possible changes to controller strategies following a switch from current operation to a simple 4DT operation with a single CTA in the sector. In current operation, controllers usually line the aircraft up before the metering fix to maintain separation. In 4DT operation, controllers do not need to line flights up before the metering fix since the separation at the metering fix is precisely ensured by the time of arrival at that fix.



(a) Position-Based Control (Current Operation) (b) Time-Based Control at a Metering Fix (4DT Operation)

Figure 4-1: Example of Strategy Difference between Current Operation and 4DT Operation

This experiment was designed to evaluate the impact of a simple version of 4DT operation on controller cognitive complexity. With the introduction of a single CTA in a sector, how will controller performance and perceived complexity change? A human-in-the-loop fast-time simulation has been developed in MATLAB to serve as the test bed for the experiment.

4.1.1 Independent Variables

The objective of this experiment was to evaluate the impact of 4DT operation on air traffic controllers' cognitive complexity as measured by controllers' performance and subjective workload rating. The design matrix is shown in Figure 4-2. Two different control types representing the current operation and a simple version of 4DT operation respectively were the primary research interests. The baseline condition was a control type referred to as Position-Based Control, which represents current operation in which aircraft were controlled by vector and speed commands. 4DT condition was represented by a control type called Time-Based Control, in which aircraft can be controlled by time-of-arrival at a metering point in addition to vectors and speeds.

		Control Type	
		Baseline: Position-Based Control	4DT: Time-Based Control
Schedule Type	None	X	X
	FCFS	X	X
	CPS	X	X

Figure 4-2: Design Matrix of Experiment 1: Time-Based Control at a Metering Fix

In Position-Based Control, the aircraft was controlled by vector and speed commands (Figure 4-3). On the other hand, in Time-Based Control condition, the aircraft can be controlled by the time-of-arrival at the metering fix in addition to vector and speed commands. When a controlled time-of-arrival (CTA) command was given to an aircraft, the aircraft would adjust its speed automatically to best meet time-of-arrival command while maintain its current route. The additional functionality of controlling time-of-arrival in Time-Based Control was facilitated by the left side of the timeline display in the simulation (Figure 4-4). The participant can click on the timeline to give the CTA command. Both the CTA and estimated time-of-arrival (ETA) were shown on the left side of the timeline display. This functionality was not available in Position-Based Control.

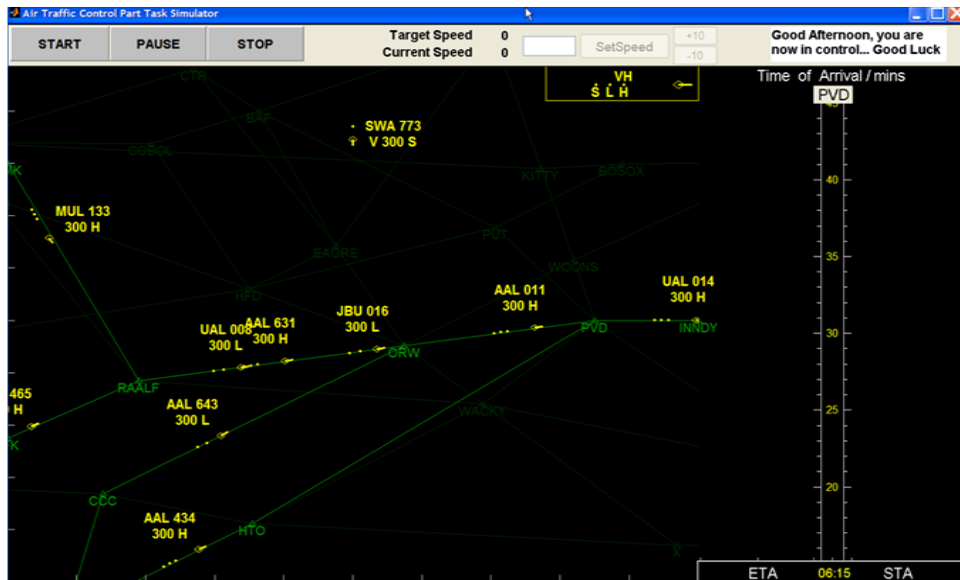


Figure 4-3: Main Display in Experiment 1 (Position-Based Control)

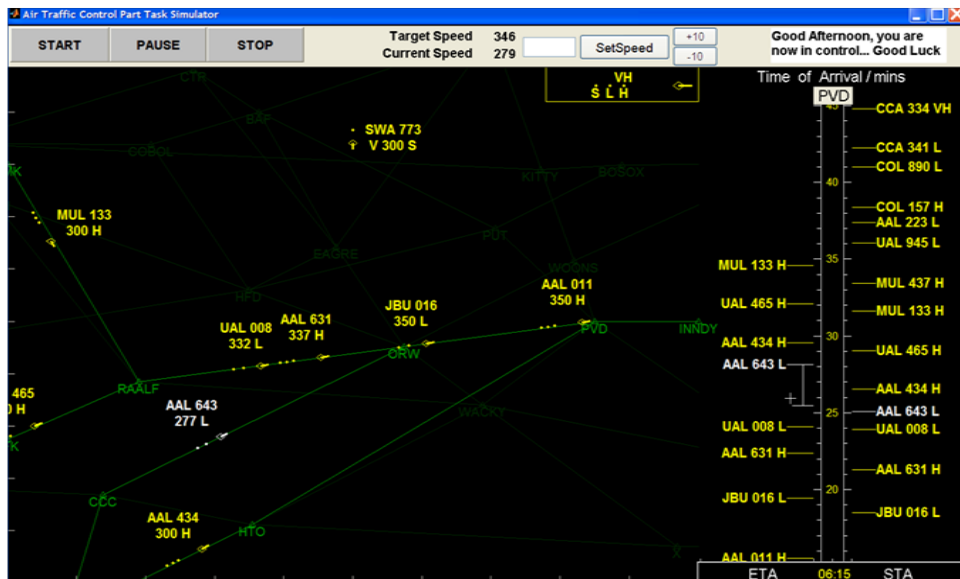


Figure 4-4: Main Display in Experiment 1 (Time-Based Control)

Another independent variable in the experiment was schedule type. The main task designed in the experiment was management of arrival traffic through a metering point. Since a schedule at the metering point will impact the system performance, schedule type was included as another independent variable to investigate how the impact of Time-Based Control changes with different schedules and what the trade-off between schedule performance and controller difficulty. Three types of schedule were included, None, FCFS, and CPS. None means that no schedule was displayed. FCFS was a schedule based on *First Come, First Served* principle. CPS which means *Constrained Position Shifting* was an optimized schedule subject to operational constraints with maximum of 1 permissible position shift. CPS schedule has the better performance in minimizing delay time. However, it might be the most difficult one for controllers as it requires swaps in the aircraft sequence. The schedules were generated by Lee's (2008) algorithm. Details about the schedules can be found in (Lee, 2008).

In the simulation, the arrival schedule was shown on the right side of the timeline display. Each flight had its Scheduled time-of-arrival (STA) when a schedule was presented.

4.1.2 Dependent Variables

Metrics of controllers' performance and perceived complexity were used to indicate the impact on controller cognitive complexity. Controllers' performance was measured by schedule conformance and operational errors. The schedule conformance was included due to the potential requirement of time conformance in NextGen environment to increase system capacity and efficiency. The schedule conformance was calculated by the difference between actual arrival time and scheduled arrival time. The operational errors were measured by the number of separation violations and aircraft exiting the airspace not through the metering fix area.

Controllers' perceived complexity was measured using a modified Air Traffic Workload Input Technique (ATWIT) (Stein, 1985). The simulation was paused at specified sample times and the perceived complexity was measured using a 7-point Likert scale to indicate the level of cognitive complexity experienced at that moment. However,

this technique had the potential to be invasive due to the interruptions in the simulation run.

4.1.3 Apparatus, Participants, and Procedure

Apparatus A human-in-the-loop fast-time air traffic control simulation was developed in MATLAB as the test bed for this experiment. Figure 4-3 shows the main display of the simulation in baseline condition. Three limitations of the test bed should be noted. In order to gather enough data in a reasonable amount of time, the simulation is accelerated to 8 times faster than real time. To avoid overwhelming the participants, the tasks were simplified to represent fundamental elements of air traffic control. Another limitation was that all the traffic was at the same altitude.

The simulation included a generic arrival airspace with multiple merge points and was generally representative of the Boston arrival flows. One metering fix was included as the reference point for all the arrival times. The traffic consisted of four major streams of arrival traffic and several crossing flights. The traffic level design was the same for all six experimental conditions. In the pilot study, participants performed with few errors at a traffic load of 12 aircraft per hour (ac/hr), the performance of participants started to decrease when traffic reached 15 ac/hr, and the performance was hardly acceptable when traffic increased to 20 ac/hr. Thus, each run started with a low traffic level (12 ac/hr), increased to a high traffic level (18 ac/hr) in the middle, and decreased to a low traffic level (12 ac/hr) again at the end.

Participants The participants for this experiment were thirteen upper class students (5 female, 24 male) in an FAA approved Air Traffic Collegiate Training Initiative (CTI) program at Daniel Webster College, NH. All the participants had been trained in real-time radar control simulations in the CTI program.

The experimental tasks were briefed to the participants before the experiment and during the practice runs. A reminder sheet with list of tasks was presented to participants during the test runs. The tasks included:

1. To maintain separation (2.5 nmi)

2. To direct arrival traffic to the metering fix
3. To manage arrival traffic to meet the schedule when a schedule is present
4. To proceed arrival traffic as fast as possible when no schedule is present

Procedure A tutorial that discussed the nature of the experiment and explained the context and use of the interface was given to each participant at the beginning of the experiment. Each participant finished two practice runs and six test runs encompassing all the conditions in the design matrix. The order of the six test runs was counterbalanced and partially randomized. Half of the participants started with the Position-Based Control, while the other half started with the Time-Based Control. Within group, the order of schedule types was randomized.

During testing, all user responses and performance data were recorded automatically. The simulation was paused at five specified sample times and the perceived complexity was measured using a 7-point Likert scale to indicate the level of cognitive complexity experienced at that moment. The Aircraft Complexity Assessment was conducted at the same time as the perceived complexity measurements during the run. High complexity aircraft were identified on the screen through the aircraft complexity assessment method. One should note that this method had a disadvantage of interrupting ongoing controller tasks.

4.1.4 Results and Discussion

The impact of the simple 4DT operational concept on controller cognitive complexity was investigated through controller performance and perceived complexity ratings. The analysis was conducted to evaluate effects of control type and schedule type on three performance measures and the perceived complexity ratings. The results indicated slight benefits of Time-Based Control in comparison to Position-Based Control. The statistical analysis showed that the effects of traffic level were marginally significant (p-values were between 0.05 and 0.1), while the effects of structure type did not show statistical significance for all dependent variables.

The two-way ANOVA test was used to analyze the three performance variables.

Assumptions that the statistical model entails have been checked using Levene tests and Shapiro-Wilk tests at significance level of $\alpha = 0.05$. The number of errors was analyzed using a square root transformation. All other parametric dependent variables passed both tests for normality and heteroscedasticity.

Schedule Conformance The schedule conformance is suggested to be a desirable requirement in future ATC system where the system will transit to a more precise time management. The value of schedule conformance was measured by the difference between actual arrival time and scheduled arrival time. The controller performance in terms of schedule conformance was compared by the control type and the schedule type. Only cases with a schedule (either FCFS or CPS), were included in the analysis. The schedule conformance was significantly improved in Time-Based Control than in Position-Based Control ($F(1, 48) = 4.86, p = .032$). However, there was no significant difference in schedule conformance due to schedule type ($F(1, 48) = 0.13, p = .722$). The interaction effect between control type and schedule type was not significant ($F(1, 48) = 0.39, p = .535$).

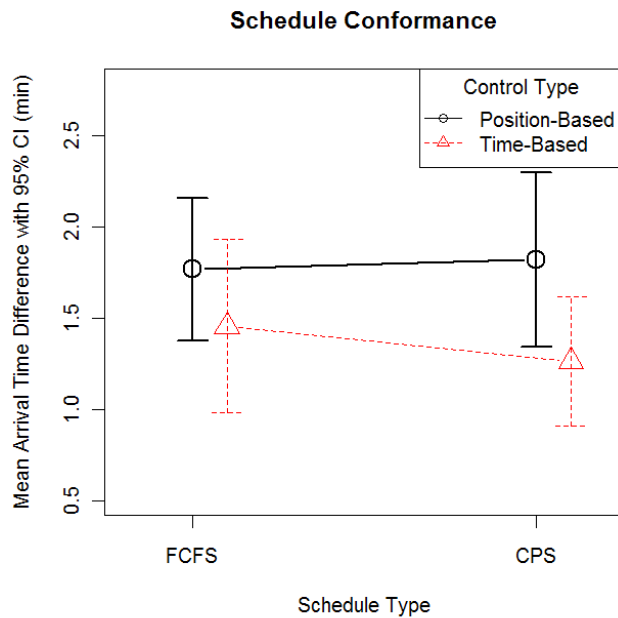


Figure 4-5: Schedule Conformance in Experiment 1

Operational Errors The operational errors were measured by the number of separation violations and aircraft exiting the airspace not through the metering fix area. The number of operational errors were fewer in Time-Based Control than in Position-Based Control. The difference was marginally significant as shown by the results of two-way ANOVA ($F(1, 72) = 3.00, p = .088$). The operational errors included separation violations and aircraft exiting the airspace not through the metering fix area. While this result is not significant at the $\alpha = 0.05$ level it does suggest that the use of Time-Based Control may slightly reduce controller error rate. Although schedule type didn't affect the number of errors significantly as shown by the ANOVA results ($F(2, 72) = 0.05, p = .949$), the mean difference between Time-Based Control and Position-Based Control was larger in CPS schedule. The results suggest that Time-Based Control can help controllers reduce the difficulty brought about by advanced schedules. No significant interaction effects were shown in the ANOVA test results ($F(2, 72) = 0.25, p = .779$).

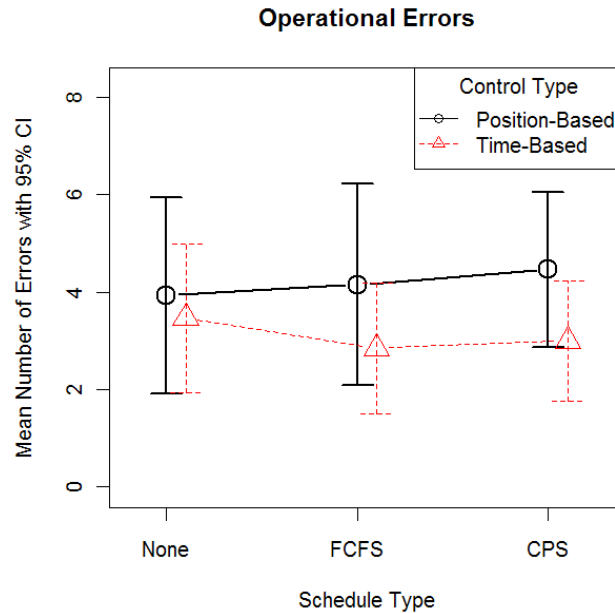


Figure 4-6: Operational Errors in Experiment 1

Perceived Complexity The results from perceived complexity ratings data showed that participants experienced a lower level of complexity in Time-Based Control than in Position-Based Control. Moreover, the ratings in the cases with a schedule were higher than ratings in the cases without a schedule. The difference between with a schedule and without a schedule showed that the requirement of schedule conformance introduced complexity to participants. A non-parametric test, the Mann-Whitney test, was used to assess the effects of control type and schedule type. The test found that control type was marginally significant ($Z = -1.71, p = .087$) in explaining differences in perceived complexity ratings. The effects of schedule type were tested using three Mann-Whitney tests. The difference between None and FCFS schedule types was significant ($Z = -2.50, p = .012$). It also showed a significant difference between None and CPS schedule types ($Z = -2.69, p = .007$). However, no significant difference was shown between FCFS and CPS schedule types ($Z = -0.73, p = .467$).

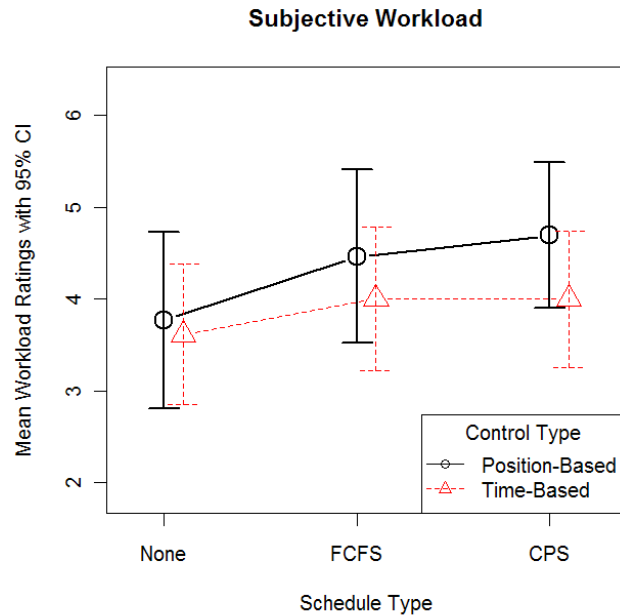


Figure 4-7: Subjective Workload Ratings in Experiment 1

4.1.5 Conclusion of Experiment 1

The impact of a simple version of 4DT operational concept was evaluated by controller performance metrics and perceived complexity ratings. The results in this experiment showed the simple version of 4DT operation enhanced controller performance and the complexity was perceived lower. The indications from all the dependent variables were consistent in showing the benefits of Time-Based Control, although some of the results were marginally statistically significant. Better schedule conformance and lower error rate were found in Time-Based Control relative to Position-Based Control. Moreover, participants perceived lower complexity in Time-Based Control than in Position-Based Control. The existence of schedule conformance requirements was a major driver influencing controller performance and perceived complexity, however, the difference between FCFS and CPS was not observed in this experiment.

4.2 Experiment 2: Dynamic Route Structure Control

NextGen (JPDO, 2007) has proposed that entire flows of aircraft and individual trajectories can be dynamically adjusted to take advantage of opportunities and avoid constraints safely and efficiently while reducing the overall impact of weather events. These operations feature dynamic route structures which replace the static route structures that characterize today's operations.

Previous work (Histon and Hansman, 2002; Histon et al., 2002a,b) on controller cognitive complexity suggested that structure, defined as the physical and informational elements that organize and arrange the ATC environment, plays an important role in helping controllers mitigate cognitive complexity. Controllers are hypothesized to internalize the structural influences in the form of abstractions which simplify their working mental model of the situation. By simplifying their working mental model, these structure-based abstractions reduce cognitive complexity. However, off-nominal conditions such as weather disruption cause complexity to grow (Cummings and Tso-

nis, 2006).

The operational concepts proposed in NextGen, dynamically adjusting flows of aircraft and individual trajectories, will affect controller working mental model. The use of dynamic route structure control can potentially enhance the use of route structure during off-nominal conditions. Controllers can continuously utilize route structure, which may reduce controller cognitive complexity in off-nominal conditions. However, controller structure-based abstractions may be altered since the route structure is adjusted dynamically, which may increase controller cognitive complexity since their working mental model needs to be adjusted at the same time. Figure 4-8 illustrates the difference between static route structure operational concept and dynamic route structure operational concept. The simulation developed in Experiment 1 was expanded to facilitate a simple version of the dynamic route structure operational concept.

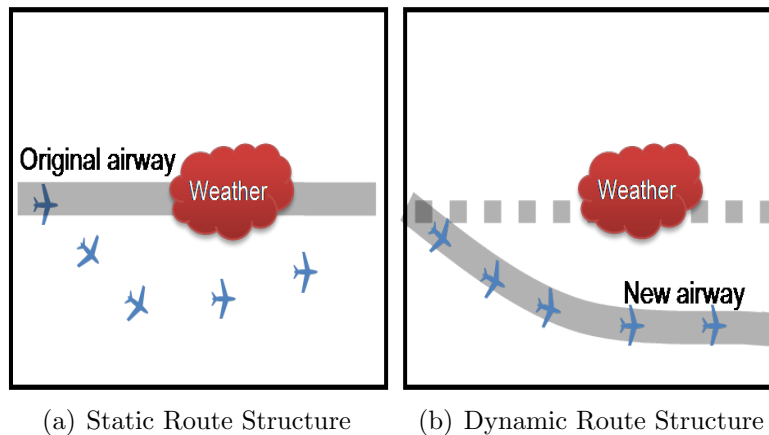


Figure 4-8: Example of Strategy Difference between Static Route Structure and Dynamic Route Structure

4.2.1 Independent Variables

The objective of this experiment was to evaluate the impact of Dynamic Route Structure Operation on air traffic controllers' cognitive complexity as measured by controllers' performance and workload during weather disruptions. Two independent variables were included: structure type (static route structure, dynamic route struc-

ture) and traffic level (medium, high, very high). The design matrix is shown in Figure 4-9.

		Route Structure	
		Baseline: Static Route Structure	4DT: Dynamic Route Structure
Traffic Level	Medium (20 ac/hr)	X	X
	High (35 ac/hr)	X	X
	Very High (50 ac/hr)	X	X

Figure 4-9: Design Matrix of Experiment 2: Dynamic Route Structure

Two types of route structure were tested in the experiment. Static route structure was used as a baseline to represent the current operation. Dynamic route structure was used to represent the new operational concept of research interest. In static route structure operation, aircraft have to be vectored out from their assigned route in order to avoid the weather that is impacting the route as shown in Figure 4-10. In dynamic route structure operation, the standard routes can be shifted to avoid the weather. The way points on the weather impacted route are selected and placed at new positions to shift the standard route. Thus, aircraft who have been assigned to that modified route can continuously fly on that route while avoiding the convective weather area(Figure 4-11).

The traffic level, represented by the number of aircraft, had been identified as the primary driver for controllers’ cognitive complexity in many ATC complexity researches (Hilburn, 2004). The impact of structure type might be influenced by the traffic level. A pilot study had been performed to set the load for each traffic level. During the pilot study, the performance of participants remained constant from 8 to 20 aircraft per hour, degraded gradually around 35 aircraft per hour, and then declined sharply starting from 50 aircraft per hour. Three traffic levels were set as 20, 35, and 50 aircraft per hour to analyze the controller performance in the medium to high workload range.

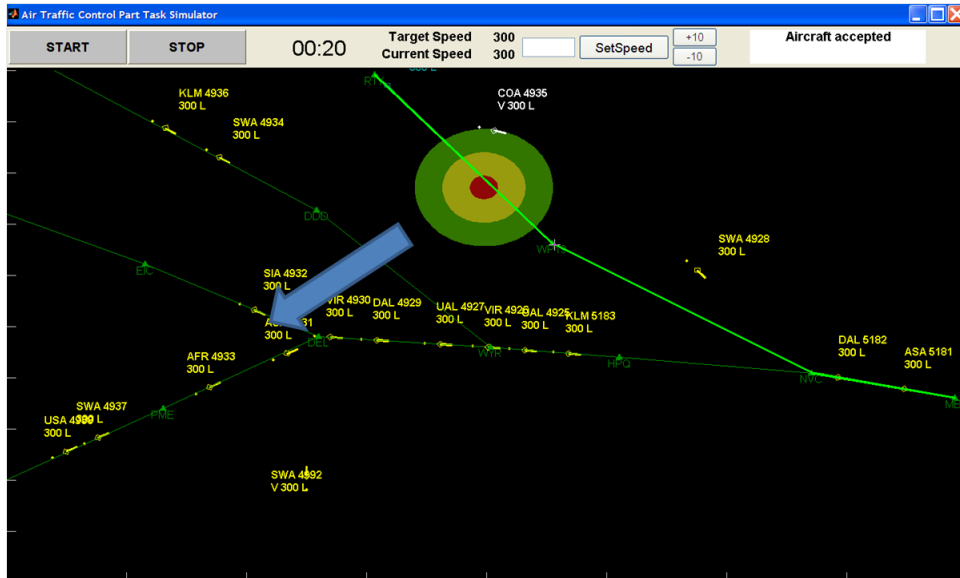


Figure 4-10: Main Display in Experiment 2

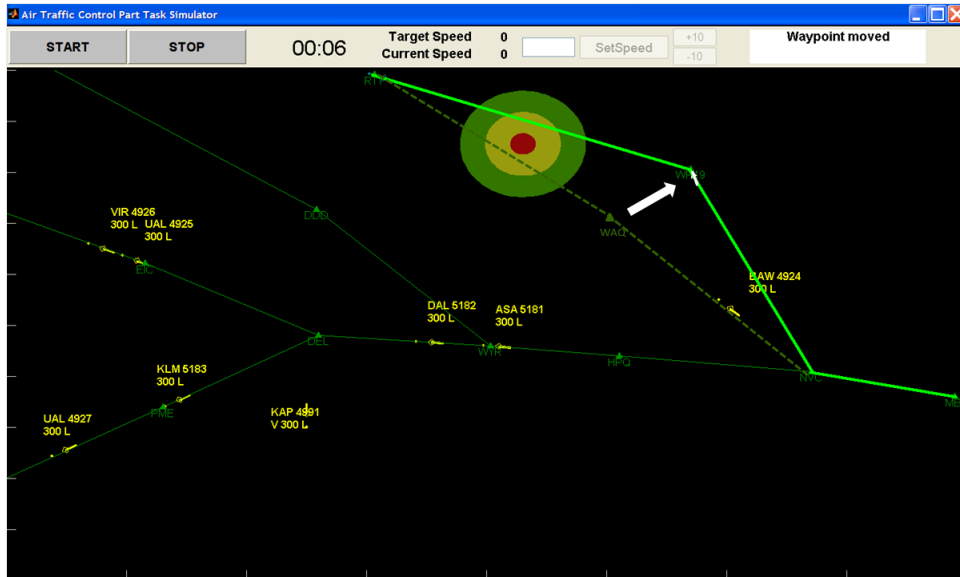


Figure 4-11: Dynamic Route Structure Control Example

4.2.2 Dependent Variables

The impact on controller cognitive complexity was measured by controllers' performance and subjective workload rating. Three dependent variables were used to measure three aspects of controllers' performance: hand-off acceptance time, delivery performance, and operational errors. Reaction time was measured by the hand-off acceptance time, defined as the time between an aircraft entering the airspace and it being acknowledged by controller. The delivery performance was used to measure the efficiency of controllers' performance. Delivery performance was defined as the ratio of the number of successful deliveries (aircraft leaving the airspace from the exit way point) to the number of total possible deliveries in a run. The operational errors included the number of separation violations and the number of weather penetrations. The primary statistical model used for the performance variables was a 2×3 two-way ANOVA with repeated measures.

Controllers' subjective workload was measured using the Air Traffic Workload Input Technique (ATWIT) (Stein, 1985), similar to Experiment 1. Subjective workload was measured in real-time by presenting auditory and visual cues that prompt a participant to press one of seven buttons on the workload assessment keypad (WAK) within a specified amount of time to indicate the amount of mental workload experienced at that moment. Non-parametric statistical tests, Friedman test and Mann-Whitney dependent test, were used for the subjective ratings data analysis.

4.2.3 Apparatus, Participants, and Procedure

Apparatus The human-in-the-loop fast-time simulation in Experiment 1 was expanded to be capable of supporting the dynamic route structure control. The main display of the simulation is shown in Figure 4-10. The simulation set-up was similar to the one in Experiment 1, except that the simulation was accelerated by a factor of 10. The weather was simulated by a constantly moving area with red, yellow and green circle zones. In order to objectively investigate the usage of structure in managing traffic for this experiment, the speed can only be changed within a range of

280 to 320 knots. All the commands were given by using the computer mouse and keyboard.

Participants Twenty nine upper class students (5 female, 24 male) in a CTI program at Daniel Webster College participated in this experiment. All the participants have the similar ATC knowledge background as the participants in Experiment 1.

The experimental tasks were briefed to the participants before the experiment and during the practice runs, and presented to participants on a reminder sheet during the test runs. The tasks included:

1. To maintain separation (3 nmi)
2. To avoid weather penetration
3. To direct arrival traffic to the exit way point
4. To deliver arrival traffic as fast as possible

Procedure A tutorial was first given the participant to explain the nature of the experiment, the context of the interface, and the use of the simulation. Each participant experienced two practice runs and six test runs including all the six conditions in the design matrix. The order of the six test runs was counterbalanced and partially randomized. Half of the participants started with the static route structure, while the other half started with the dynamic route structure. Within each type of structure, the order of traffic levels was randomized.

During testing, all user responses and performance data were recorded automatically. After each test run, the Aircraft Complexity Assessment, was conducted using the a replay function. The replay was paused at five specific times, then the participants were asked to identify high complexity aircraft at that traffic situation. This method did not interact with other parts of the experiment.

4.2.4 Results and Discussion

Controller performance and subjective workload were analyzed and compared by structure types and traffic levels. Statistical analysis of the effects of structure type

and effects of traffic level was performed using three performance measures and the subjective workload ratings.

For all dependent variables, the analysis showed that the effects of traffic level were statistically significant at $\alpha = 0.05$. Performance decreased and subjective workload increased as traffic level increased. The primary research interest, the effects of structure type, did not show statistical significance except for hand-off acceptance time. One explanation for these results could be that the dependent variables were not sensitive enough to show the impact on controller cognitive complexity.

The two-way ANOVA with repeated measures were used to analyze the three performance variables. Statistical assumptions of normality and heteroscedasticity were checked using Levene tests and Shapiro-Wilk tests at significance level of $\alpha = 0.05$. All the parametric dependent variables passed the tests.

Hand-Off Acceptance Time Hand-off acceptance time was the time between an aircraft entering the airspace and it being acknowledged by the controller. Hand-off acceptance time increased with higher level of traffic ($F(2, 50) = 19.88, p < .001$), suggesting that controllers reacted slower as they were busier with higher level of traffic.

Hand-off acceptance time was the only dependent variable to find significance at the $\alpha = 0.05$ level for the structure type factor. Dynamic route structure operation led to a significant increase in hand-off acceptance time ($F(1, 50) = 27.21, p < .001$). This result can be explained by the extra work required by controllers to move routes in the dynamic route structure cases. Apart from the tasks a controller needs to perform in the static route structure cases, he or she had a set of additional tasks in the dynamic route structure cases, such as planning the route structure, modifying the route structure, and managing aircraft already on the route being modified.

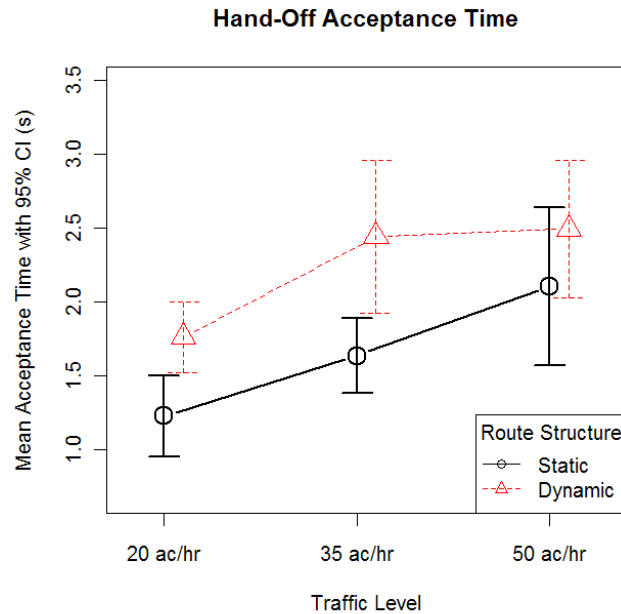


Figure 4-12: Hand-Off Acceptance Time in Experiment 2

Delivery Performance The efficiency of controller performance was measured by the delivery performance, which was defined as the ratio of the number of successful deliveries (aircraft leaving the airspace from the exit way point) to the number of total possible deliveries in a time period. The delivery performance significantly decreased as the traffic increased ($F(2, 50) = 46.69, p < .001$). The effects of structure type on delivery performance were marginally significant ($F(1, 50) = 3.21, p = .085$). While this result is not significant at the $\alpha = 0.05$ level, it does suggest that the use of dynamic route structure may slightly improve the rate at which controllers are able to deliver aircraft.

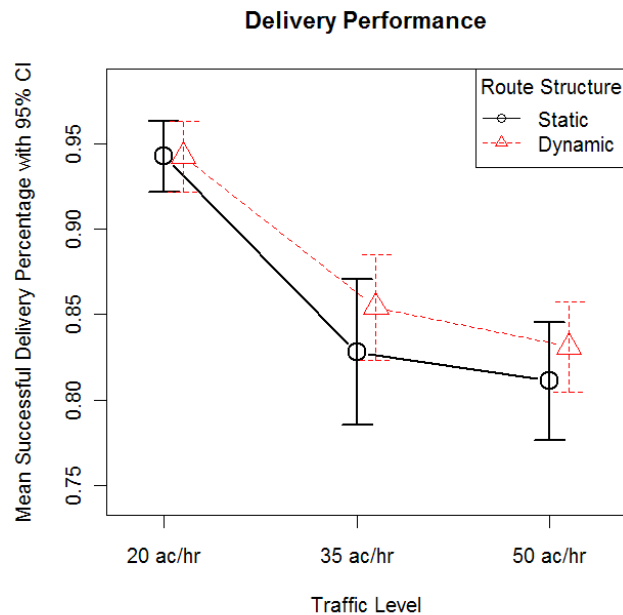


Figure 4-13: Delivery Performance in Experiment 2

Operational Errors The total number of operational errors including separation violations and weather penetrations was significantly affected by the traffic level ($F(2, 50) = 141.71, p < .001$). The total number of errors increased as the traffic level increased. The results were consistent with past literature on the impact of traffic load (for reviews, see Mogford et al., 1995; Majumdar and Ochieng, 2002; Hilburn, 2004; Loft et al., 2007).

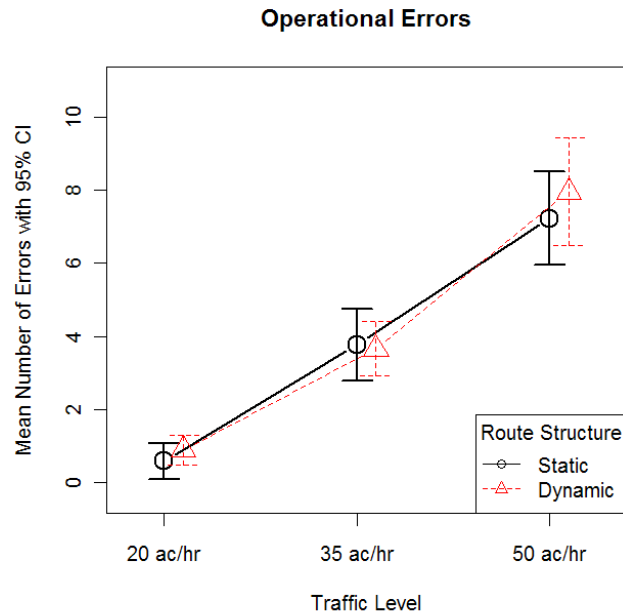


Figure 4-14: Operational Errors in Experiment 2

Structure type was not a significant factor for the number of errors ($F(1, 50) = 0.72, p = .410$). The results suggested that the change from static route structure to dynamic route structure was unlikely to have any significant impact on the controllers error rate.

In addition, different participants performed significantly differently in terms of number of operational errors. The ANOVA results of the subject factor is $F(25, 50) = 2.57, p = .002$. No significant interaction effects were evident in the test results.

Subjective Workload The subjective workload data was measured using a 7-point Likert scale. Non-parametric tests were used to assess the effects of structure type and the effects of traffic level. A Friedman rank test was used to analyze the effects of the three-level factor, traffic level. The test found that traffic level was significant ($\chi^2 = 26.17, p < .001$) in explaining differences in subjective workload. The effects of structure type were analyzed by the Mann-Whitney U test. The result showed that there was no statistically significant difference in mean subjective workload rating due to the type of route structure ($U = 1083.50, p = .454$). It was propitious that no

statistical significance found in this case given that despite dynamic route structure operation being a new concept for the subjects and despite additional tasks being required in the operation, use of this new control mechanism did not adversely affect their perceived workload.

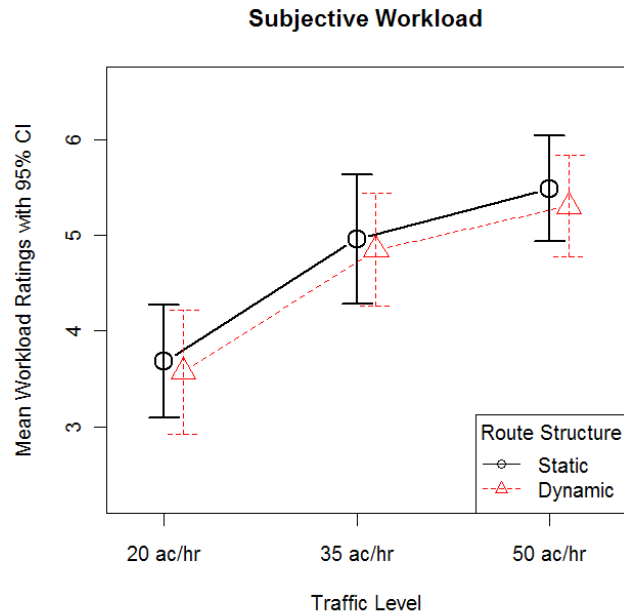


Figure 4-15: Subjective Workload Ratings in Experiment 2

4.2.5 Conclusion of Experiment 2

The purpose of this experiment included an evaluation of the impact of the dynamic route structure operational concept on controller cognitive complexity as measured by controllers' performance and subjective workload. The dynamic route structure was hypothesized to be able to minimize the controllers' cognitive complexity in off-nominal airspace structure conditions such as weather disruptions.

The results of this experiment verified that traffic level was a major driver influencing controllers' performance and subjective workload. The dynamic route structure operation did not introduce significant changes to the operational errors and the subjective ratings. The delivery performance improved slightly in the dynamic route structure operation; however, the hand-off acceptance time increased in dynamic route

structure operation, indicating that extra work was required by participants in the dynamic route structure cases. Participants did not experience significant changes in workload because of the new route structure control mechanism.

In light of the results reported here, it is likely that dynamic route structure operation might help enable continuous use of structure abstractions in airspace structure disruptions like hazardous weather; however, additional controller tasks may also be introduced by the dynamic route structure. Although the controller performance and the subjective workload ratings did not show significant changes, the impact of different operational concepts on controller cognitive complexity existed and was explored using the Aircraft Complexity Assessment method.

4.3 Summary

The impact of future operational concepts on controller performance and subjective complexity ratings have been evaluated through two fast-time simulations. The first experiment, Time-Based Control at a Metering Fix, was designed to investigate the potential impact on controller cognitive complexity of a simple version of 4DT operation. The second experiment, Dynamic Route Structure Control, was designed to explore the proposed operational concepts of flexible route definition and dynamic flow management.

In Experiment 1, a single metering fix with CTA in a sector was facilitated in a simulation to represent a simple version of 4DT operational concept. Enhanced controller performance and lower perceived complexity was demonstrated in the simplified 4DT operational concept. In this operational concept, the expected arrival time at a metering fix of each flight can be specified. As a result, controllers were able to better coordinate the arrival flights to access the capacity-limited airspace. In the second experiment on Dynamic Route Structure control, the controller performance and the subjective workload did not alter significantly by the new operational concept. The dynamic route structure control was hypothesized to reduce controller cognitive complexity in weather disruption conditions through the use of continuous

structure abstractions. However, the results did not indicate significant benefits of Dynamic Route Structure control. In addition, the increase of hand-off acceptance time implied that additional tasks might also be introduced to controllers by the dynamic route structure.

Chapter 5

Empirical Findings on Aircraft Complexity Factors from Aircraft Complexity Assessment

The proposed complexity probe, Aircraft Complexity Assessment, was found to be an effective tool to explore and evaluate the complexity implications of future operational concepts simulated in the two experiments. This complexity probe technique allowed specific aircraft which contributed high complexity load to be identified and then the aircraft complexity factors in the MAC structure were able to be evaluated based on the relationship between observable factors and high complexity aircraft percentage. Four factors were found to impact aircraft specific complexity, including proximity to other aircraft, membership of a standard flow, proximity to weather, and projected proximity to other aircraft.

5.1 Complexity Factor: Proximity to Other Aircraft

The impact of aircraft horizontal proximity on aircraft complexity contribution was analyzed using the data collected in the Aircraft Complexity Assessment method.

Proximity has been commonly accepted as an complexity factor and has been used in some complexity metrics (Chatterji and Sridhar, 2001; Kopardekar et al., 2002; Laudeman et al., 1998; Wyndemere, 1996). However, the proximity used in these metrics is calculated based on certain assumptions of distance criteria. The relationship between the distance between aircraft pairs and the impact on controller cognitive complexity has not been quantitatively examined.

The complexity contribution of an airplane was hypothesized to increase when its distance with other airplanes reduces. The attention to those proximate aircraft pairs would raise for the reason that the flexibility and the time to resolve the potential conflict reduces. The empirical results from the two experiments supported the hypothesis. Only horizontal proximity was analyzed in the study as the experiments only simulated single altitude traffic situations. The percentage of the high complexity aircraft at each criteria distance of proximity is shown in Figure 5-1, 5-2, and 5-3. The high complexity aircraft percentage was calculated by Equation 5.1. The number of airplanes within the range of a proximity criterion distance was counted to be the denominator. Among these airplanes, those considered to contribute high complexity were then recorded to be the numerator.

$$\text{High complexity ac percentage at } x \text{ nmi} = \frac{N_{\text{complex ac within } x \text{ nmi}}}{N_{\text{ac within } x \text{ nmi}}} \quad (5.1)$$

Figure 5-1 is the results by operational concepts in each experiment. Several general trends were indicated in the empirical results of both experiments. The chance of an airplane being considered as high complexity increased when the lateral distance between aircraft pairs became smaller. The percentage of high complexity aircraft was at a relatively high level (above 50%) when the distance was smaller than the separation minima (2.5 nmi in Experiment 1 and 3 nmi in Experiment 2), especially, a significant change happened around the separation requirement (3 nmi) in Experiment 2. In both experiments, the percentage leveled at around 10% to 20% as the distance increased. The 10% to 20% high complexity indicated the existence of complexity factors other than horizontal proximity. The 10% and 20% differences

might be caused by changes in the two experiment set-ups.

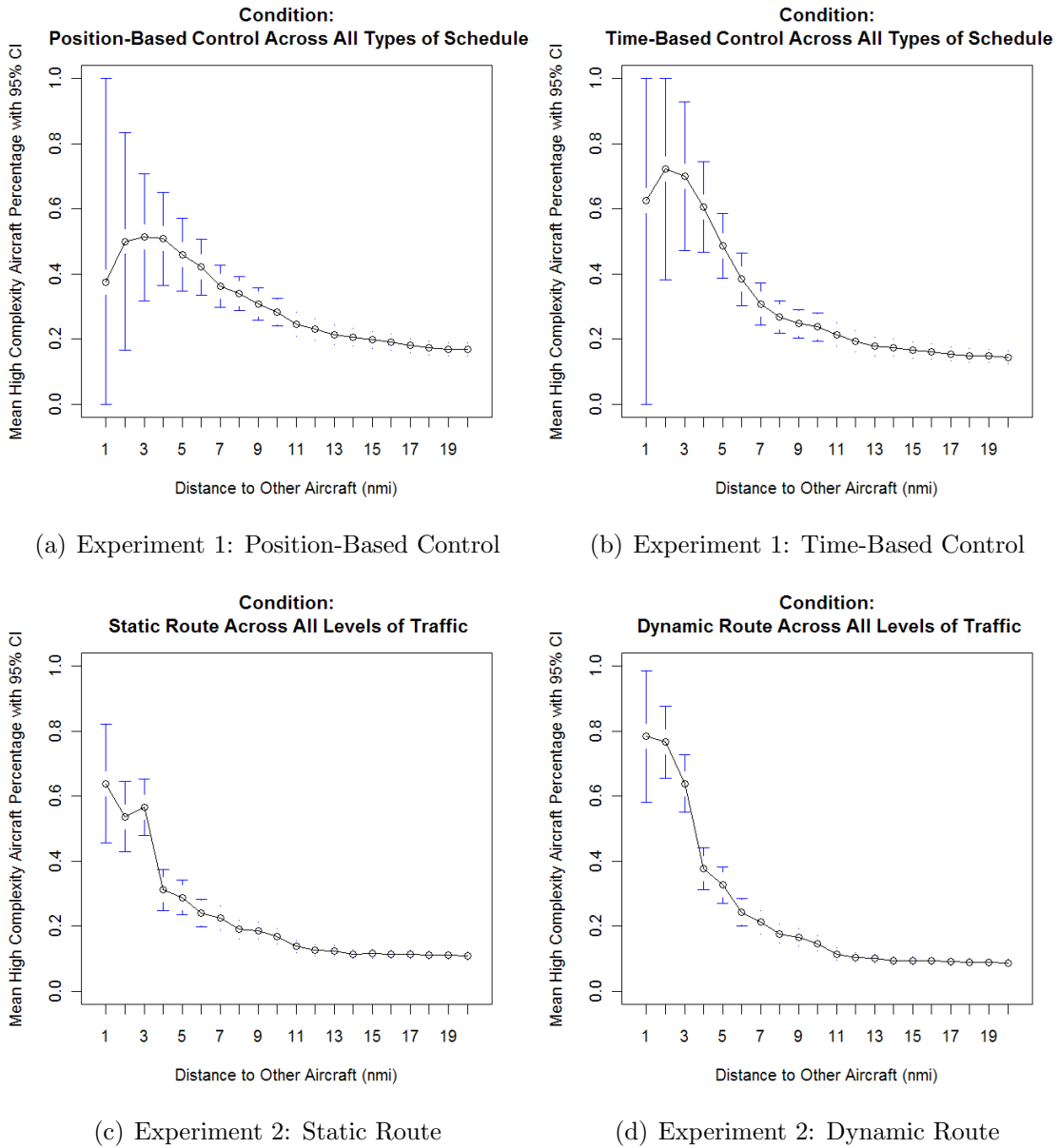
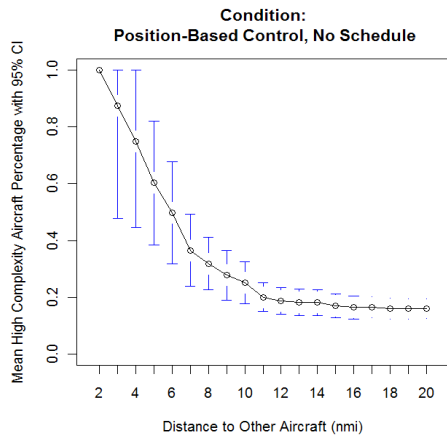
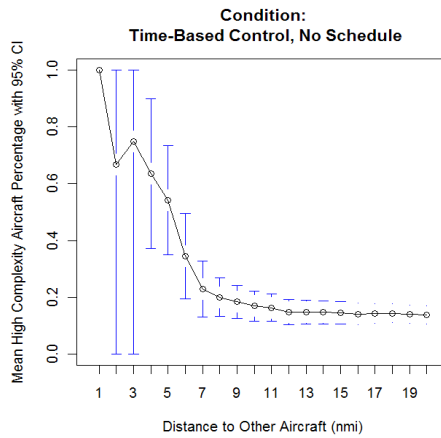


Figure 5-1: High Complexity Aircraft Percentage by Horizontal Distance to Other Aircraft by Different Operational Concepts in Two Experiments

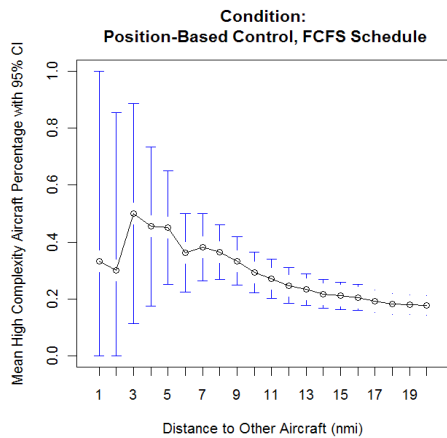
Figure 5-2 shows the results obtained from Experiment 1: Time-Based Control at a Metering Fix by types of operational concept and types of schedule. Figure 5-3 is from Experiment 2: Dynamic Route Structure by different operational concepts and traffic levels. Although the curve differed for different experimental conditions, the general trend remained the same. Four points for the general trend were summarized based on the observation. First, the contribution of cognitive complexity reduced when the distance to other aircraft decreased. Second, as indicated by the large variance of high complexity aircraft percentage in the 1 to 2 nautical miles range, controller strategy varied when the distance is smaller than the minimum separation requirement. Some participants gave up to solve the conflicts when the distance was too small. Third, traffic load affected controllers' strategy as shown in Figure 5-3. The average high complexity aircraft curves dropped down sooner when traffic level was high. This indicated that the controllers tended to pay more attention to near term problems as they had less mental capacity to project future situations in higher traffic load situation. Fourth, there were other factors contributing to cognitive complexity. The average high complexity aircraft percentage approached around 15% as distance increased to ∞ . Apart from the observations stated above, the detailed shape and value of the percentage curves might be affected by the simulation set-up, such as screen size, screen resolution, and aircraft target size, etc., nevertheless the general trend and the conclusion drawn should remain the same.



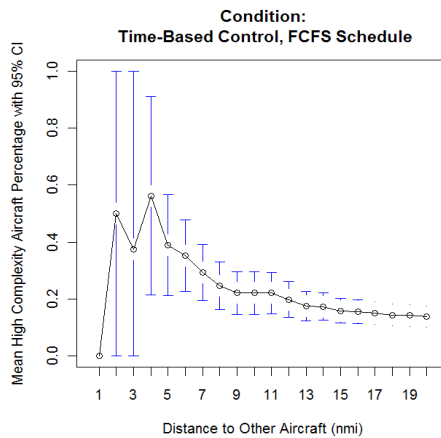
(a)



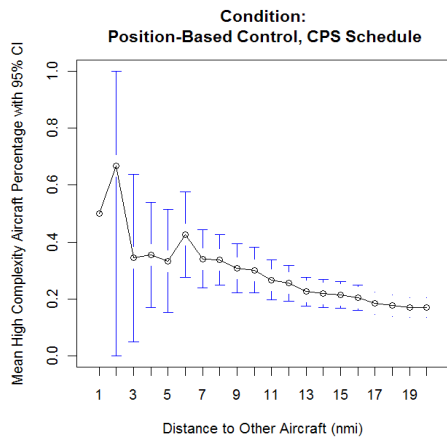
(b)



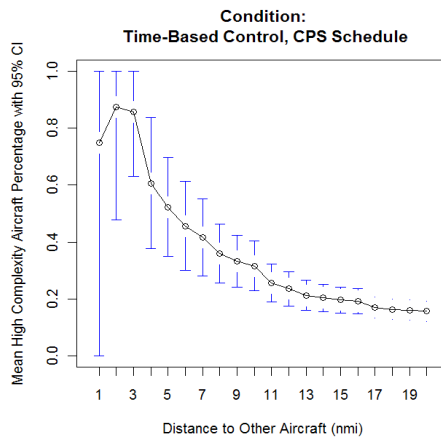
(c)



(d)

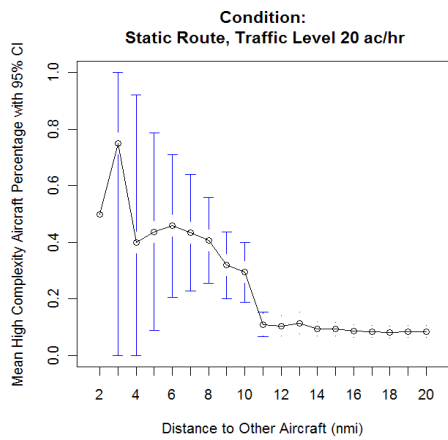


(e)

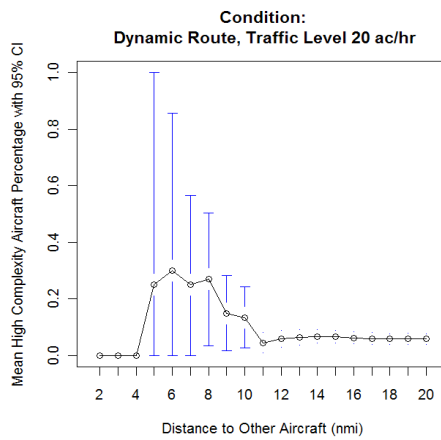


(f)

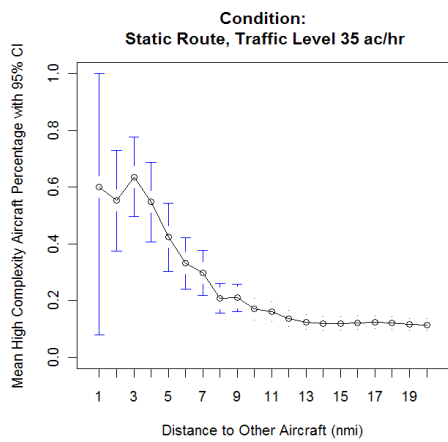
Figure 5-2: The Impact of Horizontal Proximity on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix



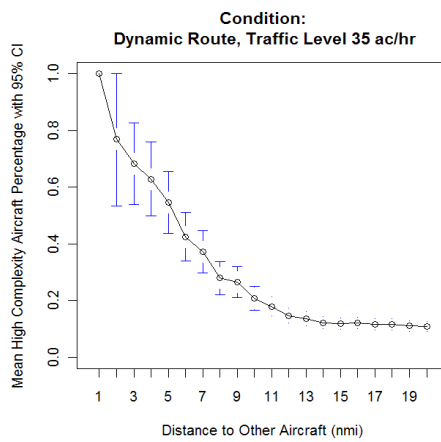
(a)



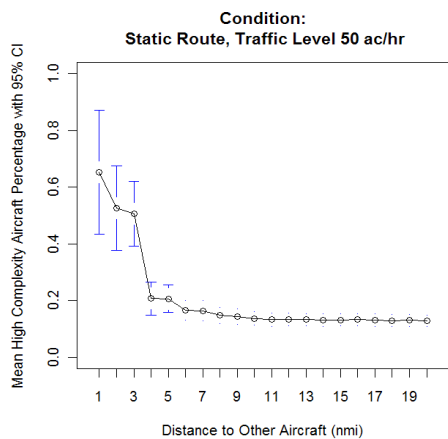
(b)



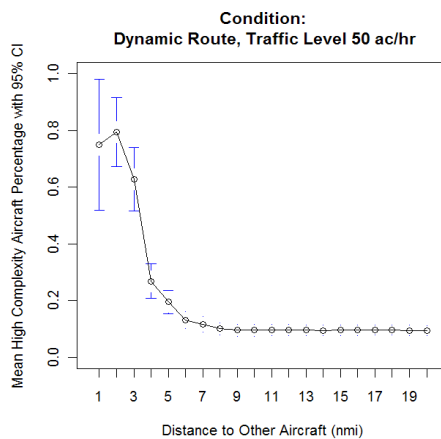
(c)



(d)



(e)



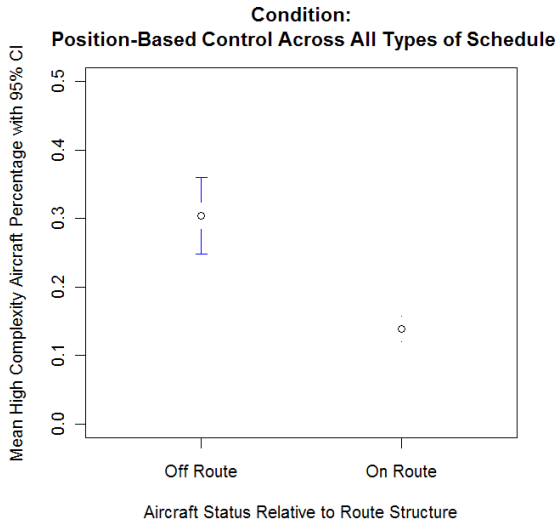
(f)

Figure 5-3: The Impact of Horizontal Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control

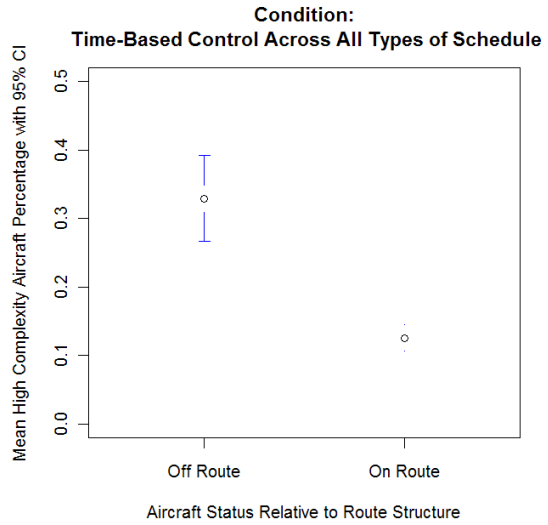
5.2 Complexity Factor: Membership of a Standard Flow

The underlying airspace structures had also been proposed as an important factor affecting controllers' cognitive complexity. The underlying airspace structure and other procedural elements are important factors in reducing a controller's cognitive complexity through the use of structure based abstractions (Histon and Hansman, 2002; Seamster et al., 1993). Histon and Hansman (2002) find that standard flows are one of the most important structure-based abstractions based on field observations. Air traffic controllers classify aircraft into standard and nonstandard classes according to their match with standard flows, which include the aircraft's future routing, ingress and egress points, coordination requirements, and crossing routes/altitude profiles (Histon and Hansman, 2002; Seamster et al., 1993). Loft et al. (2007) conclude that establishing streams simplifies the process of maintaining situation awareness, allowing air traffic controllers to work with more aircraft simultaneously and to use fewer control actions.

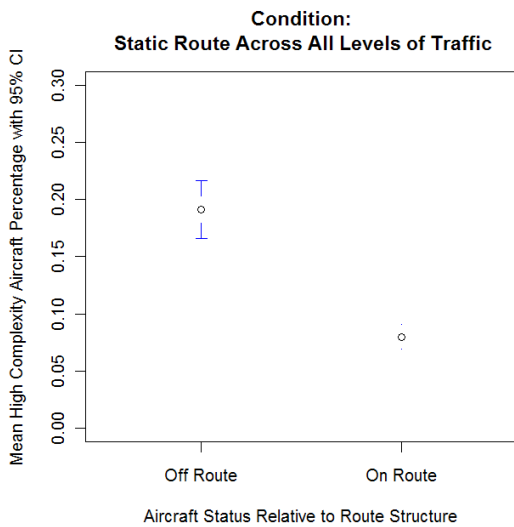
In this study, the results from the analysis of the impact of route structure on aircraft high complexity percentage supported the hypotheses on the use of structure in simplifying the cognitive complexity of air traffic control. In the analysis of the two experiments, whether an aircraft belonged to a standard flow or not were determined based its relative position to the standard route structure. If an aircraft was within 2 nautical miles of the standard routes and was flying along the routes, it was considered as an aircraft belonging to a standard flow, in other words, an on-route aircraft. Otherwise, it was an off-route aircraft. Figure 5-4 shows that off-route aircraft were more likely to be considered as of high complexity than on-route aircraft in both experiments. Statistical significance was validated using the student t-test to compare the difference between the on-route the off-route high-complexity aircraft percentage ($\alpha = 0.05$). The test results for the first experiment was ($t(425) = 8.28, p < .001$), while for the second experiment was ($t(1383) = 10.01, p < .001$). The results suggested that the abstracted underlying structures facilitated the process of simplifying



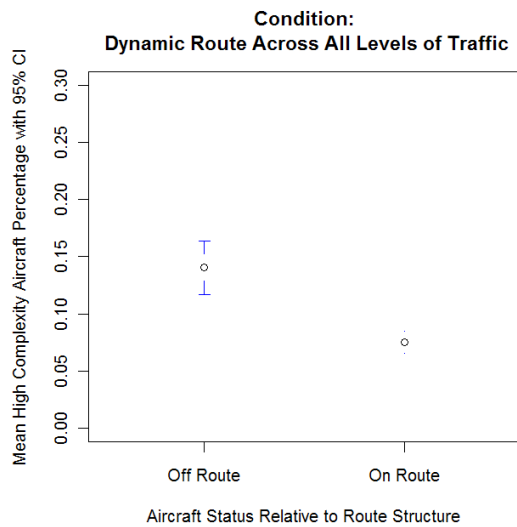
(a) Experiment 1: Position-Based Control



(b) Experiment 1: Time-Based Control



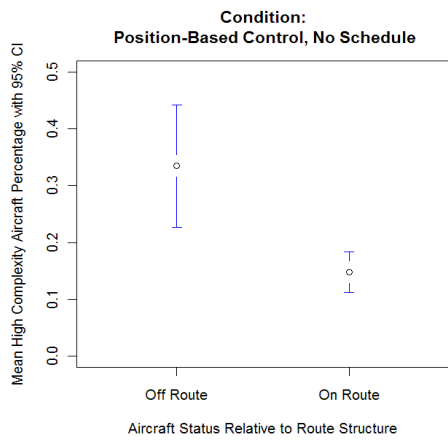
(c) Experiment 2: Static Route



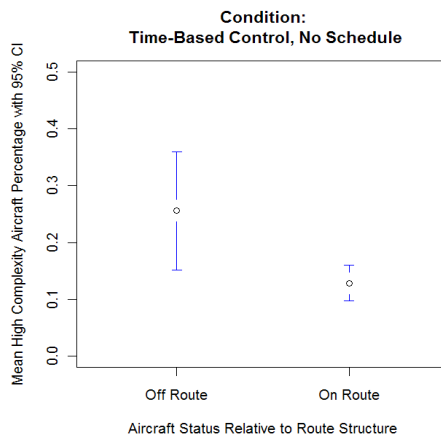
(d) Experiment 2: Dynamic Route

Figure 5-4: High Complexity Aircraft Percentage by Relative Position to Route Structure by Different Operational Concepts in Two Experiments

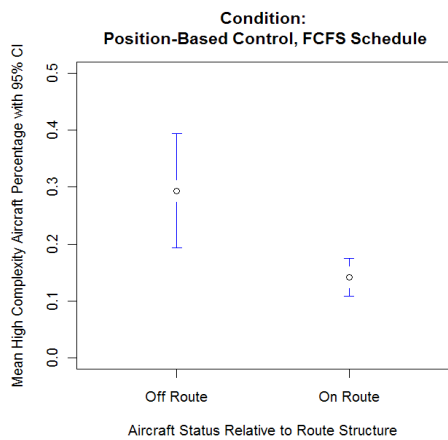
and understanding traffic pattern for experiment participants. When an airplane was off the standard route, it had a higher potential to be considered as an airplane contributing higher level of complexity. Figure 5-5 and Figure 5-6 show the results by experimental conditions in each experiment. As seen, similar effects of route structure were observed in all conditions. In Experiment 1, the control type (Position-Based Control and Time-Based Control) did not affect the structure influence on complexity, while in Experiment 2, the structure type (Static Route Structure and Dynamic Route Structure) slightly changed the impact of route structure on complexity. The average percentage of high complexity aircraft for off-route aircraft was lower in Dynamic Route conditions than in Static Route conditions. This indicated that the route structure played a more important role in cognitive complexity when the routes were static than when the routes were dynamic.



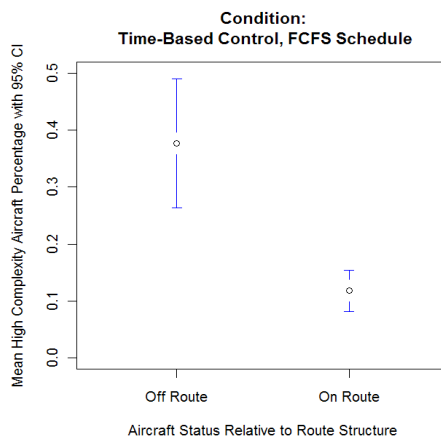
(a)



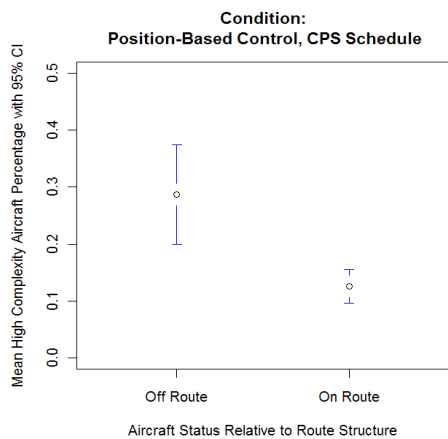
(b)



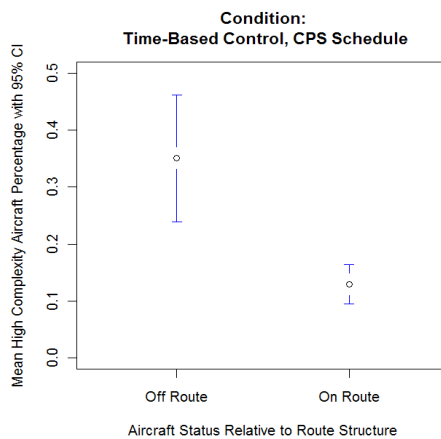
(c)



(d)

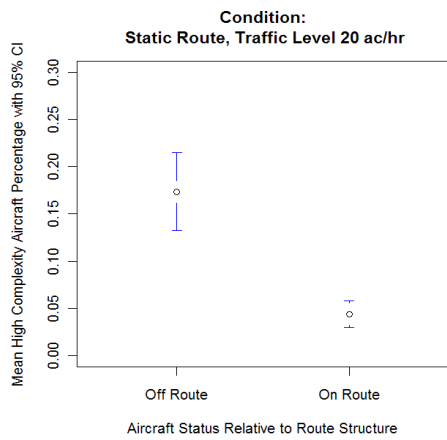


(e)

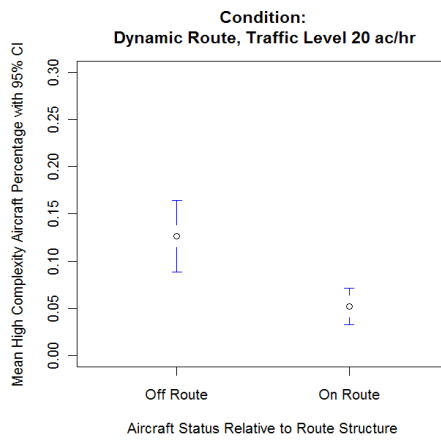


(f)

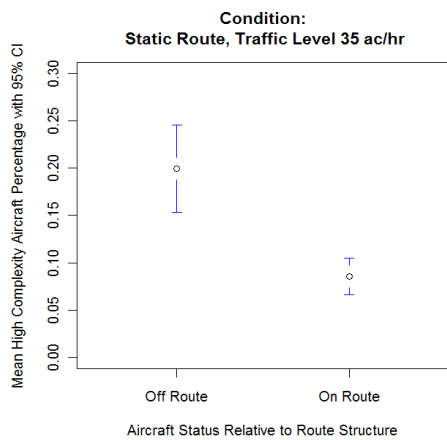
Figure 5-5: The Impact of Route Structure on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix



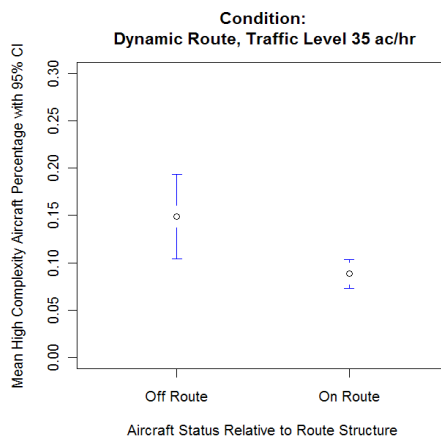
(a)



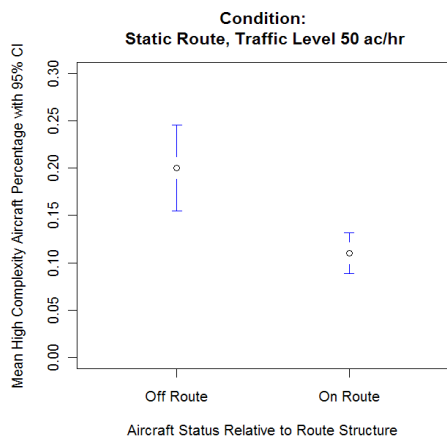
(b)



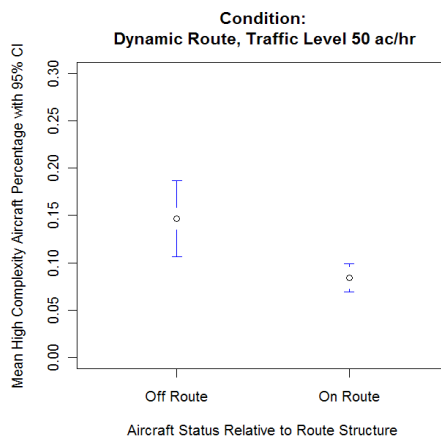
(c)



(d)



(e)

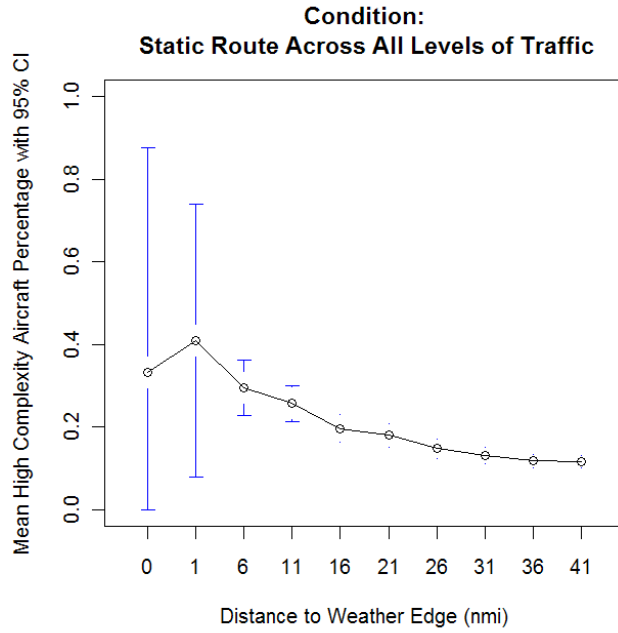


(f)

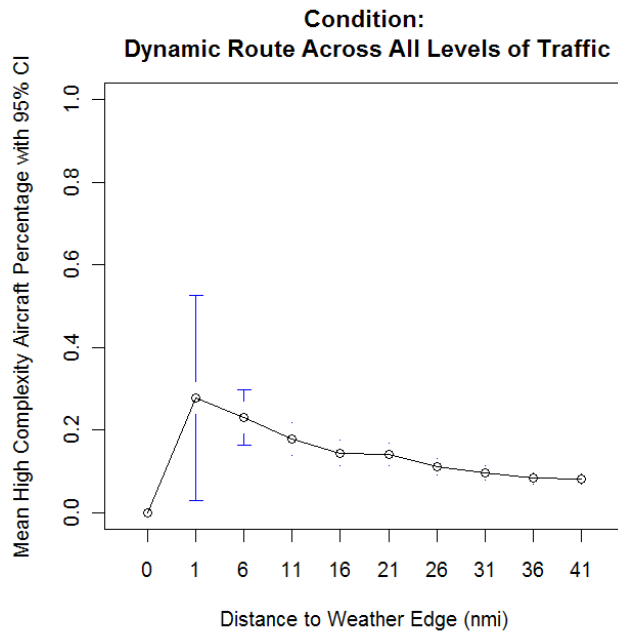
Figure 5-6: The Impact of Route Structure on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control

5.3 Complexity Factor: Weather Impacting Area Encounters

The complexity factor, Weather Impacting Area Encounters, can be measured by various observable factors, such as the distance from an aircraft to the edge of the weather impacting area, the time for an aircraft to fly into the weather impacting area, and the relationship between the heading of an aircraft and the shape of weather. The distance from an aircraft to the edge of the weather impacting area was analyzed to be consistent with the aircraft proximity factor. Figure 5-7 and 5-8) show a similar trend of the proximity of aircraft to convective weather area to the aircraft proximity. An aircraft was more likely to contribute high complexity when it was near a convective weather area. However, it might no longer be considered as a high complexity aircraft after it entered the convective weather area, as seen from the drops of the high complexity percentage when the distance to weather edge was around 1 nautical mile. This can be explained by the fact that controllers had different strategies for aircraft that already penetrated weather and aircraft that attempted to avoid weather penetration. The cognitive complexity was high when participants tried to control an aircraft to avoid the weather impact, however, the complexity might decreased when the aircraft entered the weather impacting area since strategies were adjusted to better meet the needs of that aircraft and the requirements of maintaining safety for the overall situation.

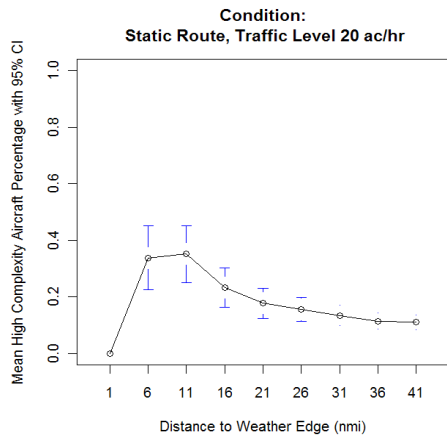


(a) Experiment 2: Static Route

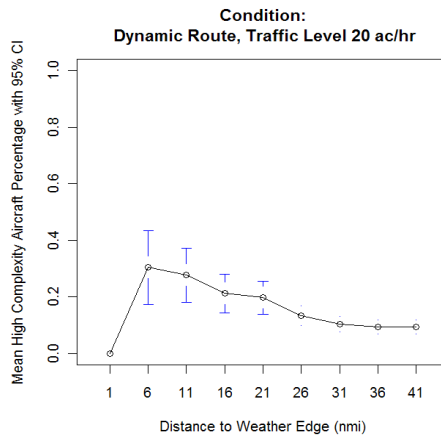


(b) Experiment 2: Dynamic Route

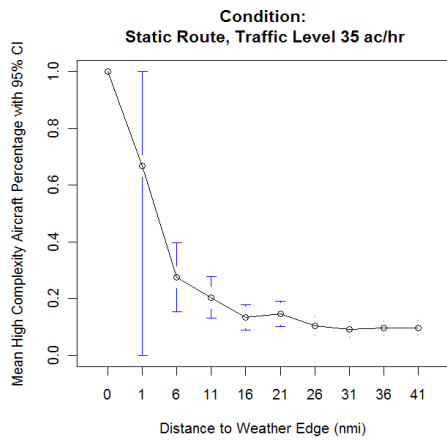
Figure 5-7: High Complexity Aircraft Percentage by Distance to Weather by Different Operational Concepts in Experiment 2



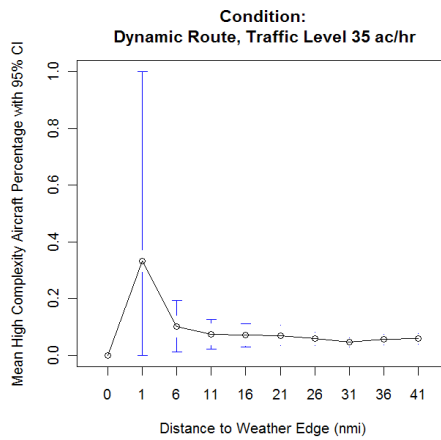
(a)



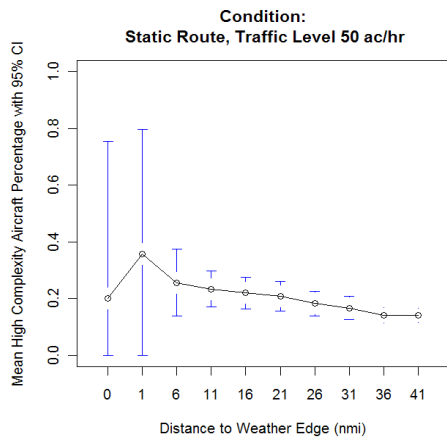
(b)



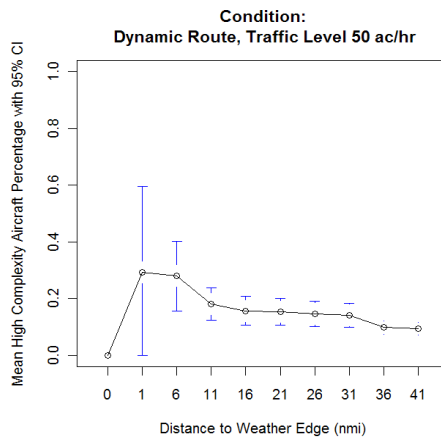
(c)



(d)



(e)



(f)

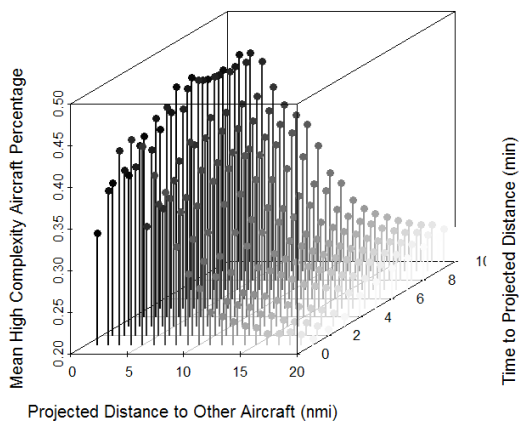
Figure 5-8: The Impact of Weather Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Route Structure Control

5.4 Complexity Factor: Projected Proximity to Other Aircraft

Controller cognitive complexity was also hypothesized to be affected by the projected air traffic situation as in the mental process model proposed in (Pawlak et al., 1996). The projection of aircraft horizontal proximity is an important part in the monitoring process. Pawlak et al. (1996) state that monitoring is one of the processes which involve checking the conformance of the current and projected air traffic situations against those expected based on the controller's current plan.

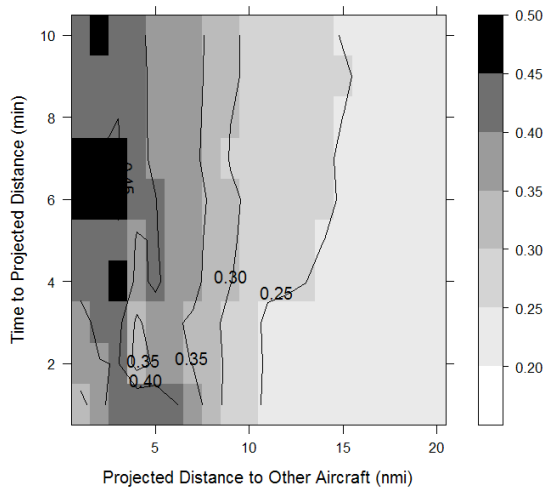
In this study, projected proximity was measured by projected nearest distance and the time to the projected nearest distance. Nearest projected distance was defined as the smallest distance between an aircraft pair in the future based on their current flight plan and speed. The time to the projected nearest distance was defined as the time in the future estimated to reach that distance for an aircraft pair. The impact of projected proximity on cognitive complexity was found to be affected by both the distance of projected proximity and the time to projected proximity. The results indicated that the chance of an airplane to be high complexity was higher when the projected smallest distance to other aircraft was small and the time to the projected proximity was short. The analysis by operational concepts in each of the two experiments is shown in Figure 5-9 and 5-10.

Condition:
Position-Based Control Across All Types of Schedule



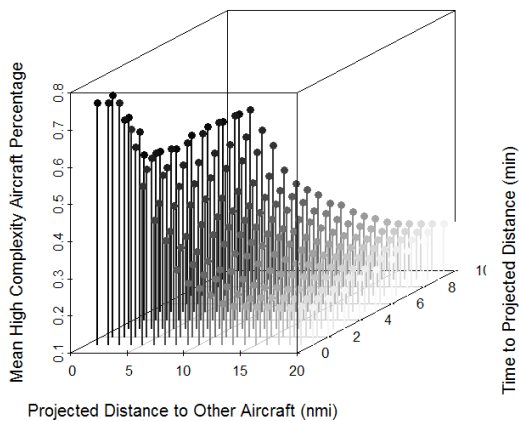
(a) Position-Based Control

Mean High Complexity Aircraft Percentage



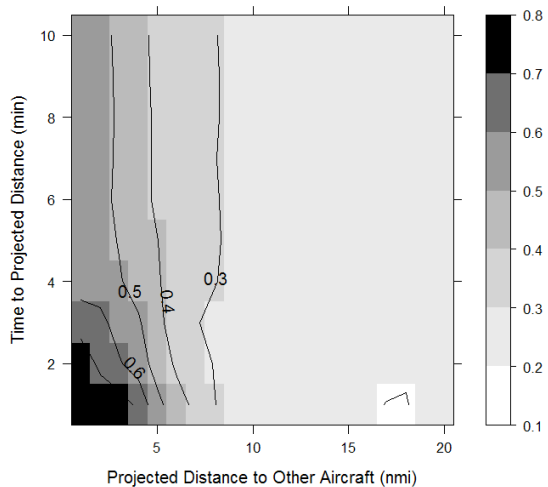
(b) Position-Based Control

Condition:
Time-Based Control Across All Types of Schedule



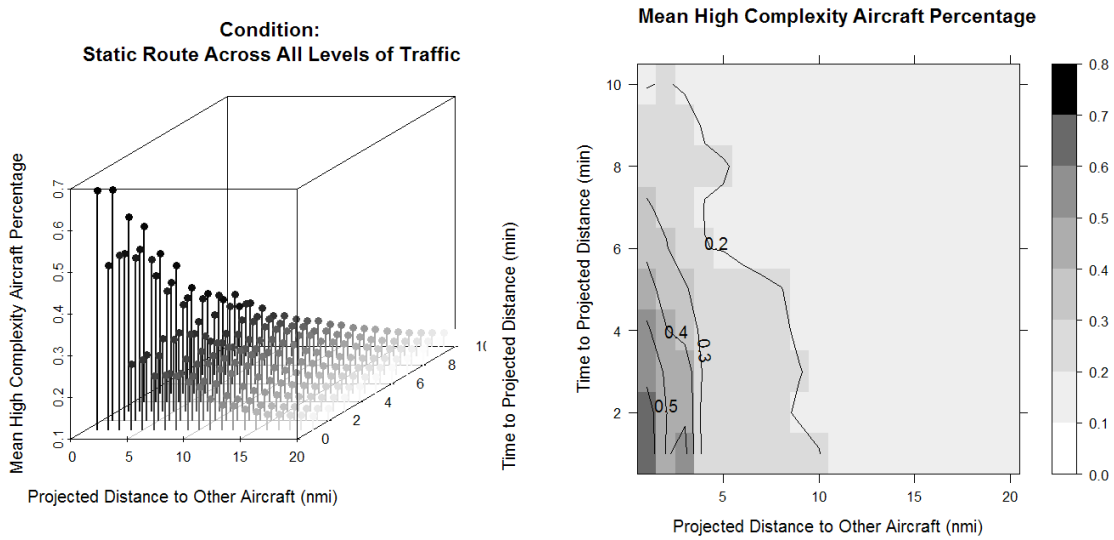
(c) Time-Based Control

Mean High Complexity Aircraft Percentage



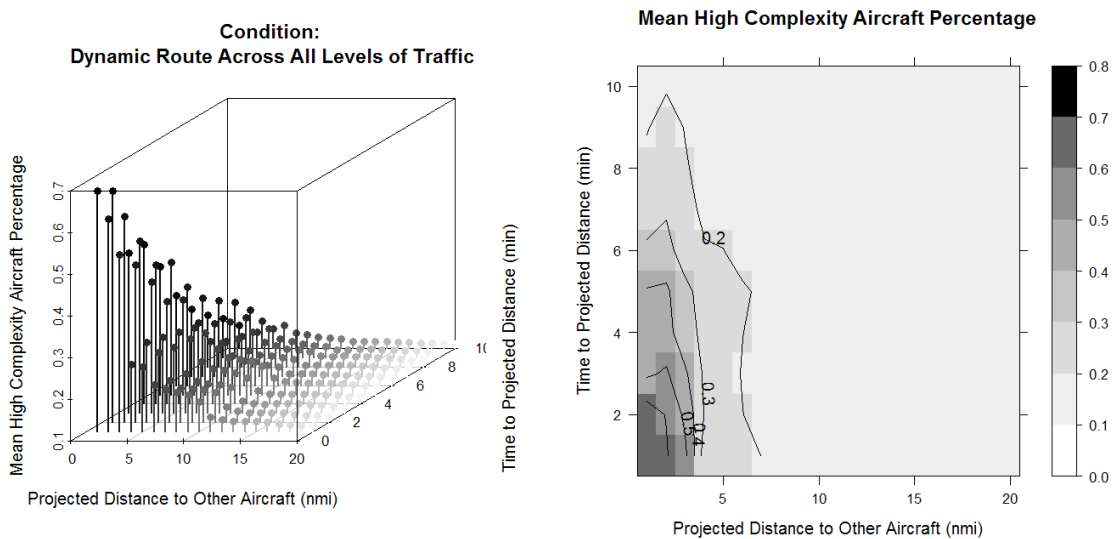
(d) Time-Based Control

Figure 5-9: The Impact of Projected Distance and Projected Time on High Complexity Aircraft Percentage by Different Operational Concepts in Experiment 1: Time-based Control at a Metering Fix



(a) Static Route

(b) Static Route



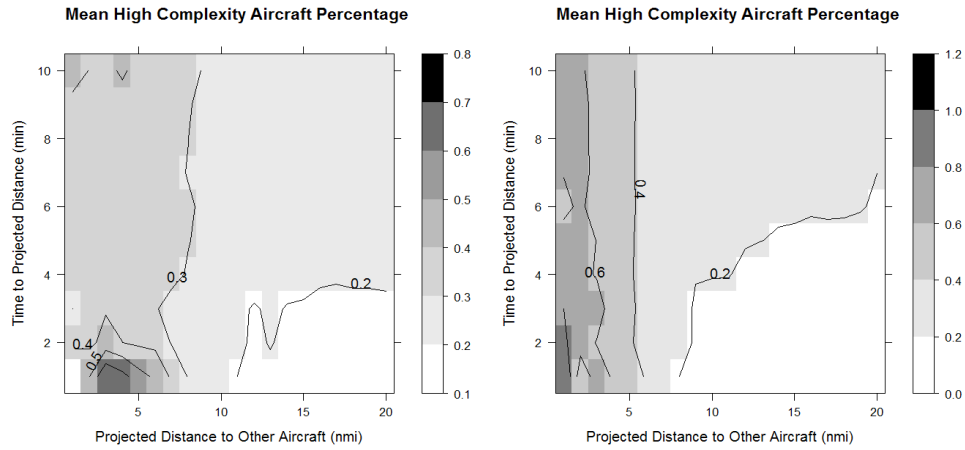
(c) Dynamic Route

(d) Dynamic Route

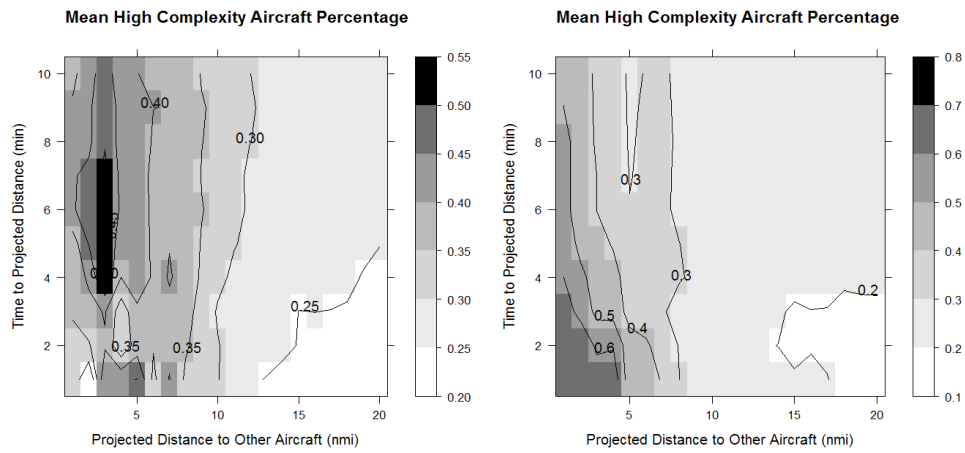
Figure 5-10: The Impact of Projected Distance and Projected Time on High Complexity Aircraft Percentage by Different Operational Concepts in Experiment 2: Dynamic Route Structure Control

In Experiment 1, the trends of high complexity aircraft by the time to the projected nearest distance were different in Position-Based Control and Time-Based Control as shown in Figure 5-9 and 5-11. The peak of high complexity aircraft percent was located around 6 to 7 minutes in the future in Position-Based Control, while the peak was located around 1 to 2 minutes in the future in Time-Based Control. The difference in time indicated that controller strategies were altered by the simulated operational concepts. In Time-Based Control, the time-of-arrival at the metering fix can be controlled precisely. Thus, participants needed to manage immediately potential conflicts caused by automated speed adjustments. On the other hand, in Position-Based Control, the projection of future states were performed by human. As a result, a larger time range was considered by participants. The potential conflicts that were in the very near future were sometimes given up by the participants because the aircraft symbols would overlap in the simulation, which made it difficult to solve the conflicts.

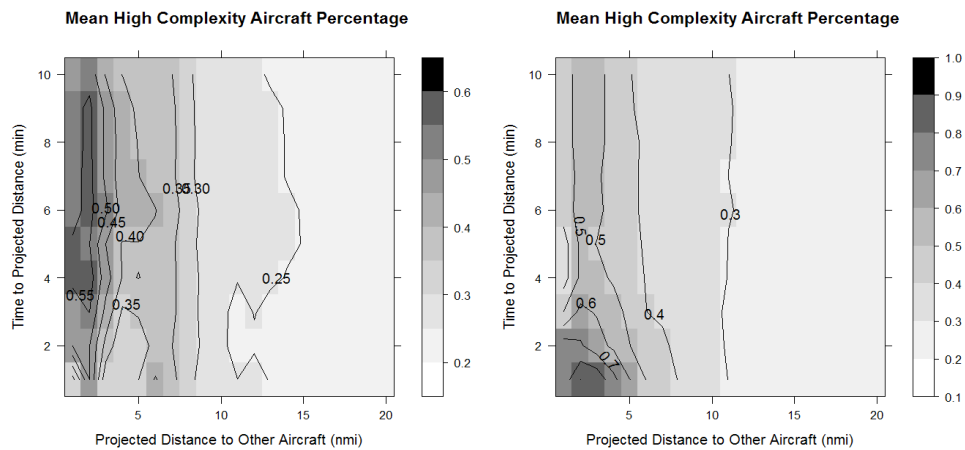
Results from Experiment 2 are shown in Figure 5-10 and 5-12. The blank range at left bottom of Figure 5-12-(b) was because that no potential conflicts were found under that criteria. Apart from that, all other result was consistent in indicating that high complexity was caused by potential conflicted in the near future and with a greater possibility (less distance). Along the projected proximity distance axis, the high complexity aircraft percentage decreased with the increase of distance. A sharp decrease in the high complexity aircraft percentage happened when the distance was around 5 to 10 nautical miles. Along the projected time axis, the aircraft high complexity percentage declined as the projected time increased. This results indicated that the uncertainty of future situations grew with the increase of time. However, differences in high complexity aircraft percentage map were shown by different traffic loads in Figure 5-12. The peaks of high complexity aircraft percentage area were smaller and were compressed to the bottom left of the color map in higher traffic load conditions. This could be explained by the impact of traffic load on controller strategies. When the traffic load was high, the attention was more focused on the potential conflicts in the near future and with less separation distance.



(a) Position-Based Control, No Schedule (b) Time-Based Control, No Schedule

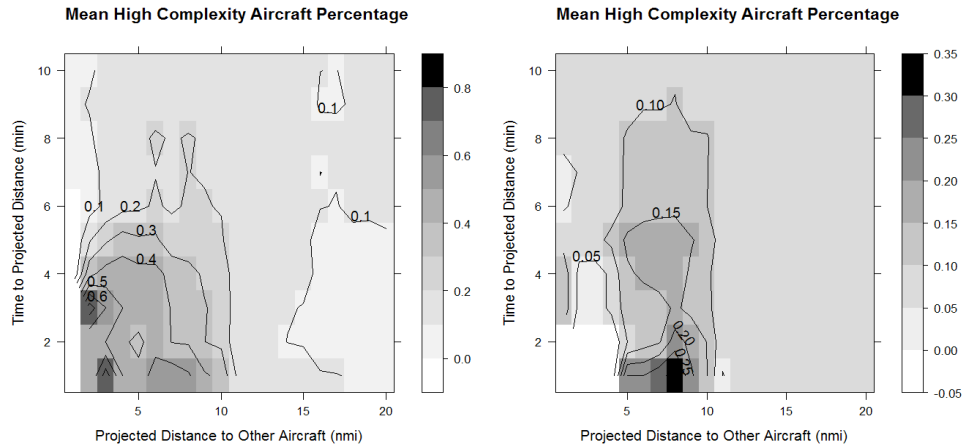


(c) Position-Based Control, FCFS Schedule (d) Time-Based Control, FCFS Schedule

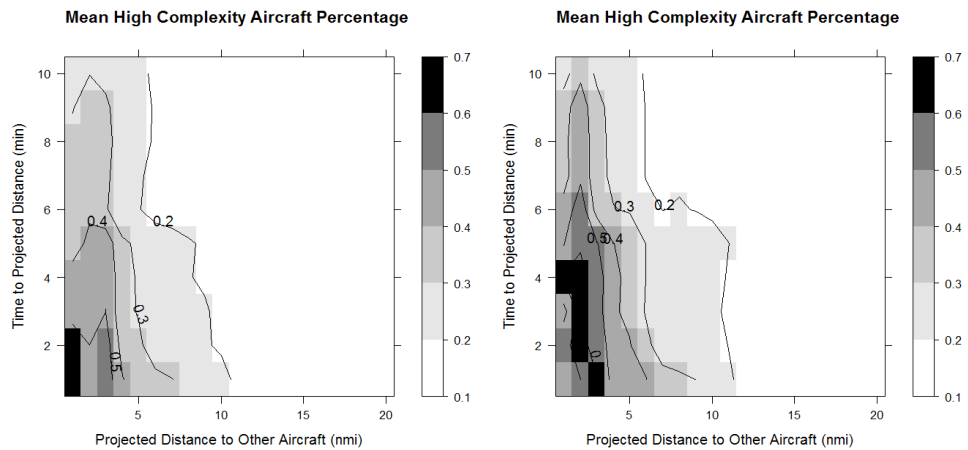


(e) Position-Based Control, CPS Schedule (f) Time-Based Control, CPS Schedule

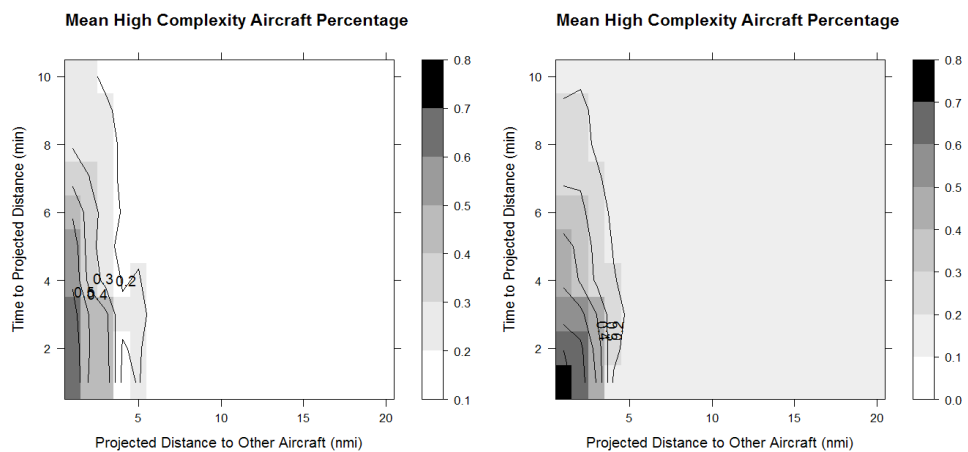
Figure 5-11: The Impact of Projected Proximity on Aircraft Complexity by Operation Types and Schedule Types in Experiment 1: Time-Based Control at a Metering Fix



(a) Static Route: Traffic Level 20 ac/hr (b) Dynamic Route: Traffic Level 20 ac/hr



(c) Static Route: Traffic Level 35 ac/hr (d) Dynamic Route: Traffic Level 35 ac/hr



(e) Static Route: Traffic Level 50 ac/hr (f) Dynamic Route: Traffic Level 50 ac/hr

Figure 5-12: The Impact of Projected Proximity on Aircraft Complexity by Operation Types and Traffic Levels in Experiment 2: Dynamic Rout Structure Control

5.5 Summary

The results from a new complexity probe method, Aircraft Complexity Assessment method, was analyzed to investigate proposed aircraft complexity factors. Observable factors which were hypothesized to drive complexity were tested based on the information associated with the identified high complexity aircraft. Cognitive complexity were quantitatively evaluated by measuring statistical relationships between observable factors and the high complexity aircraft percentage. The probability of an individual aircraft being considered as a high complexity aircraft was found to be significantly affected by several observable situation factors, including proximity to other aircraft, whether the aircraft is on the standard route structure or not, proximity to weather, and projected proximity to other aircraft. The results on proximity to other aircraft testified that the new complexity probe method was an effective tool to investigate aircraft complexity factors. The findings on membership of a standard flow supported the hypothesis proposed in (Histon and Hansman, 2002) on controllers' use of structure based abstractions to mitigate cognitive complexity.

Chapter 6

Conclusion

6.1 Thesis Summary

It was the objective of this study to develop structures for ATC complexity metrics which include cognitive considerations and investigate complexity factors in the metrics. The metrics should reflect the cognitive strategies expected to be used by controllers in future operational concepts. A structure for cognitively based complexity metrics, Modified Aircraft Count (MAC), was developed with the objectives of to be robust against different operational concepts and to provide metrics with intuitive meanings. The MAC includes aircraft specific state information, sector information, as well as information on controller strategies. The basic idea of the MAC structure is that the overall complexity level of a traffic situation is determined by each aircraft's complexity contribution and adjusted by several sector level complexity factors.

In order to explore and investigate aircraft complexity factors in MAC under NextGen operational concepts, two experiments were designed and conducted to understand how the tasks, tools and cognitive strategies change for air traffic controllers in future ATC systems. Two fast-time simulations were developed to represent key elements of two future operational concepts. Experiment 1, Time-Based Control at a Metering Fix, was designed to investigate the potential impact on controller cognitive complexity of a simple version of 4DT operation. Experiment 2, Dynamic Route Structure Control, was designed to explore the proposed operational concepts

of flexible route definition and dynamic flow management in NextGen.

Controller performance and subjective workload were measured in the two experiments. In Experiment 1: Time-Based Control at a Metering Fix, a simple version of 4DT operational concept demonstrated enhanced controller performance and lower perceived complexity comparing to a baseline condition representing current operation. Lower error rate and better schedule conformance were found in Time-Based Control than in the baseline condition. The specificity of expected time at a metering fix helped controllers to synchronize access to capacity-limited airspace and ensure separation. In Experiment 2: Dynamic Route Structure Control, the dynamic route structure operation did not result significant changes to the operation errors and subjective workload compared to the static route structure operation. Although the dynamic route operational concept might help controllers to use a continuous structure abstraction during weather disruptions, additional tasks might also be introduced by the management of dynamic routes. The results in this experiment indicated that traffic level was a major factor influencing controllers' performance and subjective workload.

A new complexity probe technique, Aircraft Complexity Assessment, was proposed and applied in the two experiments to assess aircraft specific complexity. In this complexity probe, participants were asked to identify high complexity aircraft from the screen shot of a traffic situation they had experienced. The information of identified high complexity aircraft was then used to quantify the effects of aircraft complexity factors, including proximity to other aircraft, membership of a standard flow, proximity to weather, and projected proximity to other aircraft. Observable factors which were hypothesized to drive complexity were tested in the following manner. The relationships between observable factors and the percentage of aircraft been considered as high complexity by controllers were analyzed to test the impact on cognitive complexity of that observable factor. The observable factors used in the analysis were horizontal distance to other aircraft, whether an aircraft is on route structure or not, horizontal distance to weather, and projected horizontal distance and time to other aircraft. The results from the impact of route structure on cognitive

complexity supported the hypothesis on controllers' use of structure-based abstractions in simplifying cognitive complexity proposed in (Histon and Hansman, 2002). The new complexity probe method showed to be effective to study the functions of aircraft complexity factors in MAC. The principle of the behavior of each complexity factor were similar in different operational concepts. The chance of an aircraft being considered as of high complexity increased if it was closer to another aircraft, off the standard route structure, closer to the area impacted by weather, or likely to have a conflict in the future. However, the impact on cognitive complexity of each complexity factor was shifted by different controller strategies used in different traffic situations. Both different operational concepts and different levels of traffic load were observed to have effects on the changes of controller strategies.

6.2 Conclusion

The ultimate objective of this work was to develop metrics of ATC cognitive complexity which will be applicable to NextGen operational concepts. New technologies and operational concepts will change the role and tasks of air traffic controllers but cognitive complexity will continue to be a limiting factor on system capacity. Well grounded complexity metrics would be an effective tool both for evaluating trade offs in future operational concepts but also managing cognitive complexity in future ATC systems where complexity may be one of the target or limit parameters in the control strategies.

The structure for cognitive complexity metrics, Modified Aircraft Count, was proposed to capture aircraft specific information, sector state information, and information on controller strategies. Major challenges for MAC are to formulate the impact of each proposed complexity factors and to quantify the value of the Aircraft Multipliers and Sector Multipliers. The new complexity probe technique, Aircraft Complexity Assessment was designed to investigate aircraft specific complexity. The complexity probe was applied in two experiments which simulated two future operational concepts. The Aircraft Complexity Assessment appeared to be an effective complex-

ity probe technique to retrieve information on aircraft specific complexity factors. The results from Aircraft Complexity Assessment indicated that the impact of several complexity factors were consistent in different operational concepts. Therefore, complexity metrics based on cognitive principles should be applicable to different operational concepts.

In addition, the hypothesis in (Histon and Hansman, 2002) on controllers' use of structure-based abstractions to simplify cognitive complexity was supported by the findings on the complexity factor of route structure. The high complexity aircraft percentage was different between on-route aircraft and off-route aircraft in both future operations and current operations. Hence, it is important to consider what the changes of structure will be in future ATC system, whether the changes can support controllers tasks without introducing additional cognitive complexity.

References

- Arad, B. A. (1964). The control load and sector design. *Journal of Air Traffic Control*, 12:12–31.
- Athenes, S., Averty, P., Puechmorel, S., Delahaye, D., and Collet, C. (2002). ATC complexity and controller workload: Trying to bridge the gap. In *Proceedings of the International Conference on HCI in Aeronautics*, pages 56–60.
- Averty, P., Athenes, S., Collet, C., and Dittmar, A. (2002). Evaluating a new index of mental workload in real ATC situation using psychophysiological measures. In *Digital Avionics Systems Conference, 2002. Proceedings. The 21st*, volume 2, pages 7A4-1–7A4-13 vol.2.
- Buckley, E. P., O’Connor, W. F., Beebe, T., Adams, W., and MacDonald, G. (1969). A comparative analysis of individual and system performance indices for the air traffic control system. Technical Report NA-69-40, Federal Aviation Administration, Atlantic City, NJ.
- Chatterji, G. B. and Sridhar, B. (2001). Measures for air traffic controller workload prediction. In *the First AIAA Aircraft Technology, Integration, and Operations Forum*, Los Angeles, CA.
- Christien, R., Benkouar, A., Chaboud, T., and Loubieres, P. (2002). Air traffic complexity indicators & ATC sectors classification. In *Digital Avionics Systems Conference, 2002. Proceedings. The 21st*, volume 1, pages 2D3-1–2D3-7 vol.1.
- Cilliers, P. (1998). *Complexity and postmodernism: Understanding complex systems*. Routledge, London.
- Corker, K. M., Gore, B. F., Fleming, K., and Lane, J. (2000). Free flight and the context of control: Experiments and modeling to determine the impact of distributed air-ground air traffic management on safety and procedures. In *Third Annual Eurocontrol International Symposium on Air Traffic Management*, page 1316.
- Cummings, M. L. and Tsonis, C. G. (2006). Partitioning complexity in air traffic management tasks. *The International Journal of Aviation Psychology*, 16(3):277–295.

- Davis, C. G., Danaher, J. W., and Fischl, M. A. (1963). The influence of selected sector characteristics upon ARTCC controller activities. Technical Report Contract No. FAA/BRD-301, The Matrix Corporation, Arlington, VA.
- Delahaye, D. and Puechmorel, S. (2000). Air traffic complexity: towards intrinsic metrics. In *Proceedings of the third USA/Europe Air Traffic Management R & D Seminar*, Napoli, Italy.
- Edmonds, B. (1999). What is complexity? - the philosophy of complexity per se with application to some examples in evolution. *The evolution of complexity: The violet book of Einstein meets Magritte*, 8.
- Erzberger, H. (2004). Transforming the NAS: the next generation air traffic control system. Technical Report NASA/TP-2004-212828, NASA Ames Research Center, Moffett Field, CA.
- FAA (2007). FAA Order 7210.3 Facility Operation and Administration. Technical Report 7210.3, Federal Aviation Administration, Washington, DC.
- Galster, S. M., Duley, J. A., Masalonis, A. J., and Parasuraman, R. (2001). Air traffic controller performance and workload under mature free flight: Conflict detection and resolution of aircraft self-separation. *The International Journal of Aviation Psychology*, 11(1):7193.
- Grossberg, M. (1989). Relation of sector complexity to operational errors. *Quarterly report of the Federal Aviation Administrations Office of Air Traffic Evaluations and Analysis*.
- Hilburn, B. (2004). Cognitive complexity in air traffic control: A literature review. *EEC Note*, 4(04).
- Hilburn, B., Jorna, P., and Parasuraman, R. (1995). The effect of advanced ATC automation on mental workload and monitoring performance- an empirical investigation in dutch airspace. In *International Symposium on Aviation Psychology, 8th*, pages 387–391, Columbus, OH.
- Hilburn, B. G., Bakker, M. W., Pekela, W. D., and Parasuraman, R. (1997). The effect of free flight on air traffic controller mental workload, monitoring and system performance. In *10th International Conference of European Aerospace Conference on Free Flight*, volume 14.
- Histon, J., Hansman, R., Gottlieb, B., Kleinwaks, H., Yenson, S., Delahaye, D., and Puechmorel, S. (2002a). Structural considerations and cognitive complexity in air traffic control. In *Digital Avionics Systems Conference, 2002. Proceedings. The 21st*, volume 1, pages 1C2–1–1C2–13 vol.1.
- Histon, J. M. and Hansman, R. J. (2002). The impact of structure on cognitive complexity in air traffic control. Technical Report ICAT-2002-4, Massachusetts Institute of Technology.

- Histon, J. M. and Hansman, R. J. (2008). Mitigating complexity in air traffic control: The role of Structure-Based abstractions. Technical Report ICAT-2008-05, Massachusetts Institute of Technology.
- Histon, J. M., Hansman, R. J., Aigoïn, G., Delahaye, D., and Puechmorel, S. (2002b). Introducing structural considerations into complexity metrics. *Air Traffic Control Quarterly*, 10(2):115–130.
- Jolitz, G. D. (1965). Evaluation of a mathematical model for use in computing control load at ATC facilities. Technical Report RD-65-69, Federal Aviation Administration, Atlantic City, NJ.
- JPDO (2007). Concept of operations for the next generation air transportation system version 2.0. Technical report, Joint Planning and Development Office.
- Kirwan, B., Scaife, R., and Kennedy, R. (2001). Investigating complexity factors in UK air traffic management. *Human Factors and Aerospace Safety*, 1(2):125–144.
- Kopardekar, P. and Magyarits, S. (2003). Measurement and prediction of dynamic density. In *Proceedings of the 5th USA/Europe Air Traffic Management R & D Seminar*, Budapest, Hungary.
- Kopardekar, P., Magyarits, S., Syst, T., and Landing, N. M. (2002). Dynamic density: measuring and predicting sector complexity [ATC]. In *Digital Avionics Systems Conference, 2002. Proceedings. The 21st*, volume 1, pages 2C4–1–2C4–9 vol.1.
- Kopardekar, P., Schwartz, A., Magyarits, S., and Rhodes, J. (2007). Airspace complexity measurement: An air traffic control simulation analysis. In *7th USA/Europe Air Traffic Management R/D Seminar*, Barcelona, Spain.
- Laudeman, I. V., Shelden, S. G., Branstrom, R., and Brasil, C. L. (1998). Dynamic density: An air traffic management metric. Technical Report NASATM-1998-112226, NASA Ames Research Center.
- Lee, H. (2008). *Tradeoff evaluation of scheduling algorithms for terminal-area air traffic control*. Thesis, Massachusetts Institute of Technology. Thesis (S.M.)–Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, 2008.
- Lee, P., Mercer, J., Martin, L., Prevot, T., Shelden, S., Verma, S., Smith, N., Battiste, V., Johnson, W., Mogford, R., et al. (2003). Free maneuvering, trajectory negotiation, and self-spacing concepts in distributed Air-Ground traffic management. In *Proceedings of the 5th USA/Europe Air Traffic Management R&D Seminar, Budapest, Hungary*.
- Loft, S., Sanderson, P., Neal, A., and Mooij, M. (2007). Modeling and predicting mental workload in en route air traffic control: Critical review and broader implications. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(3):376–399.

- Major, L. M. and Hansman, R. J. (2004). *Human-Centered Systems Analysis Of Mixed Equipage In Oceanic Air Traffic Control*. PhD thesis, Massachusetts Institute of Technology.
- Majumdar, A. and Ochieng, W. (2002). Factors affecting air traffic controller workload: Multivariate analysis based on simulation modeling of controller workload. *Transportation Research Record: Journal of the Transportation Research Board*, 2002(1788):58–69.
- Majumdar, A. and Polak, J. (2001). Estimating capacity of europe’s airspace using a simulation model of air traffic controller workload. *Transportation Research Record: Journal of the Transportation Research Board*, 1744:30–43.
- Manning, C. A., Mills, S. H., Mogilka, H. J., Fox, C., and Pfeider, E. (2000). Investigating the validity of performance and objective workload evaluation research (POWER). In *3rd FAA/EUROCONTROL Air Traffic Management Research and Development Seminar*, Napoli, Italy.
- Manning, C. A. and Pfeiderer, E. M. (2006). Relationship of sector activity and sector complexity to air traffic controller taskload. Technical Report DOT/FAA/AM-06/29, FAA Civil Aerospace Medical Institute.
- Masalonis, A. J., Callahan, M. B., and Wanke, C. R. (2003). Dynamic density and complexity metrics for realtime traffic flow management. In *Proceedings of the 5th USA/Europe Air Traffic Management R & D Seminar*, Budapest, Hungary.
- McAnulty, D. M. and Zingale, C. (2005). Pilot-Based spacing and separation on approach to landing: The effect on air traffic controller workload and performance. Technical Report DOT/FAA/CT-05/14, FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ.
- Metzger, U. and Parasuraman, R. (2001). The role of the air traffic controller in future air traffic management: An empirical study of active control versus passive monitoring. *Human Factors*, 43(4):519.
- Mills, S. H. (1998). The combination of flight count and control time as a new metric of air traffic control complexity. Technical Report DOT/FAA/AM-98/15, Civil Aeromedical Institute Federal Aviation Administration, Oklahoma City, OK.
- Mogford, R. H., Guttman, J. A., Morrow, S. L., and Kopardekar, P. (1995). The complexity construct in air traffic control: A review and synthesis of the literature. Technical Report DOT/FAA/CT-TN95/22, FAA, Atlantic City, NJ.
- Mogford, R. H., Murphy, E. D., and Guttman, J. A. (1994). Using knowledge exploration tools to study airspace complexity in air traffic control. *The International Journal of Aviation Psychology*, 4(1):29–45.

- Mueller, E. R. (2004). Application of UAV technology to evaluation of time-based trajectory navigation requirements. In *AIAA 3rd "Unmanned Unlimited" Technical Conference, Workshop and Exhibit*, pages 1–13.
- Pawlak, W. S., Brinton, C. R., Crouch, K., and Lancaster, K. M. (1996). A framework for the evaluation of air traffic control complexity. In *Proceedings of the AIAA Guidance Navigation and Control Conference*, San Diego, CA.
- Pfleiderer, E. M. (2005). Relationship of the aircraft mix index with performance and objective workload evaluation research (POWER) measures and controllers' subjective complexity ratings. Technical Report DOT/FAA/AM-05/16, FAA Office of Aerospace Medicine, Washington, DC.
- Pfleiderer, E. M., Manning, C. A., and Goldman, S. M. (2007). Relationship of complexity factor ratings with operational errors. Technical Report DOT/FAA/AM-07/11.
- Pina, P. E. (2007). *Cognitive and operational implications of non-homogeneous aircraft equipage for aviation system transformation*. Thesis, Massachusetts Institute of Technology. Thesis (S.M.)—Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, September 2007.
- Prevot, T., Lee, P., Callantine, T., Smith, N., and Palmer, E. (2003a). Trajectory-oriented time-based arrival operations: Results and recommendations. In *ATM 2003, FAA/Eurocontrol R&D Seminar*, Budapest, Hungary.
- Prevot, T., Shelden, S., Mercer, J., Kopardekar, P., Palmer, E., and Battiste, V. (2003b). ATM concept integrating trajectory-orientation and airborne separation assistance in the presence of time-based traffic flow management. In *Proceedings of the 22nd Digital Avionics Systems Conference*, Indianapolis, IN.
- RTCA (1995). Report of the RTCA board of directors' select committee on free flight. Technical report, RTCA, INc., Washington, DC.
- Schaefer, D., Meckiff, C., Magill, A., Pirard, B., and Aligne, F. (2001). Air traffic complexity as a key concept for multi-sector planning. In *Digital Avionics Systems, 2001. DASC. The 20th Conference*, volume 2, pages 7E5/1–7E5/12 vol.2, Daytona Beach, FL.
- Schmidt, D. K. (1976). On modeling ATC work load and sector capacity. *Journal of Aircraft*, 13(7):531–537.
- Seamster, T. L., Redding, R. E., Cannon, J. R., Ryder, J. M., and Purcell, J. A. (1993). Cognitive task analysis of expertise in air traffic control. *The International Journal of Aviation Psychology*, 3(4):257–283.
- Sridhar, B., Sheth, K. S., and Grabbe, S. (1998). Airspace complexity and its application in air traffic management. In *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, United States.

- Stein, E. S. (1985). Air traffic controller workload: An examination of workload probe. Technical Report DOT/FAA/CT-TN84/24, Federal Aviation Administration Technical Center, Atlantic City International Airport.
- Wichman, K. D., Lindberg, L. G., Kilchert, L., and Bleeker, O. F. (2004). Four-Dimensional trajectory based air traffic management. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*, pages 1–11, Providence, RI.
- Williams, D. H. (1991). *Airborne four-dimensional flight management in a time-based air traffic control environment*. Langley Research Center, Hampton, VA.
- Wyndemere, I. (1996). An evaluation of air traffic control complexity. Technical Report Final Report (Contract Number NAS2-14284), Wyndemere, Inc.
- Xing, J. and Manning, C. A. (2005). Complexity and automation displays of air traffic control: Literature review and analysis. Technical Report DOT/FAA/AM-05/4, FAA Office of Aerospace Medicine, Washington, DC.