UNDERSTANDING THE IMPACT OF POTENTIAL BEST-EQUIPPED, BEST-SERVED POLICIES ON THE EN-ROUTE AIR TRAFFIC CONTROLLER PERFORMANCE AND WORKLOAD

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ABSTRACT

New capabilities of Air Traffic Control (ATC) under development in Next Generation Air Transportation system (NextGen) will increase the system capacity to accommodate the expected growth in the air traffic. One of the key enablers of the NextGen capabilities is advanced onboard equipage of the aircraft. During the transition to NextGen, aircraft with different equipage levels will coexist in the same airspace: mixed-equipage.

To reduce the mixed-equipage period, the Federal Aviation Administration (FAA) proposed "best-equipped, best-served policy" as a governing principle for accelerating NextGen equipage, offering incentives to the early adopters of NextGen avionics. However, the policy may introduce new tasks to the air traffic controllers, increasing the cognitive workload and decreasing the controller performance.

The policy may be implemented at the strategic or the tactical level. This thesis identified two representative tactical level policies that may increase the difficulty and workload of the en-route air traffic controllers: best-equipped, first-served (BEFS) policy and best-equipped, exclusively served (BEES) policy. To investigate the impact of the potential tactical best-equipped, best-served policies on en-route controller performance and workload, a human-in-the-loop simulation was developed to compare the impacts of the two identified potential policies and the current first-come, first-served policy.

The two potential tactical best-equipped, best-served policies provided marginal operational incentives to the NextGen equipage aircraft; however, the policies significantly increased the controller errors and reduced the total system efficiency with considerable delays to the less equipped aircraft compared to the current policy. In addition, higher subjective workload rating with the potential policies, especially during heavy traffic loads, indicated an increase in the controller workload and a reduction of the controller capacity. The analysis suggests that caution needs to be exercised when considering implementation of best-equipped best-served policy at the tactical level. Therefore, a strategic level implantation of the best-equipped, best-served policy is recommended; however, this study did not address impact of the strategic level implementation of the policy.

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I thank my God, my Lord who guides me along the right path for His name's sake.

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Chapter 1

Introduction

1.1 Motivation

New technologies and procedures of Next Generation Air Transportation System (NextGen) will introduce new capabilities to the National Airspace System (NAS) in order to enhance the system efficiency and capacity. The new capabilities proposed in the NextGen Concepts of Operation and the Implementations Plans, such as performance based navigation (PBN) and 4 dimensional trajectory based operation (TBO), require aircraft to be equipped with new avionics onboard (JPDO 2007).

There are three key NextGen technical changes: Automatic Dependent Surveillance-Broadcast (ADS-B) which provide more frequent and accurate updates of the surveillance information to the air traffic controllers and surrounding aircraft; Required Navigation Performance (RNP), an advanced navigation capability that allows an aircraft to fly a more precise path; and Data Communication (DataComm), that enables digital communication between the crew and the controllers with more information and less communication errors. Not only are these new technologies onboard important to the NextGen capabilities, but a high proportion of the aircraft must also be equipped with the associated NextGen avionics in order for the capabilities to be fully functional; therefore, the users' and airlines' investment on NextGen avionics is important.

Because the users' and airlines' investment decisions will most likely vary, mixed-equipage—a situation where aircraft with different capabilities coexist within the airspace—is inevitable. In order to reduce the mixed-equipage period and to accelerate the equipage, the Federal Aviation Administration (FAA) proposed "best-equipped, best-served" policy as the governing principle for equipage. The policy, which is currently under development, is expected to provide operational priority to the NextGen equipped aircraft in order to incentivize the users and the airlines to invest on the new avionics (FAA, 2009).

However, communities and research groups have shown concerns that the change from current "first-come, first-served" basis, to "best-equipped, best-served" may change the role and tasks of the controller that may negatively impact the controller workload and performance (RTCA 2009, Goldsmith et al 2010). A human-in-the-loop simulation with representative best-equipped, best served policies and an evaluation of the controller workload and performance would help to understand the potential impact of the new task of prioritization on the controller and also help the policy design to meet the goal of equipage acceleration with maintained system performance and safety.

1.2 Research Question

The research question of the thesis is

- What is the impact of representative tactical best-equipped, best-served policies on the en-route air traffic controller cognitive workload and performance?

The research question of this thesis is focused on the understanding of the impact of best-equipped, best-served policy on the air traffic controller cognitive workload and performance. However, no study has been done focusing on the impact of the new ATC task of providing operational priority on the controller workload, and the procedures of this policy are not yet designed.

The implementation of the policy may take many different forms depending on the phase of flight and the airspace structure. Also, it may be applied at different ATC system levels and phases of mixed-equipage. Therefore, this initial research needs to review the definition and the intention of the policy and identify representative best-equipped, best-served policies that may have potential impact on controller workload and performance for further detailed analysis. For the purpose of this study, the research will focus on the impact of the tactical level best-equipped, best-served policy on the en-route phase of the flight.

With the identified representative policies, an experiment will be designed in which the identified potential polices and the current first-come, first-served policy's impacts on the controller performance and cognitive workload will be compared through a human-in-the-loop simulation. Because the best-equipped, best-served policy may be implemented at different stages of the mixed-equipage, the experiment will measure the impact of the policies in separate test runs with different equipage ratios. Also, the number of aircraft in the simulated sector will vary throughout each test run, in order to evaluate the impact of the policies during different traffic loads.

1.3 Study Overview

In order to address the proposed research question, FAA's intention of the best-equipped, best-served policy and the current ATC procedures were reviewed to identify potential areas of prioritization in order to identify representative best-equipped, best-served policies. With the identified policies, a human-in-the-loop simulation was designed to explore the impact of the potential policies. Controller performance and subjective workload in the simulated operational environment were examined.

In chapter 2, a literature review was performed focusing on the proposed best-equipped, best-served policy in order to identify representative policies and their potential impact on the controller performance and workload.

First, the background and the definition of the best-equipped, best-serve policy proposed by the FAA were reviewed. The prioritization introduced by the policy may be provided at different system levels; therefore potential implementation levels of the policy were identified, in order for this study to focus on the policy that may have direct impact on the controller. Furthermore, two representative policies and procedures were identified for an experimental study. Finally, past-studies on the air traffic controller cognitive process were reviewed to understand the current controller tasks and strategies. Then, potential changes to controller cognitive process introduced by the identified best-equipped, best-served policies were speculated in order to hypothesize their impact on the controller performance and cognitive workload.

In chapters 3 and 4, a human-in-the-loop simulation was designed to investigate the impact of the two identified representative best-equipped best-served policies on the controller workload and performance. The simulation details, experimental variables and experiment procedures were discussed. Based on the experimental results, the controller performance and subjective workload were compared between the representative best-equipped, best-served policies and the current first-come, first-served policy. The results were analyzed and discussed to address the research question presented. Finally in chapter 6, the overall study was summarized with a conclusion of the experiment and future study to address further research questions present in the conclusion.

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Chapter 2

Background and Literature Review

New advanced avionics are the key enablers of the new capabilities that NextGen will introduce to the ATC system. Not only will each of these avionics introduce new capabilities to the aircraft, but those avionics will also work together to provide more information to the pilots and the controllers, enhance the performance of the system and enable new concepts of operation that are proposed in NextGen implementation plans. It is important to review those new avionics' capabilities and benefits to the ATC system, and also the current equipage process of each of the avionics

In order to expedite the transition to NextGen and reduce the hazardous mixed-equipage period, the FAA proposed best-equipped, best-served policy as a governing principle for NextGen equipage. The policy is expected to provide incentives for the users and airlines to invest on the new avionics. The policy may be implemented at different system levels. And depending on the implementation levels, the shift from current first-come, first-served basis operation to best-equipped, best-served may alter the controller's tasks and cognitive strategies. It is important to understand how those changes impact the air traffic controller workload and performance, because it may have adverse effects on the system capacity and safety

This chapter will first review the important NextGen avionics and their current equipage process. Then, the definition and intention of the best-equipped, best-served policy will be reviewed, and potential implementation levels will be discussed. For this initial research, a few representative policies that may introduce negative impacts on the controller performance and workload will be identified for further experimental study. Past studies on controller cognitive process and workload will be reviewed in order to investigate potential impact of the identified potential best-equipped, best-served policies on the controller workload and performance. The identified potential best-equipped, best-served policies will be analyzed in more detail during the experimental study in the following chapters of this study.

2.1 NextGen Equipage

New technologies of NextGen will introduce changes in all major building blocks of the ATC system including the communication, navigation and surveillance (CNS). Together with the advanced ground facilities, new avionics will enhance the ATC system with more transferred and shared information and more accurate and advanced performance with less human errors (FAA, 2011), There are three major NextGen technical changes associated with each component of the CNS: Automatic Dependent Surveillance – Broadcast (ADS-B), Required Navigation Performance (RNP), and Data Communication (DataComm). Each of the technical changes and the associated NextGen avionics are discussed is this chapter.

Automatic Dependent Surveillance – Broadcast (ADS-B)

ADS-B is an advanced surveillance system of NextGen, which is a shift from the current radar based surveillance to the aircraft broadcasted information based surveillance. Currently there are two types of radar: Primary and Secondary. The Primary radar sends out an electromagnetic signal and determines the presence of an aircraft by receiving an echo of the signal off the aircraft. The location of an aircraft is determined by the elapsed time between transmission of the signal and reception of the echo. The Secondary radar uses an amplified return of the signal by the transponder, which includes flight information such as aircraft ID and altitude, etc.

The ATC surveillance with ADS-B depends on the avionics on the aircraft. There are many different ADS-B avionics, with different cost and benefit implications. The most basic enabler is ADS-B Out, where the aircraft's position and flight data are broadcast by avionics to ground facilities and other aircraft who can receive the broadcast. The ADS-B Out enables the NextGen ATC surveillance with more frequent updates and enhanced accuracy. Additionally, the flight data included in the broadcast includes much more detailed flight information compared to the current Secondary radar. Using the flight data received, the controllers will provide air traffic separation and advisory services.

On top of the ADS-B Out capability, aircraft with ADS-B In may receive the broadcasted flight data and integrate it with different controls and displays, such as Cockpit Display of Traffic information to provide enhanced situation awareness to the flight crew. More advanced capabilities such as interval management and advanced conflict detection will be enabled when most of the aircraft are equipped with both ADS-B Out and ADS-B In.

In the United States, two different avionics have been adopted for ADS-B; the 1090 MHz Extended Squitter (1090 ES) and the 978 MHz Universal Access Transceiver (UAT). The 1090 ES will be required for aircraft that operates in Class A airspace and the 978 UAT is primarily intended for general aviation aircraft that operate in other controlled airspace (FAA, 2006).

Required Navigation Performance (RNP)

Traditionally, aircraft navigation has been reliant on ground-based radio navigation system called navigational aid (NAVAID). The aircraft receives signals from the ground systems and determines the aircraft position relative to the NAVAIDs. The position is then displayed in the cockpit for the crew to navigate following the flight plan through the NAVAIDs.

The RNP capability enables the aircraft to fly flight path that is not constrained by the location ground navigation aids with satellite-based navigation using the GPS. The RNP enables the aircraft to fly with greater accuracy and fewer waypoints. There are varying performance and functional requirements, from 10 nautical miles (nm) course width accuracy (RNP-10) to 0.1 nm precision and curved path of RNP 0.1 Authorization Required (AR) approaches)

With the greater navigation precision the aircraft can fly new routes, procedures and approaches that are more efficient. And the separation standards can be reduced together with the enhanced surveillance provided by the ADS-B. The reduced separation will increase the efficiency and capacity of the airspace (FAA, 2006).

Data Communication

Currently, primary communication between the crew and the air traffic controllers are exchanged through voice communication over Very High Frequency (VHF) radio. However, the voice communication is usually prone to human errors and consists of repetitive tasks that increase controller taskload. Additionally, complicated information required in the NextGen such as 4D trajectories with multiple waypoints and required time of arrivals cannot be exchanged through voice.

Data communications, enabled by Future Air Navigation System (FANS), provide a pilot-and-controller data link and enable transmission of flight data such as departure clearance and airborne reroutes. With the data communication, the routine task of the controllers and the crew could be done autonomously, enabling the controllers to focus more on managing traffic. And the digital transfer of data also enables complicated flight information between the crew and the controllers to be transferred instantly, to multiple aircraft if necessary, and without human errors that are common in the voice communication (FAA, 2007). The data communication is a key enabler of the future concepts of operation that require complicated 4-dimentional trajectory information that is difficult to be conveyed through the voice communication.

Equipage Process

Because the users and the airlines' investment decision on the advanced avionics will most likely vary, there will be an equipage transition period when aircraft with various equipment and capabilities coexist in the same airspace, called mixed-equipage. Figure 2-1 below represents three phases of mixed-equipage.

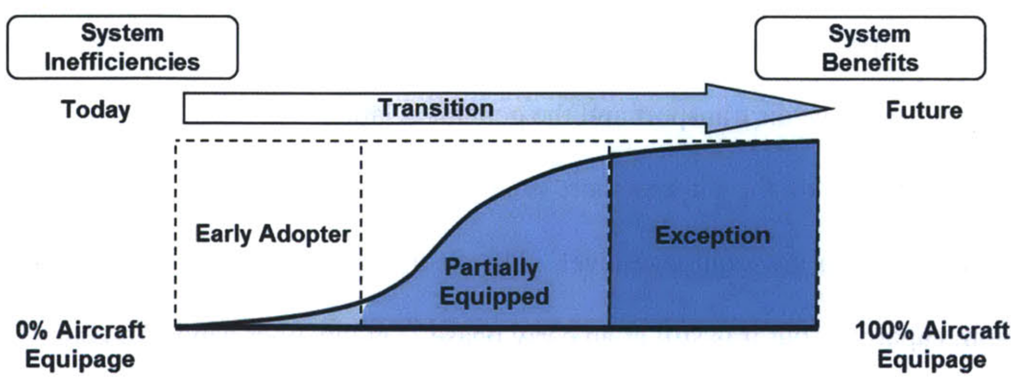

Figure 2-1: System Transformation and Mixed-Equipage (Pina, 2006)

In the "early adopter" phase, very few aircraft are equipped with the new avionics and the controllers will manage aircraft mostly with the current procedure. As the new avionics become more widely adopted, "partially equipped" phase of the mixed-equipage arises, in which the controller have to deal with mixed capabilities and procedures during most of their tasks. Finally, during the "exception" phase, most aircraft are equipped with the new avionics, and the controllers apply new procedure with few exceptions of the unequipped aircraft (Pina, 2006).

Each avionics has different capabilities and associated cost, and expected benefit varies with the users and the airlines; therefore the equipage process will vary with avionics and the user group. Table 2-1 below from the NextGen Implementation Plan 2011 represents current equipage levels of available avionics for the air transport and the general aviation.

Table 2-1: Current Equipage Levels (FAA, 2011)

New Capability	*Enablers*	*Air Transport*	*General Aviation*
RNP	**RNP 10**	**58%**	**<5%**
	RNP 4	**58%**	**<5%**
	RNP AR	**36%**	**<5%**
ADS-B	**ADS-B Out**	**0%**	**0%**
	ADB-S IN (CDTI)	**<5%**	**<5%**
DataComm	**FANS 1A (SATCOM)**	**36%**	**0%**
	FANS 1A+ (VDL mode2)	**12%**	**0%**

As shown in the table, the current equipage levels of the key NextGen avionics are mostly at early-adopter or partially equipped phase. It is also important to note the difference in equipage level between the air transport and the general aviation.

The RNP equipage of the air transport is at "partially equipped" phase, and the ADS-B equipage is still at very a low equipage level. The air transport has started to be equipped with the DataComm capability but it is still at an early phase. On the other hand, the general aviation, which is a significant part of fleet in the US, is currently at a very low equipage level, for all three of the main technologies of NextGen. The current equipage level shows that in order for the system to be fully transformed, the current system has to go through all three mixed-equipage phases and policy and procedure design must account for the impact of different phases of mixed-equipage.

2.2 Best-Equipped, Best-Served Policy

Policy Intention and Definition

The new system, Next Generation Air Transportation (NextGen) is currently under development in order to increase the capacity of the airspace through new technologies and capabilities. Aircraft equipage with new NextGen avionics onboard is one of the key factors of the implementation and success of NextGen technologies and capabilities; however, the expensive investments on new avionics hinder the users and the airlines to equip until clear benefits of the new technologies are demonstrated. In the transition from the current system to NextGen, the investment decision on the new avionics will most likely vary and, introducing a period of aircraft with different equipage levels coexisting in the same airspace, which is called mixed-equipage as described in the previous chapter.

Many studies and human-in-the-loop simulation experiments were performed in order to understand the impact of mixed-equipage on the ATC system and the controllers (Pina and Hansman, 2006 and Major and Hansman, 2006). The studies have shown an increase in the controller workload and a decrease in the performance. Many participants of the studies have expressed the difficulty of managing aircraft with different capabilities at the same time within the airspace. More importantly, because of the difficulty, the participants decided to use the baseline capabilities of aircraft by treating all aircraft equally in order to reduce their cognitive workload; on the other hand, when new capabilities were easier to resolve the situation, participants preferred to utilize NextGen equipped aircraft to manage traffic.

Both of the controller behaviors to reduce workload in mixed-equipage may have negative impact on the equipage transition to NextGen, because they do not provide immediate benefits to the users and the airlines for their investments on the new avionics. The underutilization of new capabilities does not provide operational and economic benefits to early adopters of the new technology, and the overuse of new capabilities will induce more commands and maneuvers of the equipped aircraft which may result unexpected disadvantages for the users' investment (Pina and Hansman, 2006 and Major and Hansman, 2006).

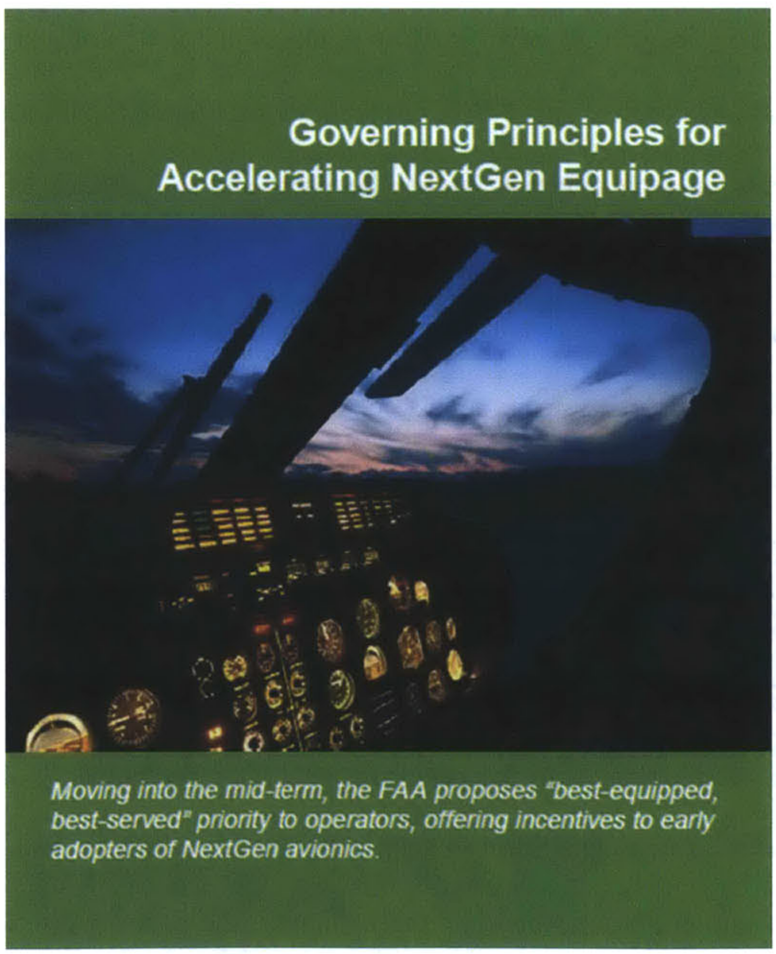

Figure 2-2: Best-Equipped, Best-Served Policy Proposed in the NextGen Implementation Plan 2009

In order to reduce the period of mixed-equipage that has negative impact on the controller workload and performance and to expedite the transition to full implementation of NextGen, the FAA proposed "best-equipped, best-served" as a governing principle for accelerating NextGen equipage in the NextGen Implementation Plan 2009 as shown in Figure 2-2. The policy will provide priority to operators and offer incentives to the early adopters of NextGen avionics. The FAA has not yet proposed further details of the policy.

Policy Implementation Levels

The best-equipped, best-served policies may provide operational benefits to the NextGen equipped aircraft at different systems levels, depending on the policy implementation. This study categorized the potential policy implementation into three system levels. Table 2-2 below summarizes the different implementation levels.

Table 2-2: Policy Implementation Levels

Implementation Levels	*Method*	*Applications*
Structure Level	Mandate	Make certain airspace only available for aircraft with a predetermined minimum equipage.
Strategic Level	Incentivise	Planning and scheduling to provide sequential priority or better trajectories to higher equipage aircraft
Tactical Level	Incentivise	Management of mixed-equipage aircraft within the airspace, prioritizing aircraft according to their different equipage levels

The highest level is the structure level implementation of best-equipped, best-served policy. This policy will bring substantial structural changes to the current airspace system by making certain airspace only available to the equipped aircraft. This mandate may be applied to an entire sector or redefine airspace above a certain flight level. This structural level policy will create most notable operational priority to the NextGen equipped aircraft and the air traffic controllers may not have to deal with mixed-equipage; however, this may induce heavy congestion in low performance airspace, especially during the early phase of the mixed-equipage with low proportion of equipped aircraft. The increase in traffic load will have adverse impact on the controller workload in those sectors, and may result in significant delays for the non-equipped aircraft, reducing the overall performance and efficiency of the ATC system.

The strategic level best-equipped, best-served policy is a traffic flow manager level prioritization of aircraft according to the equipage. The policy will create flight plans to the aircraft according to their equipage prior to departure, providing operational priority through better routes with less delay. With this policy, the air traffic controllers will still manage mixed-equipage in the sector; however, the aircraft will be spatial or sequentially separated according to the flight plans prior to the sector entry. The partial segregation may reduce the controller workload due to mixed-equipage.

Lastly, the tactical level best-equipped, best-served policy is an air traffic controller level implementation of the policy, in which the controllers have to identify aircraft's equipage at the sector entry and provide operational priority accordingly. The operational priority includes less delay and more efficient routes. The controller may have to constantly monitor equipage of the aircraft and compare outcomes of possible decisions to provide priority to the NextGen equipped aircraft over the non-equipped aircraft. The study focused on the tactical level best-equipped, best-served policy because the policy has the most direct impact on the controller task. The new task of prioritization has a potential adverse impact on the controller workload and performance.

Representative Tactical Best-Equipped, Best-Served Policies

The study identified two tactical level best-equipped, best-served policies with representative procedures for further experimental study. The first policy was best-equipped, first-served (BEFS) policy. The policy does not allow higher equipage aircraft to be delayed because of the lower equipped aircraft; therefore during conflict resolutions between aircraft with different equipage levels, the controller has to maneuver lower equipage aircraft by providing unconstrained trajectories to the equipped aircraft. Also whenever the airspace has preferred elements such as shorter routes, the controller has to provide unconstrained access to the higher equipage aircraft. Therefore, the lower equipage aircraft has access to the preferred elements only when its access does not delay the higher equipage aircraft.

Next representative policy was best-equipped, exclusively-served (BEES) policy. The policy also prevents the higher equipage aircraft from being delayed due to the lower equipage aircraft during conflict situations. The policy provides more rigorous priority to the higher equipage aircraft by providing the access to the preferred elements in the airspace only to the higher equipage aircraft. Therefore with the policy, the lower equipage aircraft has to use less preferred elements in the airspace.

2.3 Controller Workload

Concerns on Controller Workload

Controller cognitive workload, which is directly related to controller performance and capacity, will remain one of the limiting factors of the capacity of the future air traffic control (ATC) system (Majumdar and Polak, 2001; Hilburn, 2004). New technologies and procedures of the Next Generation Air Transportation System (NextGen) currently under development expect to increase the capacity and efficiency of the National Airspace System (NAS) to meet the expected growth of air traffic. However, the new system may change the roles and tasks of the controllers and may thus affect their cognitive workload. Increase in cognitive workload may reduce the controller performance and the system capacity and may also affect the system safety. Therefore, it is important to understand the new procedures' impact on the controller and to consider them during the design and implementation process of the new ATC system. The thesis focuses on changes in the system which may change controllers' role and tasks which may impact the controller's workload and performance.

The FAA expects that the best-equipped, best-served policy will provide enough incentives to the users and the airlines to quickly adopt the new avionics. However, the policy may introduce further increase in the controller workload during mixed-equipage, reducing the capacity and efficiency benefits of NextGen capabilities during the transition period. Aviation communities and research groups have expressed worries about this new policy and suggested to understand the potential impact of the policy on the ATC system and the controllers prior to the policy design and implementation (RTCA 2009, Goldsmith et al, 2010).

The Radio Technical Commission for Aeronautics, RTCA task force, which develops consensus-based recommendations regarding communications, navigation, surveillance, and air traffic management, has articulated a few concerns regarding the best-equipped, best-served policy (RTCA 2009):

- **FAA must consider the way in which equipage information is provided to the controller**
    - If operational decisions is influenced by equipage, then the information must be visible to the controller on his scope in order to enable him to make these decisions quickly and safely
- **FAA must examine the effect the changes would have on controller workload**
    - The policy may have a profound increase in controller workload, particularly at busy terminal facilities.
    - Problematic if under-equipped airlines were consistently forced into holding patterns in condensed airspace
    - Exacerbate already severe delays, dangerous workload and coordination situation

- **It is important to realize that a BEBS policy, at least in the short term, may have a negative impact on the overall efficiency of the ATC system**
    - Current policy "First-Come, First-Served"– utilize limited runways and airspace in the most expeditious manner.
    - With BEBS, additional factor for the controller to consider in making decisions other than efficiency (i.e. Equipage, Preferences).

Current En-Route Operation

In order to hypothesize the potential impact of tactical best-equipped, best-served policy on the en-route air traffic controller, the current en-route operation was reviewed through the controller cognitive process model. From the literature review of the human factors papers, current en route ATC operation was summarized and explained through the model of controller cognitive process developed by Jonathan Histon in Figure 2-3 below.

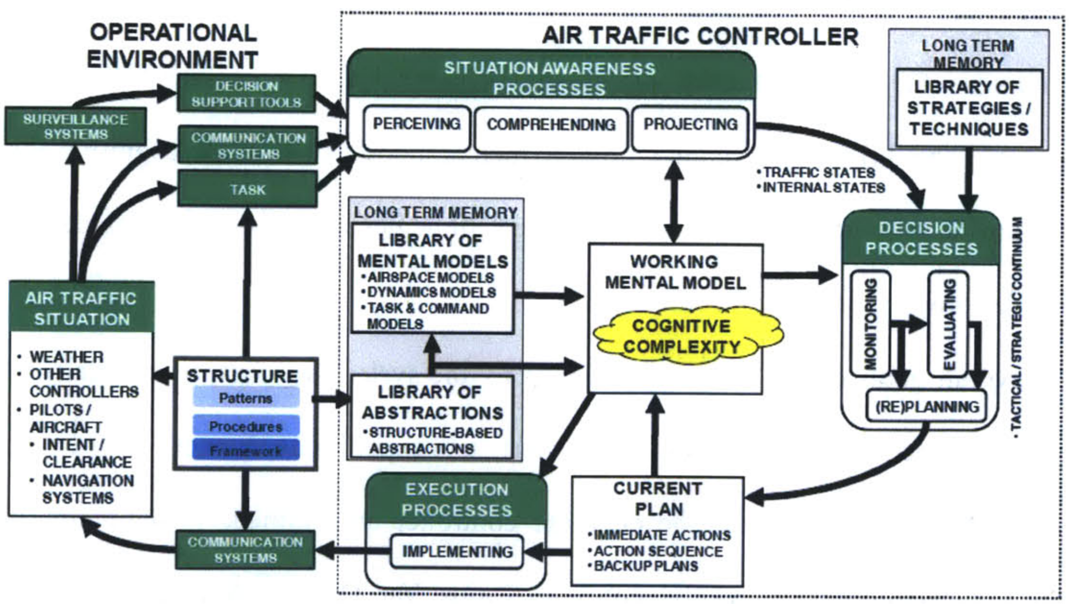

Figure 2-3: Histon's Air Traffic Controller Cognitive Process Model

The model represents the interactions between the operational environment and the air traffic controller. The air traffic situation with associated tasks, defined by the structure of the system, feeds into the air traffic controller cognitive process through a surveillance system, decision support tool and communication system. The information first goes through the situational awareness process where the controller perceives and understands the traffic situation to the level of being able to project the future state of the system. The understandings of the situation then go through the decision process where the controller monitors and evaluates the situation, and then plan the course of suitable actions. The decision process creates current plans which will be implemented according to the scheduled time sequence during the execution process through the communication system.

The structure of the system plays a very important role in this model. The structure represents the underlying pattern, procedure and framework of the airspace. The pattern of the traffic flow and procedures to manage them are stored in the controller's long-term memory creating a library of abstractions. From the abstractions, the controller creates a mental model of the airspace and control strategies. The working mental model of the controller retrieves information from the current situation and integrates them with the mental model created in long-term memory. The difficulty of maintaining the mental model is where the cognitive complexity arises. Controllers use the abstractions and control strategies from the mental model to manage the cognitive complexity at a controllable level.

The overall goals of the controller defined by the system are first, to maintain separation standard and second, to manage traffic in an orderly and expeditious manner. In order to achieve those goals, three main tasks for the en route controller are defined: 1) maintain situational awareness 2) detect conflict 3) resolve conflict (Kallus, Van Damme, & Dittman, 1999). These three main tasks are decomposed into specific subtasks that are applied to en-route traffic situations induced from the underlying structure. Those subtasks include: accept and hand off of aircraft, provide metering at a merge point, issue clearances (descent, vectoring, speeding, waypoint) to reroute, and conduct communication and coordination between the flight crew and other controllers.

The traffic situation is displayed in the control screen of the controller using radar as the primary surveillance system. The controller communicates to the flight crew and other controllers using radio voice communication system.

Using the display of the control screen, the controller obtains or maintains situational awareness. The controller views the traffic information and understands the current traffic situation including the flow, heading and speed of the aircraft. Using this information, the controller projects the future traffic flow and potential conflict (Endsley, 1995).

Using the obtained situational awareness, the controller monitors traffic to check the conformance of the aircraft following the future projection of the flow and the executed past commands. From the monitoring, the controller evaluates the situation and identifies traffic situations where he/she needs to intervene, such as hand offs and potential conflicts at merge or crossing. During the process, the controller uses First-Come, First-Served basis to develop human projection of the order in which aircraft would arrive. Then the controller plans courses of suitable actions to manage those situations. The controller then evaluates the sequence of the current plan and times to execute different commands. Then at the scheduled time, the controller issues clearances or commands through voice communications.

As described above, the underlying structure of the airspace plays a very important role in the controller cognitive process. (Histon & Hansman 2002) The structure of the airspace is described by the air traffic pattern of the airspace and associated procedures for controllers to manage. The sector-specific patterns include structural elements such as major flows, and critical points including merge, diverge, crossing and ingress/egress points of the airspace. Those elements in the structure and associated ATC procedures are stored into the controller long-term memory through training and experience.

Using the structure, the controller develops the library of abstractions in their long-term memory. These abstractions of the airspace become controller's control strategies, which are, used by the controller in his or her working memory to help the cognitive process by maintaining a controllable level of the cognitive complexity (Histon & Hansman 2002).

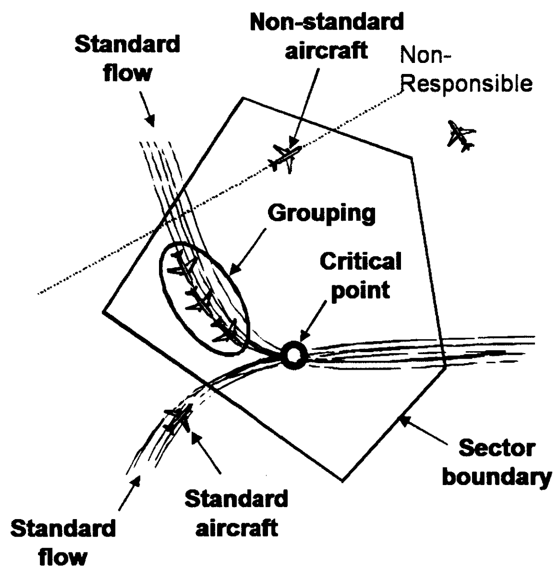

Figure 2-4: Examples of Structure-Based Abstraction

The abstraction is a simplification of the traffic situation by creating a mental model of the airspace as illustrated in Figure 2-4 above. By creating a metal model the controller can develop expectations of the traffic situation in the airspace. The major flow of the airspace represents the expected trajectories of most of the aircraft that pass through the sector. The expected trajectories simplify controller's mental projections of the aircraft that are in the major flows. Then the controller can effectively allocate cognitive attention to aircraft that do not follow common trajectory. The controller also uses grouping strategies to group aircraft that are in proximity and are following the same flow in order to simplify the monitoring task (Histon & Hansman 2002). For detection of the conflicts, the controller can focus on critical points where the major flows merge, cross or diverge, for most of the conflicts in the airspace occur at those points. When resolving the conflict at those critical points, the controller retrieves solution from the library of conflict resolution, which is stored in the long-term memory so that the controller does not have to come up with new solutions but can simply use past solutions that are proven safe (Kallus, Van Damme, & Dittman, 1999).

Controllers use the above control strategies and abstractions to maintain their cognitive complexity level. The controller's complexity level can be maintained as long as the air traffic pattern is consistent with the controller's mental model; therefore, the controllers manage their traffic so that the traffic flow will adhere to their simplified mental picture of the airspace. The utilization of those control strategies are driven and formulated by prioritization in the order of safety, orderliness and expeditiousness (Kallus, Van Damme, & Dittman, 1999).

Potential Impact of Tactical Best-Equipped, Best-Served Policy on Controller

The best-equipped, best-served policy is a major operational change from the current first-come, first-served policy, especially from the air traffic controller's point of view. The current controller cognitive process was reviewed in the previous chapter, and based on the understanding, the potential impact of tactical best-equipped, best-served policy on the air traffic controller was hypothesized.

The most important impact of the best-equipped, best-served policy is the new constraints imposed on the controller's strategy of simplifying mental model using the structure-based abstraction. With the current first-come, first-served policy, the controller treats the aircraft in the airspace equally regardless of their equipage. Therefore the controller is able to create major flow and grouping abstractions to treat all aircraft that are in similar traffic pattern or in proximity with similar control strategies, reducing the workload of monitoring traffic, maintaining situational awareness, and making appropriate decisions.

However with the tactical best-equipped, best-served policy, the controller is no longer able to treat aircraft in the same structural flow equally, because they may have different equipage level, and the policy has different procedures for the aircraft with different equipage levels.

When the policy was applied, the controller will have difficulty maintaining situational awareness and monitoring of air traffic due to the additional variable of equipage that they have to identify. The difficulty of maintaining situational awareness will rise rapidly during high traffic density especially when large number of under equipage aircraft on holding pattern or being vectored out of the major flows.

During the decision process, such as conflict resolutions, or waypoint and altitude assignments, the controller's number of options to resolve a situation gets reduced because of the best-equipped, best-served policy. The policy may only allow an aircraft with certain equipage to be maneuvered to resolve conflict. The constrained controller strategies may force the controllers to choose an option that may increase their cognitive workload or result in a more difficult traffic situation.

2.4 Summary

This chapter first reviewed the major technological changes of NextGen. The technologies' capabilities, benefits and associated advanced avionics were discussed. The changes include all key areas of the ATC system: surveillance, communication and navigation. However, it was also found that current equipage levels of the major avionics are very low and the users and the airlines must be provided with enough incentives for investment in the new technologies.

The FAA proposed best-equipped, best-served policy in order to incentivize the users and the airlines to adopt the NextGen avionics, by providing operational priority to the aircraft equipped with the advanced avionics. However, there were concerns from the aviation communities and research groups that the new task of prioritization may have adverse impacts on the controller performance and workload, and further study is required to understand the potential impact of the policy.

Because the best-equipped, best-served policy is currently under development, the potential implementation of the policy was categorized into three major system levels, and this study decided to focus on the tactical level best-equipped, best-served policy. Two representative policies and procedures were developed for further experimental study in following chapters.

Cognitive analysis was performed in order to hypothesize the potential impact of the tactical level best-equipped, best-served policy on the controller workload and performance. The analysis used the controller cognitive process model to understand the changes in controller cognitive process and control strategies from the current first-come, first-served policy to the tactical best-equipped, best-served policy. The analysis hypothesized that the additional variable of equipage and associated tactical level procedures will impose constraints on the controller strategy of structure-based abstraction, which may impair their situational awareness and decision process, resulting in adverse impacts on the controller performance and workload.

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Chapter 3

Experimental Design

In order to understand the impact of the policy, an experimental study was designed and performed to evaluate the impact of tactical best-equipped, best-served policy on the en-route air traffic controller workload and performance. For this experiment, potential areas of prioritization in the current ATC procedures were reviewed, and two tactical level representative best-equipped, best-served polices were developed. This chapter will focus on the design of the experiment including the experiment objective, experiment variables, detailed simulation environment, and the experiment procedure.

3.1 Experiment Overview

New task of prioritization introduced by tactical best-equipped, best-served policy may increase the task complexity and the workload of air traffic controllers, which may also degrade the system efficiency and capacity. A human-in-the-loop simulation of an en-route ATC environment with air traffic controllers performing the prioritization task is needed to test the hypothesis of the potential impact of the new policy. The objective of the experiment is to evaluate the impact of the tactical representative best-equipped, best-served policies on the en-route air traffic controllers through a human-in-the-loop simulation.

The potential tactical best-equipped, best-served policy is a shift from the current first-come, first-served policy. Therefore, the experiment was designed to measure the participants' performance with different policies: the representative best-equipped best-served policies and the baseline first-come, first-served policy. Then, the results from the best-equipped, best-served policies were compared to the result from the first-come, first-served policy in order to evaluate the impact of the potential policies.

The experiment measured controller performance, system efficiency, and subjective workload. Controller performance includes the number of controller errors, the average flight time, and the average number of control commands. Subjective workload was measured through a rating scale from 1 to 7 during the simulation.

The best-equipped, best-served policy may be implemented during the different phases of the mixed-equipage with different ratios of NextGen equipped to non-equipped aircraft. Additionally, the traffic density of the airspace varies depending of the time of the day and the time of the year, which may also influence the impact of the best-equipped, best-served policy. For each policy, the experiment had multiple test runs with different mixed-equipage ratios and varying traffic density in order to comprehensively evaluate the tactical best-equipped, best-served policy's impact during different traffic situations.

3.2 Independent Variables

This experiment had three independent variables to understand the impact of the potential tactical best-equipped, best-served policies on the controller performance and workload during different phases of mixed-equipage and varying traffic load. As shown in the design matrix in

Figure 3-1, the experiment consisted of 7 test runs with different policies and mixed-equipage ratios. The key independent variable was the policy.

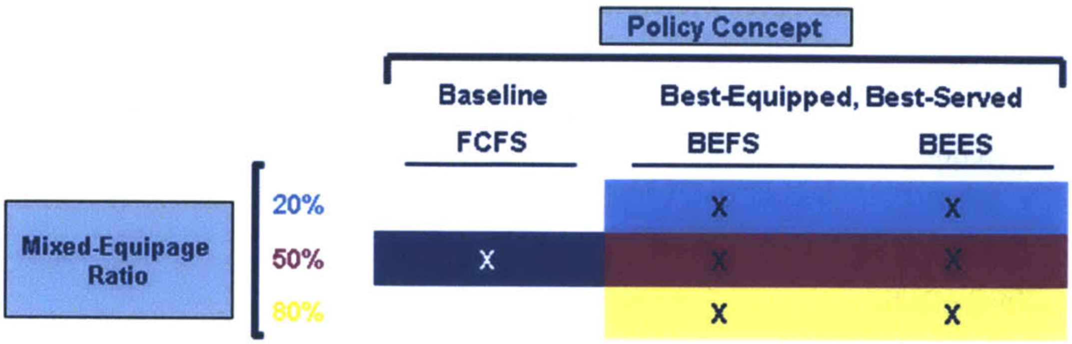

Figure 3-1: Design Matrix of the Experiment

Policy

There were three policies: one first-come, first-served basis policy representing the current ATC procedure serving as a baseline of the experiment denoted with P0, and the two potential best-equipped best-served policies denoted with P1 and P2. The current first-come, first-served policy (P0) in this experiment did not restrict controllers to maintain the order of the aircraft as they enter the sector, but it meant to treat all aircraft equally in terms of prioritization.

Two representative tactical best-equipped, best-served policies were best-equipped, first-served (P1) and best-equipped, exclusively-served (P2). They were identified in the previous chapter for this experiment for they may have a negative impact on the controller workload and performance.

As described in the previous chapter, both of the two tactical best-equipped, best-served policies provide unconstrained flight path to the equipped aircraft during potential conflict situations. Therefore the controllers need to control under-equipped aircraft during a conflict between aircraft with different equipage levels. The best-equipped, first-served policy (P1) provide equipped aircraft with priority to enter or use preferred elements in the airspace, whereas the best-equipped, exclusively-served policy (P2) restrict under-equipped aircraft from using the preferred elements in the airspace. Preferred element in this simulation is a shorter route leading to the next sector. The structure of the airspace is explained in more detail in the simulation environment section.

Mixed-Equipage Ratio

As shown in Figure 2-1, the period of mixed-equipage can be categorized into three different phases: “early adopter”, “partially equipped”, and “exception” phase. In order to understand the impact of the new policy during the different phases of mixed-equipage, each of the two best-equipped, best-served policies had three test runs with different mixed-equipage ratios.

20 percent high equipage ratio represent the “early adopter” phase when most of the fleets are not equipped with the NextGen avionics, and 50 percent and 80 percent high equipage ratios respectively represent the “partially equipped” and “exception” phase. Because the baseline policy disregarded the equipage of the aircraft, the first-come, first-served policy was not repeated three times for the different mixed-equipage ratios, but the policy had one test run with 50 percent mixed-equipage ratio as shown in the experiment matrix in figure 3-1.

Traffic Density

In order to evaluate the impact on the policy during different traffic load, the traffic density was increased throughout each of the seven test runs. The experiment started with an entrance rate of 15 aircraft per hour and ended with 45 aircraft per hour. The rate was adjusted so that the sector capacity limit would be reached by the end of the test run. The experiment deliberately increased the traffic load to saturate the airspace in order to understand the changes in controller capacity under different policies. Figure 3-2 represents the average number of aircraft in the sector during the test runs.

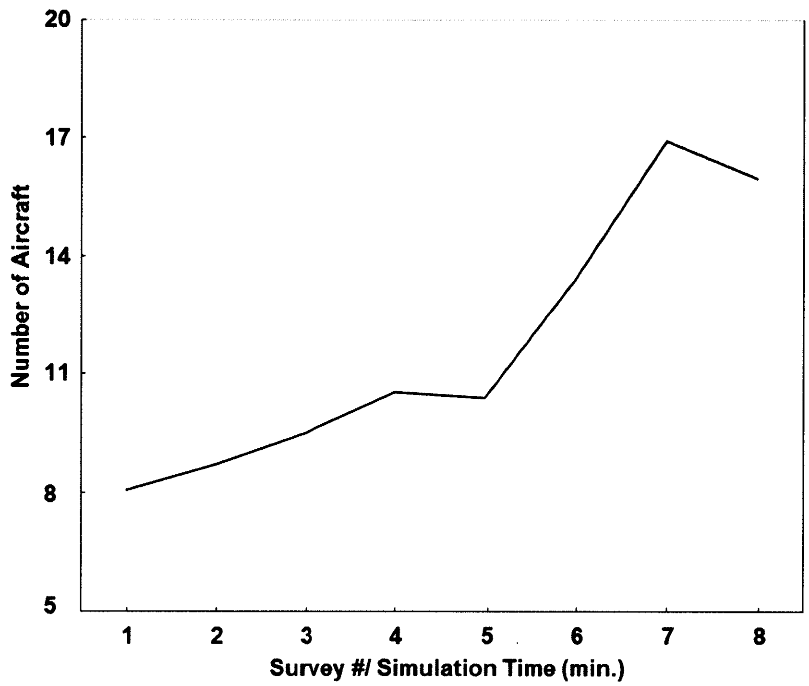

Figure 3-2: Average Number of Aircraft in the Sector

3.3 Dependent Variables

The experiment included both an objective measurement and a subjective measurement to evaluate and compare the impact of the different policies on controller performance and subjective workload.

Objective Measurement

The flight time of the aircraft spent in the simulation sector was measured to evaluate the system efficiency in terms of sector throughput and also to measure operational incentives provided to equipped aircraft by the best-equipped, best-served policies. The number of controller commands was also recorded to measure the controller task load and operational incentives provided by the potential policies. As a primary task performance measurement, the number of controller errors was recorded. Controller errors included loss of 5 NM separation events, penetrations of the restricted airspace, and incorrect deliveries of aircraft. Aircraft delivered to an incorrect sector according to the flight plan and aircraft led to incorrect metering fix, and thus violating the run's policy, were considered as an incorrectly delivered aircraft.

Subjective Measurement

The controllers were asked to rate their current workload level as soon as the workload rating keypad appears at the left side of the screen as a secondary task. The time of workload rating since the keypad appears was measured as a secondary task performance. Figure 3-3 shows the workload rating keypad.

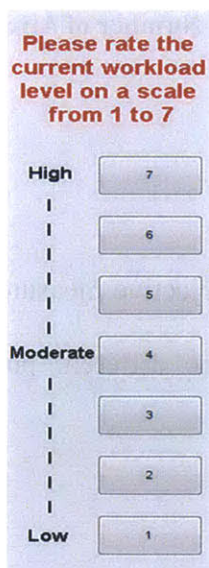

Figure 3-3: Workload Rating Keypad

The workload rating on a rating scale of one to seven was measured every minute during the test run as traffic density increased. The workload measurement method used in the experiment was a widely used method in the ATC simulation called Air Traffic Workload Input Technique (ATWIT), which was developed at the FAA technical center (Stein, E.S., 1985). The technique measures mental workload in real-time by presenting auditory and visual cues that prompt the controller to press one of seven buttons on the workload assessment keypad (WAK). The method was chosen for its low intrusiveness because it does not stop the simulation to measure the workload.

Before the experiment, the definition of workload was discussed with the participants, in order to have common understanding of the concept. And also, each of the scale had anchors and description of the associated cognitive state of the participants. Table 3-1 below represents each anchor of the scales and associated definitions.

Table 3-1: Workload Rating Scales' Anchors and Definitions

Anchors	*Definition*
7. Very High	- Reactive and scramble mode - falling behind in routine tasks, cannot take on any additional tasks, ignoring the policy.
6. High	- Working reactively instead of proactively. Very difficult to follow the policy.
5. Somewhat High	- Focusing more on the separation management. Difficult to follow the policy.
4. Moderate	- Following the policy and managing conflicts without much trouble.
3. Somewhat Low	- Proactively looking for conflict, following the policy at the same time.
2. Low	- Time to give best routes, Easy to follow the policy
1. Very Low	- Hardly anything to do

After each test run, the participants were each given a brief subjective questionnaire to evaluate the overall task difficulty and subjective rating of the policy conformance. At the end of the entire experiment, the participants were asked what the most difficult and the easiest policy to follow were, and the reasons for their choices.

3.4 Simulation Environment Overview

Simulation Environment

The simulation environment was a high en-route sector with a main task of transferring aircraft from the previous sector to the next sector according to their flight plans. The simulation was designed to incorporate basic elements of the ATC system and procedures of the R-side en-route air traffic controller; however, it is important to note that the simulated airspace only had a single altitude due to the simulation's limitation, so the controller could not give any altitude commands. Also, due to limited experiment time, the simulation was 8 times faster than the real time. Figure 3-4 illustrates the simulated airspace.

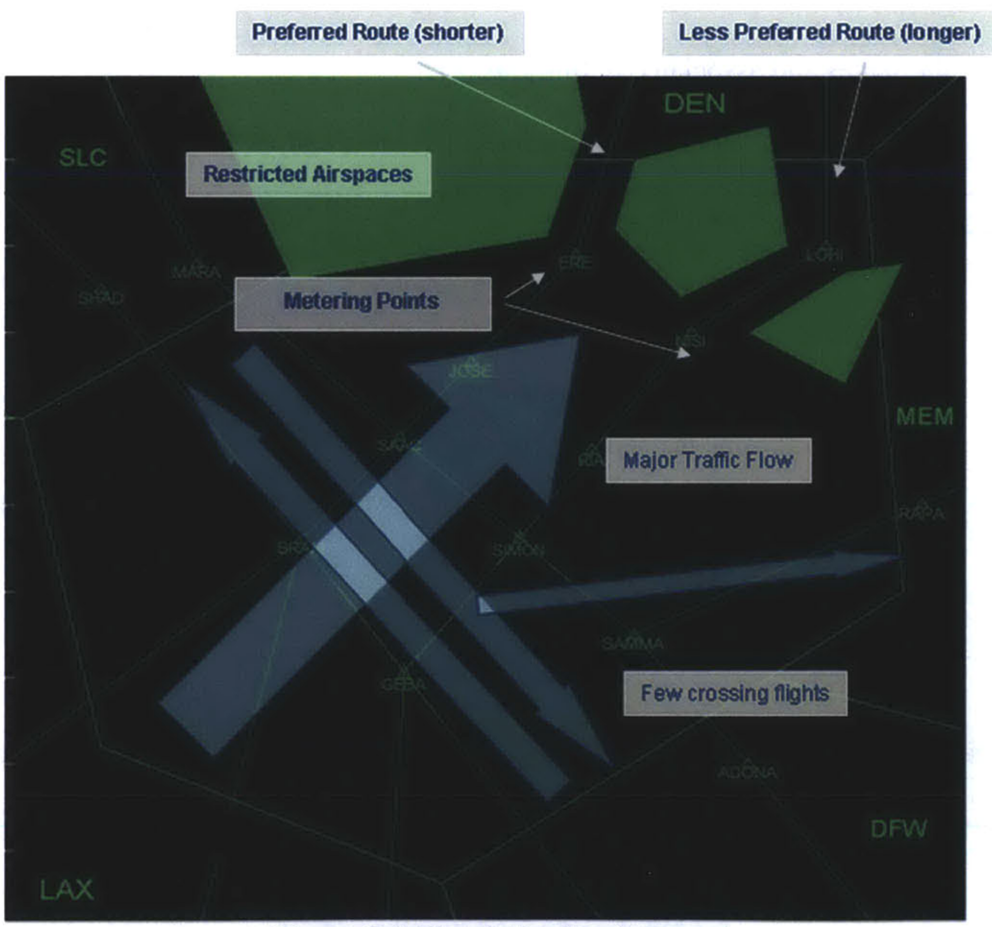

Figure 3-4: Simulation Environment

The simulated airspace was a fictitious high altitude sector of South West US. There was a major traffic flow from Los Angeles (LAX) heading to Denver (DEN), and a few crossing flights between Dallas Forth Worth (DFW), Salt Lake City (SLC) and Memphis (MEM). Because the participants had no experience with this representative airspace, the direction of the origins and destination airports were denoted with the three letter acronyms in the control screen as shown in Figure above.

There were restricted airspaces presented at the sector boundary, where the aircraft were prohibited to enter. The penetration of restricted airspace was considered as one of the controller errors of the simulation. Because of the restricted airspace, the major flow heading to Denver had to be lead to one of the two metering fixes ERE and NISI, which created a shorter route and a longer route to the destination. The two routes represented the preferred and the less preferred elements in the airspace for the tactical best-equipped, best-served policy to be implemented.

Controller Tasks

The participants of the experiment were to perform the following primary tasks as en-route air traffic controllers:

1. Maintain separation (5nm) and avoid entering the restricted airspace
2. Direct traffic to the next sector according to their destinations
3. Manage traffic according to the run's policy rules
4. Minimize flight time and traffic delay

The participants' primary tasks were similar to the normal ATC tasks in managing en-route traffic. Most importantly, the controllers needed to manage traffic with maintained minimum 5nm separation between the aircraft. 5nm was represented with a separation circle with a radius of 2.5nm around each aircraft body symbol and the contact of these circles indicated a loss of separation.

Controllers had to accurately transfer aircraft from its previous sector to the next sector according to each aircraft's flight plan indicated in the flight data block and the simplified flight strip on the right side of the screen. Aircraft heading to Denver needed to be delivered to one of the two metering fixes due to the restricted airspaces. In order to aid participants who are not familiar with the structure of the simulated airspace, surrounding sectors were noted with destination airport acronyms.

Each test run was assigned with one of the three policies defined for the experiment: the current first-come, first-served policy or the two potential best-equipped, best-served policies. The participants needed to manage the traffic according to the run's policy rules.

Lastly, the participants needed to maximize the sector throughput by minimizing the aircraft's flight time and reducing traffic delay. The participants were given incentives to perform those tasks with a $20 gift card as a reward prize to the participant who had the least operational errors and the minimum average flight time.

Simulation Interface

The simulation and user interface was developed using MATLAB. The simulation interface was designed to include basic features of the actual air traffic controller's control screen including the sector boundaries, the aircraft and associated flight data blocks, waypoints, air routes, and restricted airspaces. It is important to note that due to the simulation's limitations, the commands of the controllers to the aircrafts were provided with mouse clicks instead of actual voice communications. Figure 3-5 shows the simulation user interface.

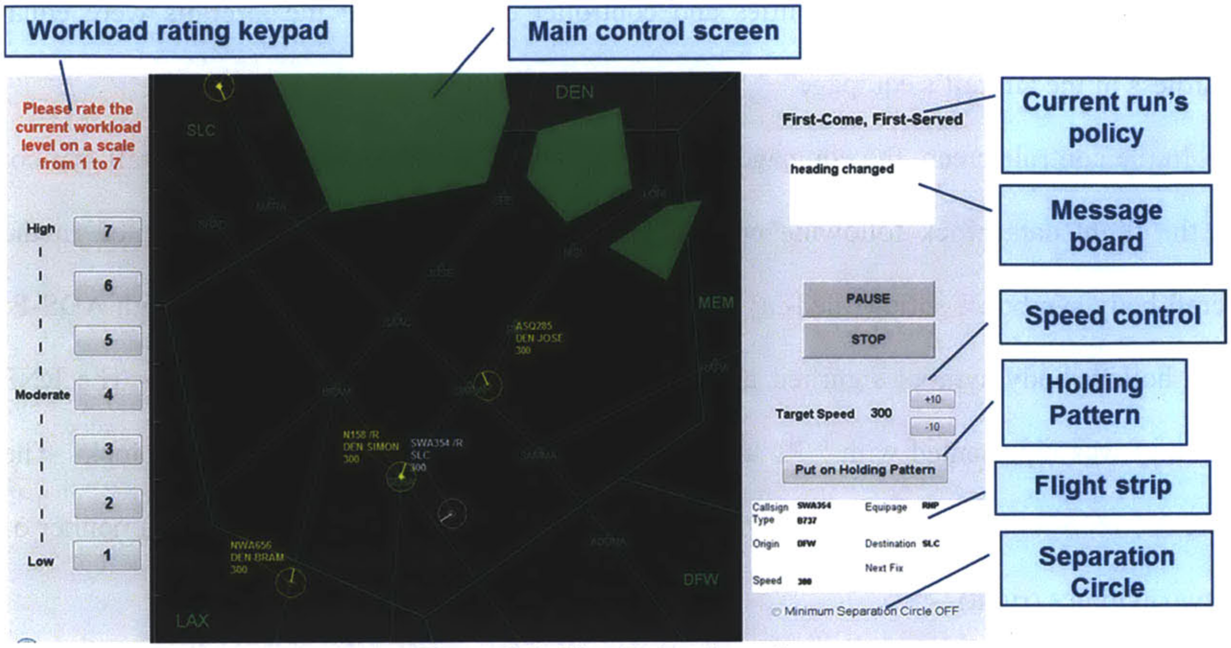

Figure 3-5: Simulation Interface

Using the interface, the controllers were able to perform basic commands of managing en-route traffic including heading changes, waypoint designations, speed changes, and holding pattern assignments. The heading changes and waypoint assignments were commanded by clicking an aircraft and then the airspace or waypoints in the control screen. The speed changes or holding pattern assignments were made using the control panel in the right side of the control screen. Hand-offs were automated to simplify the simulation, and there was no altitude assignment because there were no multiple altitudes in the simulated airspace.

The simulation was designed so that the experiment results were recorded automatically. The simulation recorded experiment variables such as aircraft flight time, controller commands and errors, and subjective workload ratings.

Aircraft Equipage Representation

There were two NextGen equipages in this experiment: RNP capability and ADS-B, which are primary avionics for the new capabilities in NextGen. However, in order to solely evaluate the impact of the policies, capabilities and controller commands of the aircrafts were equal regardless of the aircraft's equipage.

In the control screen, the equipages of each aircraft were represented in its aircraft symbol and the flight data block following conventional rules. The ADS-B was represented in the aircraft body symbol; a solid (filled-in) body symbol signified an aircraft equipped with ADS-B, and a hollow body symbol signified an aircraft that is not equipped with ADS-B. The RNP capability was represented with "/R" after the call sign in the aircraft's flight data block. The figure 3-6 represents an aircraft with both ADS-B and RNP (left) and an aircraft with neither of the two avionics (right).

Figure 3-6: Aircraft Equipage Representation

The best-equipped, best-served policy may be implemented to give priority to multiple levels of NextGen equipage. In the experiment, the policy was implemented with two levels of equipage: high equipage and low equipage. High equipage indicates aircraft with both ADS-B and RNP, and low equipage indicates aircraft with either or none of the two NextGen equipages. The tactical best-equipped, best-served policies in this experiment provided operational priority to the high equipage aircraft.

3.5 Participants

Because the air traffic controller tasks require specialized skills that are built only after a long time of training, recruiting participants from the general population may introduce large variation in the experimental result. Therefore, participants with ATC experience were needed to be recruited for the simulation. In order to have sufficient number of participants within the experiment budget, the participants were recruited from ATC trainees instead of the certified air traffic controllers.

Participants who performed in the simulation as air traffic controllers were recruited from the Air Traffic Control Collegiate Training Initiative (CTI) program at Daniel Webster College, New Hampshire. 28 participants (13 female, 15 male) volunteered for the experiment. They were all upper class students in the CTI program who were highly experienced with real-time radar control simulations.

3.6 Experiment Procedure

Each experiment session was about 2 hour long, including a briefing, a tutorial, practice runs, test runs, post-run and post-experiment questionnaires. Before the actual test runs, the participants were introduced to the experiment with a short briefing explaining the objective and simulation details of the experiment. The briefing was followed by a tutorial to familiarize the participants with the simulation interface. The experiment procedure was illustrated with Figure 3-7.

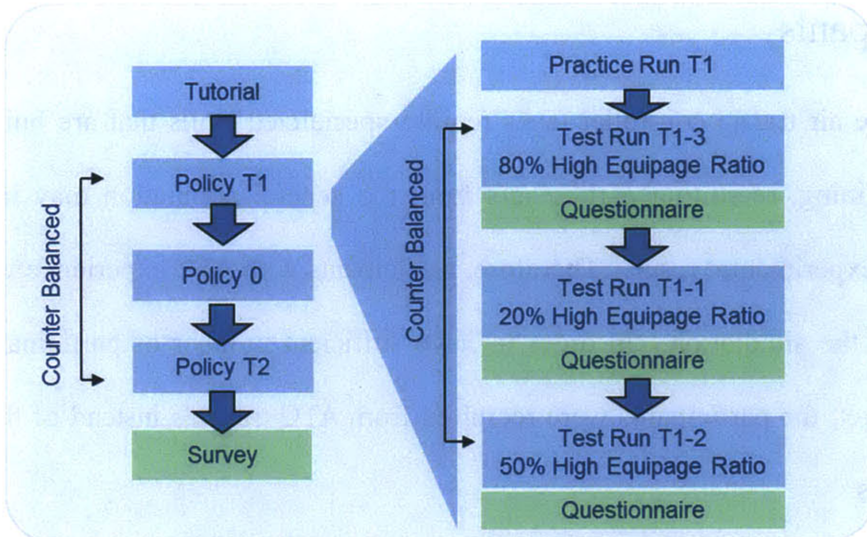

Figure 3-7: The Experiment Procedure

There were three sets of test runs with different policies: one test run with the current first-come, first-served policy, and three test runs with different mixed-equipage ratios for each of the two potential best-equipped, best-served policies, for a total of seven test runs. A practice run was performed before the actual test run for each policy so that the participants could get familiar with the policy rules. The order of the policies and the order of the mixed-equipage ratios were counterbalanced in order to minimize learning effect.

After each test run, the participants were asked to evaluate the controllers' subjective rating of the difficulty of policy conformance and to provide associated reasons in a short questionnaire. Also, another short questionnaire was given to the participants after the entire experiment to find out which policy was the easiest or the hardest to follow.

Chapter 4

Experimental Result/ Data Analysis

The data analysis first compared the average flight time of high equipage aircraft and the low equipage aircraft in order to evaluate the incentive provided by the best-equipped, best-served policies. Then the overall flight time was evaluated to measure the policy's impact on the system efficiency and sector throughput.

Next, the numbers of controller commands were compared between the high and the low equipage aircraft in order to measure the operational priority provided to NextGen equipped aircraft with the potential policies. Then, the number of commands on the entire traffic was evaluated to measure the changes in controller taskload and system efficiency due to the potential policies.

The numbers of controller errors and subjective workload ratings were compared between the potential policies and the current policy in order to evaluate the policies' impact on the controller performance and subjective workload. Lastly, findings from the subject questionnaires were discussed in order to identify the factors behind changes in the controller workload and performance with the tactical best-equipped, best-served policies.

Table 4-1 below summarizes the experimental variables used to analyze the impact of the representative policies in this chapter.

Table 4-1: Experiment Variables

Experiment Variables		***Measure***
Flight Time	Overall	Controller Performance, System Efficiency
	High Equipage	Policy Incentive
	Low Equipage	
Number of Commands	Overall	Controller Taskload, System Efficiency
	High Equipage	Policy Incentive
	Low Equipage	
Total Controller Errors		Controller Performance
Workload Rating		Controller Subjective Workload

The following chapters will discuss the experimental results and statistical analysis of the results for each of the dependent variables. The normality of the distributions was evaluated using the Kolmogorov-Smirnov test. The distributions of flight time, number of commands and controller errors were all normally distributed; therefore, when comparing the results between the different policies, the two-way Analysis of Variance (ANOVA) test was used to compare between multiple policies and mixed-equipage ratios at the same time. The distribution of the subjective workload rating was not normally distributed; therefore, the workload ratings between the different policies were compared through Friedman's non-parametric test, which is a non-parametric version of the two-way ANOVA test.

4.1 Average Flight Time

The purpose of the best-equipped, best-served policy is to provide operational benefits to

NextGen equipped aircraft in order to incentivize users and airlines to invest in the new avionics, thus accelerating the transition to NextGen. In the human-in-the-loop experiment, operational benefits to the high equipage aircraft were fewer delays and maneuvers, and reduced flight time from using the shorter route.

First, the average aircraft flight time of the high equipage aircraft and the low equipage aircraft were compared to evaluate the incentives provided by the best-equipped, best-served policy. Figure 4-1 below illustrates the average flight time of a high and low equipage aircraft from 7 test runs from the experiment. First column is the average flight time under the first-come, first-served policy, which was compared to the rest of the columns. The two sets of three columns represent the two tactical best-equipped, best-served policies with three different mixed-equipage ratios: 20, 50 and 80 percent respectively.

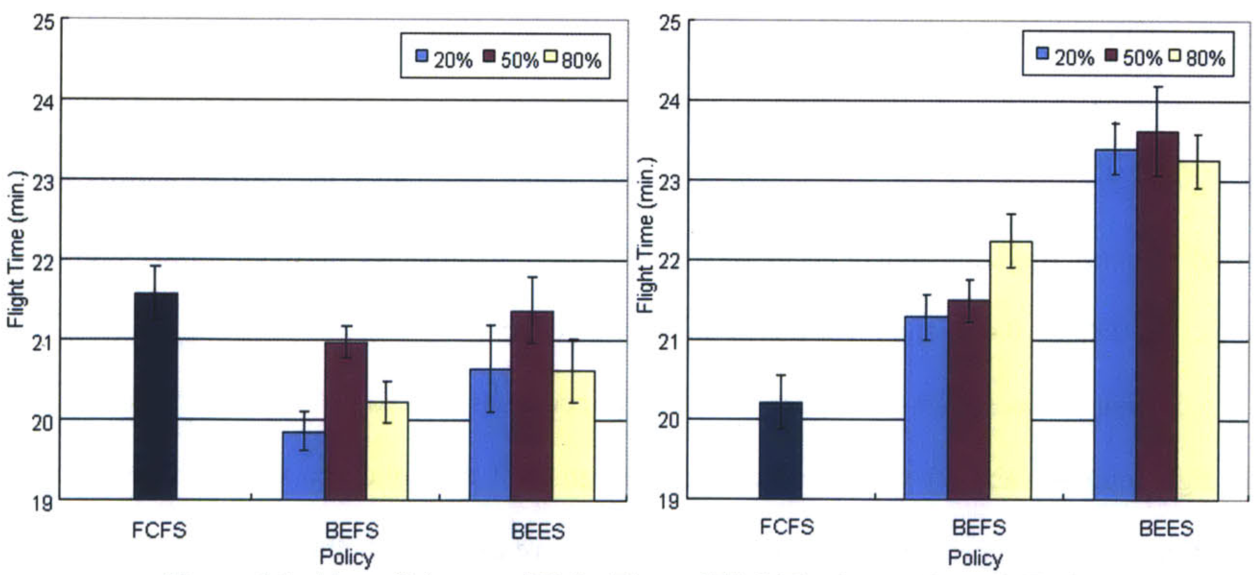

Figure 4-1: Aircraft Average Flight Time of High Equipage Aircraft (Left) and Low Equipage Aircraft (Right)

The results show that the average flight time of an aircraft with the two best-equipped, best-served policies were shorter than the average flight time with the first-come, first-served, especially with the 20 and 80 percent mixed-equipage ratios, indicating that the best-equipped, best-served policy provided an incentive to the high equipage aircraft. The results show that the participants could provide a more incentive when one type of equipage level was dominant.

The average flight time of high equipage aircraft was significantly reduced with the best-equipped, best-served policies ($F = 9.31$, $p < 0.001$) with the ANOVA result. The average decrease in flight time under the best-equipped, best-served policies was 0.96 min. There were marginal differences between the mixed-equipage ratios ($F = 2.66$, $p = 0.0719$) because the decrease in high equipage aircraft's flight time was more significant with the 20 and 80 percent high equipage ratios. No significant interaction effects were shown ($F = 0.77$, $p = 0.5466$).

On the other hand, there was a significant increase in the average flight time of the low equipage aircraft under the two best-equipped, best-served policies. The increase was substantial for all mixed-equipage ratios and was larger with the best-equipped, exclusively-served compared to the best-equipped, first-served. The average flight time of low equipage aircraft was increased significantly ($F = 68.43$, $p < 0.001$) under the best-equipped, best-served policies. The average increase in the low equipage aircraft flight time under the best-equipped, best-served policies was 2.35 min. There was no statistical significance between mixed-equipage ratios ($F = 0.8$, $p = 0.45$), and there was no interaction effect ($F = 0.93$, $p = 0.44$).

Overall it was shown that under the best-equipped, best-served policies, the flight time of the high equipage aircraft was reduced, which means that the policy provided an operational incentive to the equipped aircraft. However, the incentive came at a higher cost with large delay with the low equipage aircraft.

This increase in the low equipage aircraft flight time was larger than the decrease in the high aircraft flight time, which may have negative impact on the system efficiency and sector throughput. Therefore, the system efficiency was measured through the average aircraft flight time of the entire fleet. Figure 4-2 below compares the average flight time of an aircraft from the entire traffic between the three different policies.

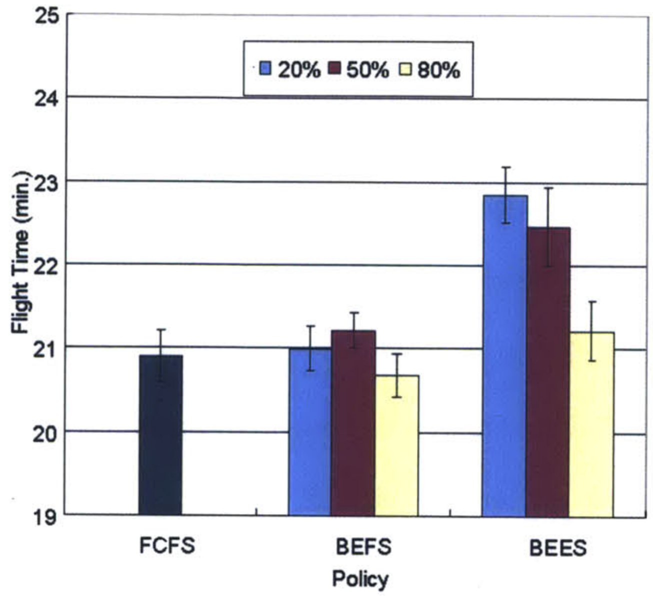

Figure 4-2: Aircraft Average Flight Time

The result shows that under the best-equipped first-served policy, there was no improvement in the total system efficiency, and there were decreases in the system efficiency under the best-equipped, exclusively-served policy, during early and intermediate mixed-equipage phases. The benefit of reduced flight time provided to the high equipage aircraft under the best-equipped, first-served policy was nullified with the increased delay of the low equipage aircraft, resulting in an unimproved overall efficiency. The increased delay of the low equipage aircraft overrode the reduced flight time of the high equipage aircraft resulting reduced overall efficiency under the best-equipped, exclusively-served policy.

The statistic tests showed no significant difference in the average aircraft flight time between the first-come, first-served policy and the best-equipped, first-served policy ($F = 0.07$, $p = 0.7893$). However, there was a significance increase in the average flight time with the best-equipped, exclusively-served policy ($F = 19.2$, $p < 0.001$).

4.2 Number of Controller Commands

The operational priority provided to the NextGen equipped aircraft by the potential best-equipped, best-served policies was evaluated by comparing the number of controller commands between the baseline first-come, first-served policy and the two best-equipped, best-served policies. Because the two best-equipped, best-served policies required the controllers to minimize the delay of the high equipage aircraft, the low equipage aircraft had to be maneuvered between the high equipage aircraft, reducing the number of command on the high equipage aircraft during conflict resolution. Figure 4-3 shows average number of controller commands on a high equipage aircraft and a low equipage aircraft.

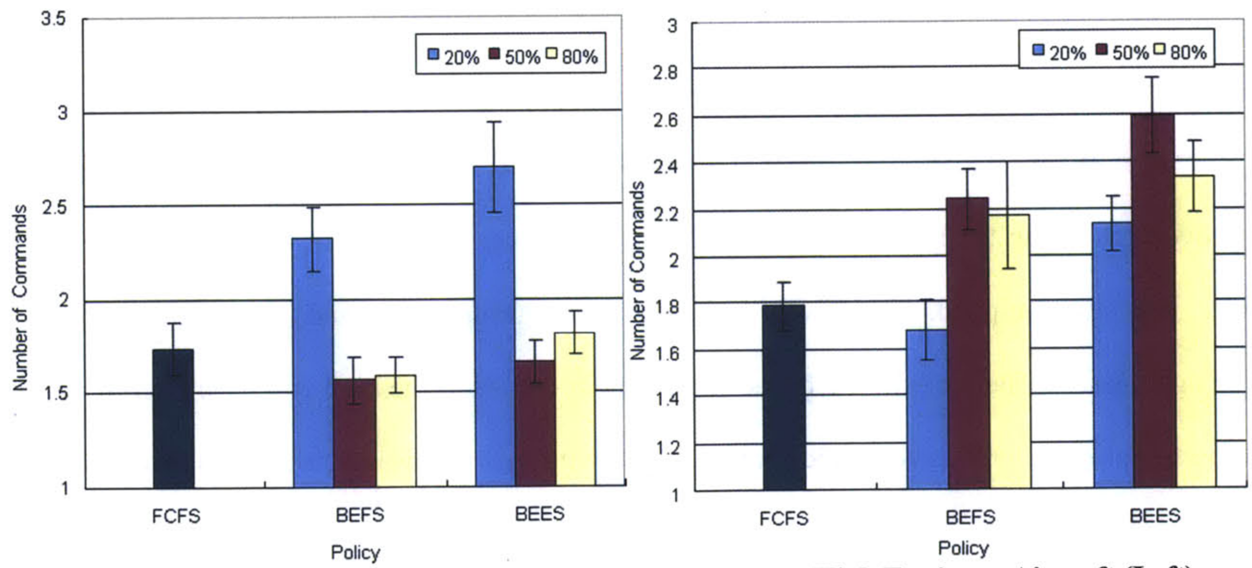

Figure 4-3: Average Number of Controller Commands on a High Equipage Aircraft (Left) and a Low Equipage Aircraft (Right)

However, there was no significant decrease in the average number of commands on a high equipage aircraft with the best-equipped, best-served policies during the 50 and 80 percent mixed-equipage ratios, and there was an increase in the number of commands during the 20 percent mixed-equipage ratio ($p= 0.001$) as shown in the figure above.

There was a significant increase in the number of commands on a low equipage aircraft ($F = 10.43$, $p < 0.001$). Increase in the number of commands increases the controller taskload which may negatively impact the controller workload and performance.

Number of commands on the entire traffic was analyzed to evaluate the impact of the policy on controller taskload in Figure 4-4. There was no statistical difference in the average number of controller commands on an aircraft between the first-come, first-served policy and the best-equipped, first-served policy ($F = 0.25$, $p = 0.6191$). However, there was a significant increase in the number of commands under the best-equipped, exclusively-served policy ($F = 10.57$, $p= 0.0014$).

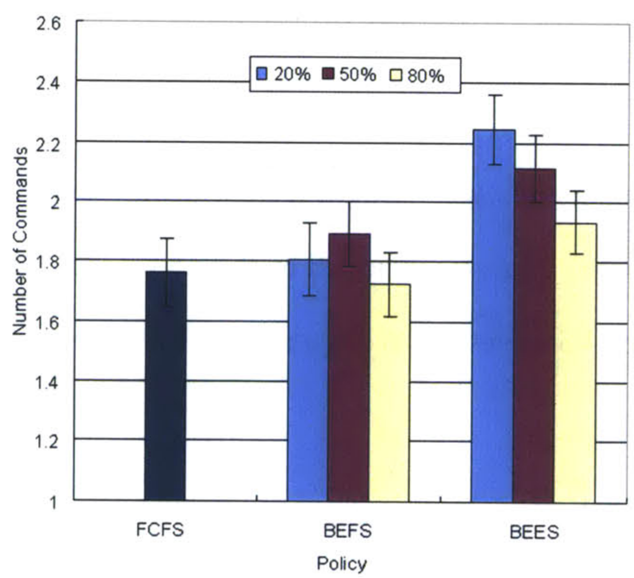

Figure 4-4: Average Number of Controller Commands on an Aircraft

The results showed that under the potential best-equipped, best-served policies, the number of controller commands on the high equipage aircraft was not reduced, indicating that there was no incentive provided to the high equipage aircraft in terms of fewer maneuvers. There was an increase in the number of commands on the low equipage aircraft with the best-equipped, best-served policies, and there was an increase in overall number of commands with the best-equipped, exclusively served policy. The results indicate an increase in the taskload of the controllers, which may have negative impact on the controller performance and workload.

4.3 Number of Controller Errors

The policy's impact on the controller performance was evaluated in terms of the number of controller error. There were three types of controller errors in this experiment: 1) loss of separation events 2) restricted airspace penetrations, and 3) incorrect delivery of aircraft. The following subsections compared the number of errors between the baseline first-come, first-served policy and the best-equipped, best-served policies for each of the three types of controller errors.

Loss of Separation

The minimum separation distance in the experiment was 5nm same as the normal ATC rules in the en-route airspace. 5nm was indicated by the 2.5 nm radius separation circle around each aircraft body. Figure 4-5 represents average number of loss of separation events for each test run.

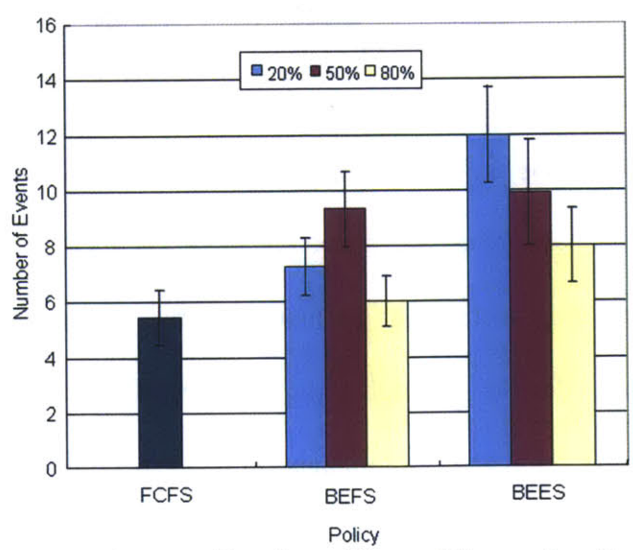

Figure 4-5: Average Number of Loss of Separation Events

The number of loss of separation events was significantly increased with the two best-equipped, best-served policies compared to the baseline first-come, first-served policy ($p = 0.0052$). There was substantial increase with the 20 and 50 percent mixed-equipage ratios for both best-equipped, best-served policies, and the increase was larger under the best-equipped, exclusively served policy.

Restricted Airspace Penetration

There were restricted airspaces located in the sector boundary between the controlled sector and the sector leading to Denver. The controllers needed to manage traffic to avoid entering the restricted airspace. Figure 4-6 shows average number of restricted area penetration for each test run.

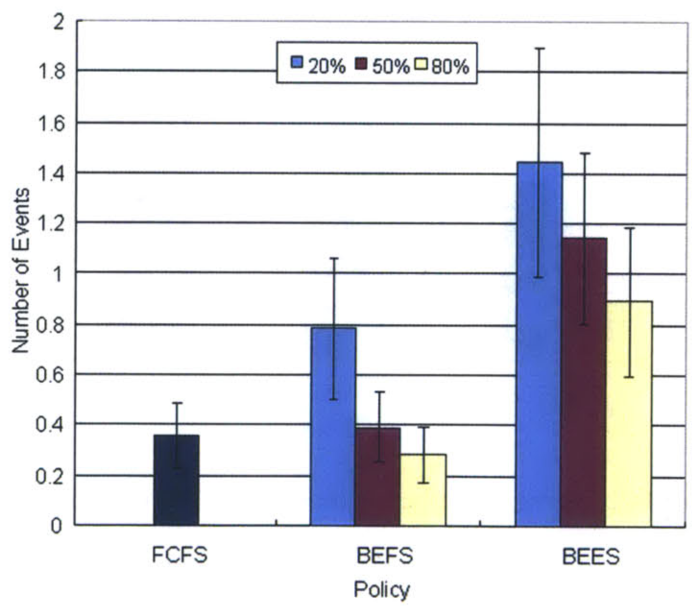

Figure 4-6: Average Number of Restricted Area Penetrations

As shown in the figure, there was an increase in the number of restricted airspace penetration events observed for the best-equipped, best-severed policies, especially for the 20 percent mixed-equipage ratio and the best-equipped, exclusively served policies. However, because the number of restricted airspace penetration events per test run was too low, there was no statistical significant between the policies.

Incorrect Delivery

Incorrect deliveries in the experiment include aircraft sent to an incorrect sector according the aircraft's flight plan and aircraft delivered to an incorrect metering point according to the flight plan. The best-equipped, exclusively-served policy did not allow the low equipage aircraft to use the shorter route. Figure 4-7 represents average number of incorrectly delivered aircraft for each test run.

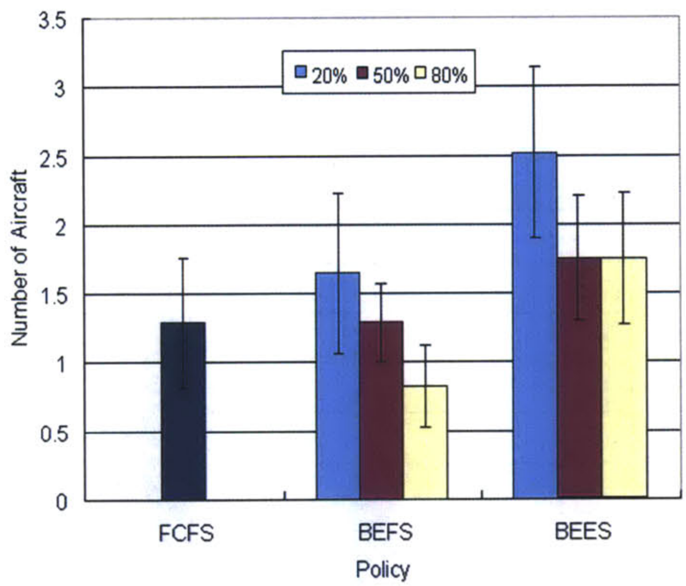

Figure 4-7: Average Number of Incorrectly Delivered Aircraft

There was an increase in the number of incorrectly delivered aircraft observed under the best-equipped, best-severed policies compared to the first-come, first-served policy, especially during the 20 percent mixed-equipage ratio. However, because the number of restricted airspace penetration events per test run was too low, there was no statistical significant between the policies.

Aggregated Controller Errors

Lastly, the three types of controller errors were aggregated to evaluate the policy's impact on the controller performance. The result is shown in Figure 4-8.

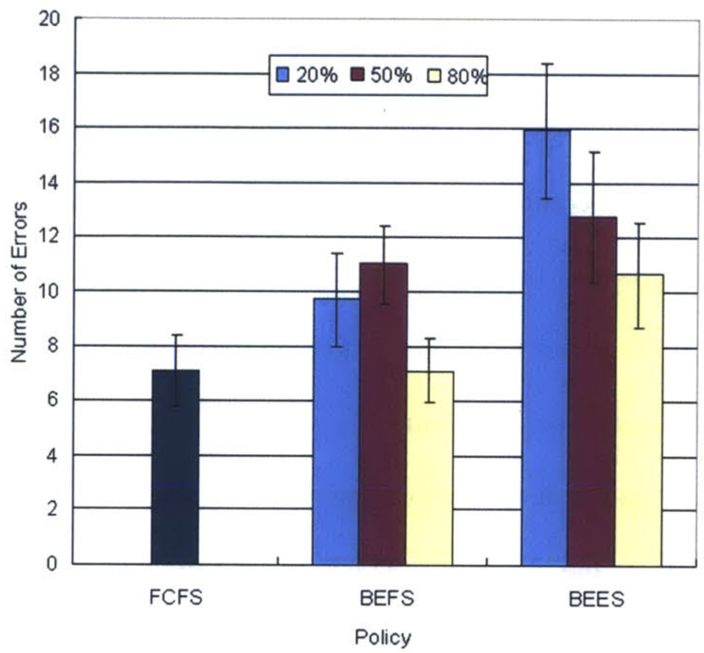

Figure 4-8: Average Number of Aggregated Controller Errors

Generally, there was an increase in the number of controller errors under the two tactical best-equipped, best-served policies. The increase was greater under the best-equipped, exclusively-served policy, which is a more restricted policy in terms of the route assignment. Under both of the policies, the increase was greater during the 20 and 50 percent mixed-equipage ratios, which means that there was a decrease in the controller performance with a large number of low equipage aircraft. These results suggest that the best-equipped, best-served policies had negative impact on the controller performance, increasing the number of controller errors.

The statistics showed that there was a marginal increase in the controller errors under the best-equipped, first-served policy (F = 3.76, p = 0.0543). And there was a significant increase under the best-equipped, exclusively served policy (F = 14.98, p = 0.0002).

4.4 Subjective Workload Rating

The number of aircraft in the sector is the most widely used metric to define sector capacity, because the complexity of traffic increases with an increase in traffic number. Past studies have shown that the controller workload increases drastically when the number of aircraft exceeds the sector capacity, because controller loses his or her mental model when the complexity of the traffic reaches too high due to high traffic density (Wickens, 1992, Lee, 2005). Therefore, a larger increase of the controller workload with the same increase in the traffic density may indicate a change in the sector capacity.

In order to evaluate the change in the controller workload and sector capacity, the traffic density was increased throughout during each test run. The subjective workload rating on a scale from 1 to 7 was rated every minute during the test run. The results from each of the two best-equipped, best-served policies were analyzed.

Best-Equipped, First-Served

The comparison of the workload ratings between the policies plotted in Figure 4-9 shows that the participants experienced higher workload under the best-equipped, first-served policy compared to the first-come, first-served policies. There were substantial differences in the workload ratings for all three mixed-equipage ratios under the best-equipped, first-served policy especially when the number of aircraft in the sector increased more rapidly after 5 min of the test run. A non-parametric test, the Friedman's test, was used to assess the impact of the policy. The test found that there was a significant difference with the best-equipped, first-served policy (χ^2 = 14.91, p = 0.0019).

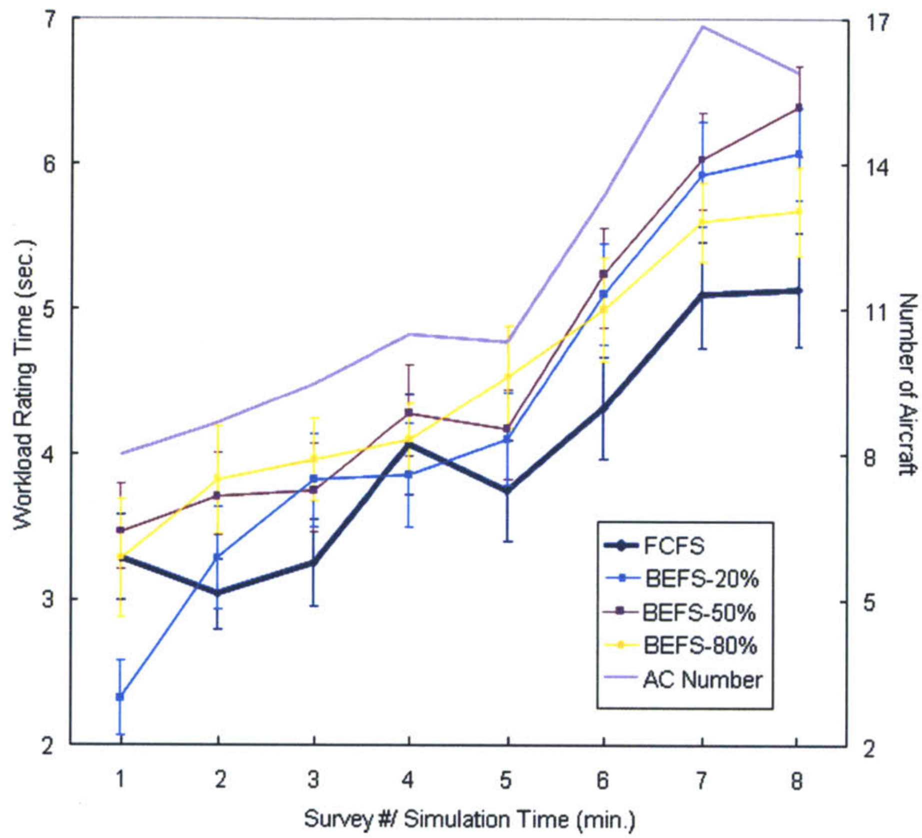

Figure 4-9: Subjective Workload Rating with Best-Equipped, First-Served Policy

Best-Equipped, Exclusively-Served

Figure 4-10 representing workload rating comparison between the best-equipped, exclusively-served policy and the first-come, first-served policy showed a similar trend. There were substantial differences in the workload ratings for all three mixed-equipage ratios under the best-equipped, exclusively-served policy when the number of aircraft in the sector increased more rapidly after 5 min of the test run. A non-parametric test, the Friedman's test found that there was a significant difference with the best-equipped, exclusively-served policy (χ^2 = 15.55, p = 0.0014).

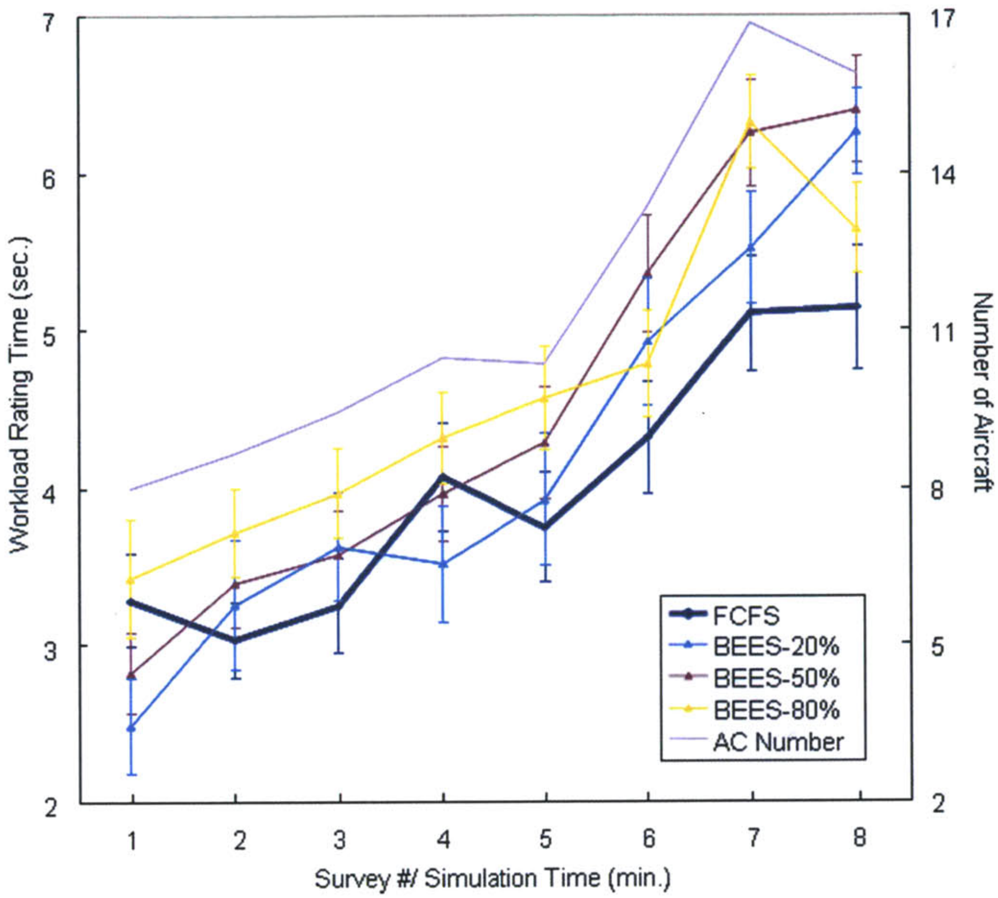

Figure 4-10: Subjective Workload Rating with Best-Equipped, Exclusively-Served Policy

These results suggest that both of the tactical level best-equipped, best-served policies had negative impact on the controller cognitive workload. The significant increase in the average workload rating during high traffic density suggests that the policy may have reduced the controller cognitive capacity, which has direct impact on the system capacity.

4.5 Workload Rating Time (Secondary Task Performance)

As a secondary task, the controllers had to rate their workload as soon as the workload rating keypad appeared on the left side of the control screen. Auditory alerts notified participants when the keypad appeared and the visual notification blinked until the controller rated his or her current workload. The time participants took to rate the workload was recorded as a secondary performance. The length of time to rate was an indirect measure of the workload of the controllers who were performing their primary task of managing traffic. However, the distribution of the data was too large and the statistical test did not show difference between the policies.

4.6 Subjective Questionnaire

Post Run Questionnaire

After each test run, controllers were given a short questionnaire for subjective ratings of the difficulty of policy conformance and the proportion of successful implementation of the policy.

Question1. **How difficult was it for you to follow the policy? (1-5 scale)**

1 Very Easy
2 Easy
3 Neutral
4 Difficult
5 Very Difficult

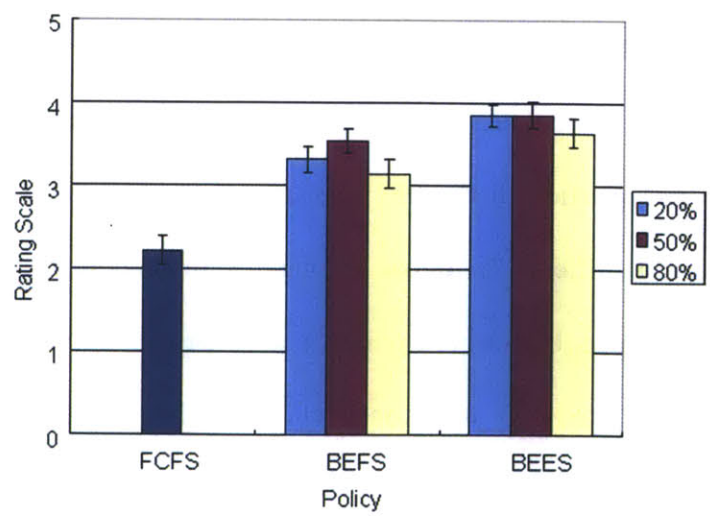

Figure 4-11: Difficulty Rating of Policy Conformance

Question 2. **How many time were you able to successfully implement the policy?**

1 Never
2 Rarely, ~10% of the chances
3 Occasionally, ~30% of the chances
4 Sometimes, ~50% of the chances
5 Frequently, ~70 % of the chances
6 Usually, ~90% of the chances
7 Every time.

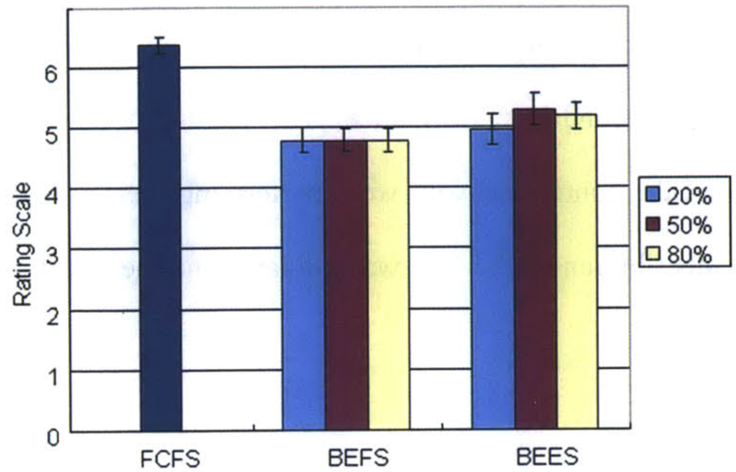

Figure 4-12: Rating of Successful Policy Implementation

The results from the questionnaires shown in Figure 4-11 and 4-12 suggest that the participants felt more difficulty following the two potential best-equipped, best-served policies, and also that they felt they were less successful implementing the policy rules under the potential policies. The results from the questionnaires were consistent with the objective measurements and the subjective ratings, suggesting that the best-equipped, best-served policies negatively impacted the controller workload and controller workload.

Post Test Questionnaire

After the entire experiment, two short questionnaires were given to the participants. The first question of the first questionnaire asked the participants to identify which policy was the most difficult to follow among the three policies: 1) first-come, first-served policy, 2) best-equipped, best-served policy, and 3) best-equipped exclusively served policy. The result shown in Figure 4-13 was consistent with the objective measurements and subjective ratings. All participants except one participant (96%) chose one of the two best-equipped, best-served policies as the most difficult policy.

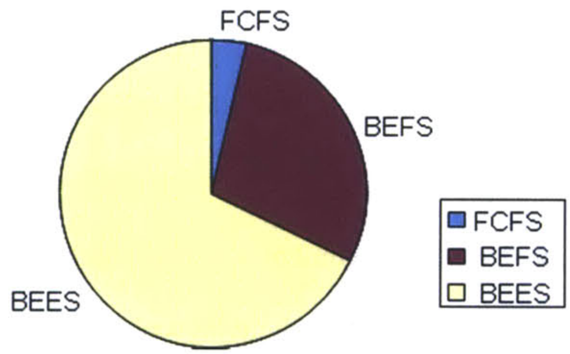

Figure 4-13: Post-Experiment Questionnaire 1 Result.

In order to identify factors which made the two best-equipped, best-served policies difficult to follow, the participants were asked to provide reasons for their choices in the previous question, and they were allowed to provide multiple reasons. Excluding the outliers, there were two dominating answers from the questionnaire: 1) "The best-equipped, first-served policy was the most difficult", 2) "the best-equipped, exclusively-served policy was the most difficult." The reasons of the two answers could be classified into four main categories: route assignment, conflict resolution, equipage identification, and general traffic management, as shown in Table 4-2 below.

Table 4-2: Reasons for the Answers to the Post-Test Questionnaire 1

Answers / *Reasons*	*"Best-Equipped, first-served policy was most difficult"*	*"Best-equipped, exclusively-served policy was most difficult"*
Route Assignment	1 (10%)	13 (65%)
Conflict Resolution	2 (20%)	3 (15%)
Equipage Identification	6 (60%)	3 (15%)
Traffic Management	1 (10%)	1 (5%)

Among the participants who thought that the best-equipped, first-served policy was the most difficult policy, equipage identification and conflict resolution were the main reasons for their choice. The participants stated that the policy created an additional task of equipage identification, and that this additional variable to their decision process made the controller task more difficult. They also stated that the policy also restricted their solutions to conflict resolution, which made them choose more difficult and less efficient solutions.

The participants who thought that the best-equipped, exclusively-served policy was most difficult stated that the restricted route assignment was the biggest factor that increased their difficulty level. They stated that it was difficult to re-sequence the traffic according to the aircraft's equipage, and that the impact was greater when the traffic load got heavy. They also stated that it could have been easier if the traffic was sequenced according to the equipage before the traffic entered the airspace.

Similarly, the second questionnaire asked the participants to identify which policy was the easiest to follow, among the three policies: 1) first-come, first-served policy, 2) best-equipped, best-served policy, and 3) best-equipped exclusively served policy. The result shown in Figure 4-14 was also consistent with the objective measurements and subjective ratings; most of the participants (93%) chose the first-come, first-served policy as an easiest policy to follow.

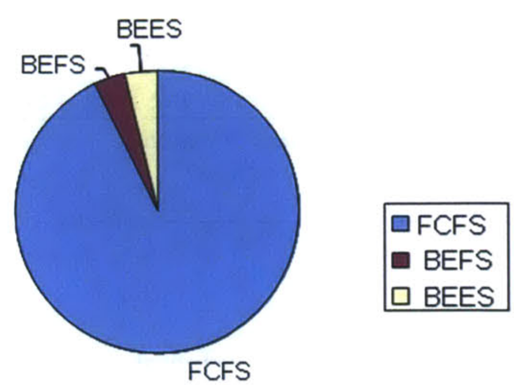

Figure 4-14: Post-Experiment Questionnaire 2 Result.

Most of the participants thought that the first-come, first-served policy was easier than the two tactical best-equipped, best-served policies. Reasons behind the answer could be also classified into four main categories: route assignment, conflict resolution, equipage identification, and general traffic management. As shown in Table 4-3, the biggest reason was that they did not have to focus on the equipage of the aircraft, and simply treated all of them equally. They thought that it was hard to keep track of the aircraft equipage under the best-equipped, best-served policies, especially when large traffic load was presented. Lastly, they stated that the restricted route assignments and conflict resolutions under the best-equipped, best-served policies made the first-come, first-served policy the easiest policy among the three.

Table 4-3: Reasons for the Answers to the Post-Test Questionnaire 2

Reasons \ *Answers*	*"First-come, first-served was easiest"*
Route Assignment	9 (32.1%)
Conflict Resolution	3 (10.7%)
Equipage Identification	10 (35.7%)
Traffic Management	6 (21.4%)

The reasons they provided in the post-test questionnaires were consistent with the initial hypothesis of this study. The additional task of equipage identification makes the monitoring task of the controllers more difficult, and the restricted control strategy reduces the solution sets of the controllers. Due to an additional variable to consider with each aircraft, it is more difficult to track each of the aircraft, because even though the aircraft are in a same major flow, the controllers can no longer treat them equally and apply similar strategies. The loss of important cognitive abstractions makes the controllers easier to lose the mental model of the airspace during increased traffic density.

4.7 Discussion and Summary

The experimental results suggest that the tactical level best-equipped, best-served policies have adverse impact on the controller performance and workload. The results demonstrated decrease in the controller performance with increase in the number of controller errors, and increase in the controller cognitive workload, reducing the system efficiency and capacity. Table 4-4 below summarizes the experimental result. For each experimental variable, the positive impact of the policy was denoted with green and the negative impact was denoted with red. Yellow represents the neutral impact of the policy.

Table 4-4: Summary of the Experiment Result

Experiment Variables		***Measure***	***Best-Equipped, Best-Served vs. First-Come, First-Served***	
			Best-Equipped, First-Served	**Best-Equipped, Exclusively-Served**
Flight Time	Overall	Performance Efficiency	**No Difference**	**Increase**
	High Equipage	Preferential Treatment	**Decrease**	**Decrease**
	Low Equipage		**Increase**	**Increase**
Number of Commands	Overall	Taskload Efficiency	**No Difference**	**Increase**
	High Equipage	Preferential Treatment	**No Difference**	**Increase**
	Low Equipage		**Increase**	**Increase**
Total Controller Errors		Performance	**Increase**	**Increase**
Workload Rating		Subjective Workload	**Increase**	**Increase**

Positive **Negative** **Neutral**

The best-equipped, best-served policies provided an operational benefit of shorter flight time to the high equipage aircraft; however, the delays in the low equipage aircraft were larger.

The overall system efficiency was not improved under the best-equipped, first-served policy, and the efficiency was degraded under the best-equipped, exclusively served policy.

The number of controller commands on a high equipage aircraft was not reduced and the overall number of controller commands increased under the best-equipped, exclusively-served policies, which indicate an increase in the controller taskload, thus increasing the controller workload.

Under both of the tactical best-equipped, best-served policies, controller error rates increased significantly compared to the current first-come, first-served policy. And the results of controller subjective workload rating also show that the workload was increased with the best-equipped, best-served policies, especially during high traffic density which indicates that the policies may have negative impact the controller cognitive capacity.

These results suggest that caution needs to be exercised when considering the implementation of the tactical level best-equipped, best-served policy, because the policy may have negative impact on the system efficiency, controller workload and performance that is beyond the operational incentive provided to the NextGen equipped aircraft.

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Chapter 5

Conclusion and Future Work

The best-equipped, best-served policy proposed by the FAA is currently under development. The policy is expected to provide incentives to the users and the airlines to quickly adopt the new advanced avionics that are required in transition to NextGen. However this new task of prioritization may introduce adverse impacts on the air traffic controller performance and workload. The controller workload is one of the limiting factors of the new system, therefore changes in controller tasks and procedures must evaluated for its potential impact on the controller prior to the implementation, in order to receive full benefit of the changes and to maintain the system safety.

The best-equipped, best-served policy may provide the incentivization at two system levels: strategic and tactical level. This thesis focused on the tactical level policy, because it may create controller tasks that have adverse impacts on the controller performance and workload. In order to investigate the impact of the policy, two representative tactical level policies and procedures were identified and a human-in-the-loop simulation was designed to evaluate impact of the representative policies on the controller workload and performance.

The findings from the experiment showed that the potential tactical best-equipped, best-served policies have adverse impacts on the controller performance and workload. The results demonstrated decrease in the controller performance with increase in the number of controller errors, and increase in the controller cognitive workload, reducing the overall system efficiency and the capacity. This suggests that the strategic level implementation of the best-equipped, best-served policy must be considered instead of the tactical level; however, this thesis did not address the impact of the strategic level policy.

Therefore, a future work is required to investigate the impact of the strategic best-equipped, best-served policy on the air traffic controller performance and workload. The tactical level policy required the air traffic controllers to identify equipage of the aircraft and manage mixed-equipage environment, whereas the strategic policy will partially segregate the aircraft at the traffic flow manager level, depending on the aircraft equipage prior to the sector entry. The aircraft may be spatially or sequentially segregated, so that the air traffic controller can separately manage the aircraft with different capabilities and provide the operational priority. The potential impact of the strategic policy must be evaluated through a human-in-the-loop experiment.

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Appendix

Pre-Test Questionnaire

Participant ID #:_______________

Age: ________________________

Gender: ______________________

Major and Year: ________________________

Please answers to following questions.

1. How long did you study Air Traffic Control at Daniel Webster College or other academic institutions?

- Less than 1 year........................☐
- 1 ~ 2 years...............................☐
- 2 ~ 3 years...............................☐
- More than 3 years.......................☐

2. Have you ever trained on Air Traffic Control real-time simulation?

Yes **No**

If yes, how often did you practice on it within last 3 months?

-
- Never..................................... ☐
- Monthly.................................. ☐
- At least one a week.....................☐
- Several times a week...................☐
- Daily......................................☐

Any questions before I introduce you to the ATC simulation and begin the experiment?

Post-Run Questionnaire
Run#________

Scenario_________

Participant ID #:_______________

Please circle your response

1. How difficult was it for you to follow the policy?.

1	**2**	**3**	**4**	**5**
Very Easy	Easy	Neutral	Difficult	Very Difficult

2. How many time were you able to successfully implement the policy?

1	**2**	**3**	**4**	**5**	**6**	**7**
Never	Rarely, In less than 10% of the chances	Occasionally, in about 30% of the chances	Sometimes, in about 50% of the chances	Frequently, in about 70 % of the chances	Usually, in about 90% of the chances	Every time.

3. Did aircraft with certain equipage made it more difficult for you to follow the policy?

Yes **No**

If yes, which aircraft? (Please select all that apply)

- Aircraft with both ADS-B and RNP.................................... ☐
- Aircraft with ADS-B only... ☐
- Aircraft with RNP only.. ☐
- Aircraft that has neither ADS-B nor RNP........................... ☐

Why? (Please explain)

____

Post-Test Questionnaires

Participant ID #:_______________

Please circle answers to following questions.

1. Which policy was **most difficult** to follow?

1. First-Come, First-Served (Current Operation)

2. Best-Equipped, First-Served

3. Best-Equipped, Exclusively-Served

Why? (Please explain your reason briefly)

____

____

2. Which policy was **easiest** to follow?

1. First-Come, First-Served (Current Operation)

2. Best-Equipped, First-Served

3. Best-Equipped, Exclusively-Served

Why? (Please explain your reason briefly)

____

____