Technology Transition in the National Air Transportation System: Market Failure and Game Theoretic Analysis with Application to ADS-B

by

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Submitted to the Department of Aeronautics and Astronautics
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Abstract

This research analyzes the problem of technology transition in the national air transportation system, focusing on the implementation of Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B is a key technology in the Federal Aviation Administration's plan to modernize the national civil air transportation surveillance system. Data regarding airline perception of benefits, barriers, and knowledge of ADS-B is presented. Market mechanisms that could potentially cause technology implementation failure are identified through game theoretic analysis of airline interview data. Potential market failures identified include public goods failures, cost-benefit asymmetries, information asymmetries, and risk dominance. Potential institutional failures identified include organizational process failures and bureaucratic interests and politics. Government action to correct market failures is explored. Government mechanisms to correct market failures include technology value, support infrastructure development, positive incentives, putative measures, and mandates.

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Acronyms

ACARS Aircraft Communications Addressing and Reporting System

ADS-B NRA ADS-B Non-Radar Area

ADS-B Automatic Dependent Surveillance-Broadcast

ADS-R Automatic Dependent Surveillance-Rebroadcast

AOC Airline Operations Center

AOPA Aircraft Owners and Pilots Association

ASDE-X Airport Surface Detection Equipment Model X

ATA Air Transport Association

ATC Air Traffic Control

BOS Boston Logan Airport

CDA Continuous Descent Approach

CDTI Cockpit Display of Traffic and Information

Conops Concept of Operations Document

COUHES Committee On the Use of Human Experimental Subjects

CPDLC Control Pilot Data Link Communications

EFB Electronic Flight Bag

ETMS Enhanced Traffic Management System

EWR Newark Liberty Airport

FAA Federal Aviation Administration

FANS Future Air Navigation System

FIS-B Flight Information Service-Broadcast

FMS Flight Management System

GA General Aviation

GoMex Gulf of Mexico

GPS Global Positioning System

HFOM Horizontal Figure of Merit

HPL Horizontal Protection Limit

IDS Interdependent Security Problems

IFR Instrument Flight Rules

LCC Low Cost Carrier

LRU Line Replaceable Units

MFD Multifunction Displays

Mode-S ES Mode-S Extended Squitter

NAC Navigation Accuracy Category

NAS National Air Space

NextGen Next Generation Air Transportation System

NIC Navigational Integrity Containment

NPRM Notice of Proposed Rulemaking

NUC Navigational Uncertainty Category

OEP Operation Evolution Partnership

ONT Ontario California Airport

PHL Philadelphia International Airport

PRM Precision Runway Monitor

RNP Required Navigation Performance

ROI Return on Investment

RTCA Radio Technical commission for Aeronautics

SBS Surveillance and Broadcast System

SDF Louisville International Airport

SEA Seattle Tacoma International Airport

SFO San Francisco International Airport

SIL Surveillance Integrity Level

STC Supplemental Type Certificate

TCAS Traffic Collision Avoidance System

TIS-B Traffic Information Service-Broadcast

U.S. United States of America

UAT Universal Access Transceiver

UPS United Parcel Service

VFR Visual Flight Rules

WAAS Wide Area Augmentation System

Chapter 1

Introduction

1.1 Objective

This thesis examines the problem of technology adoption in air transportation, focusing on the case of Automatic Dependent Surveillance Broadcast (ADS-B). The goal is to identify the market mechanisms that might impeded technology implementation and to explore the potential role of government in correcting those problems. This thesis also seeks to understand how stakeholders think about the costs and benefits of ADS-B.

1.2 Motivation

Air traffic demand is increasing, but capacity is constrained by an antiquated air traffic control (ATC) infrastructure. The number of air traffic passengers in the U.S. is expected to grow from 738 million in 2005 to 1 billion in 2015. The number of commercial airline flights is expected to grow from 13 million in 2005 to 15 million in 2015. [22] Figure 1-1 shows the growth in air traffic demand in the United States in recent years.

ADS-B, a satellite-based surveillance system, offers an opportunity to modernize the civil air traffic surveillance system. It is a key enabling technology for the Federal Aviation Administration's (FAA) Next Generation Air Transportation System

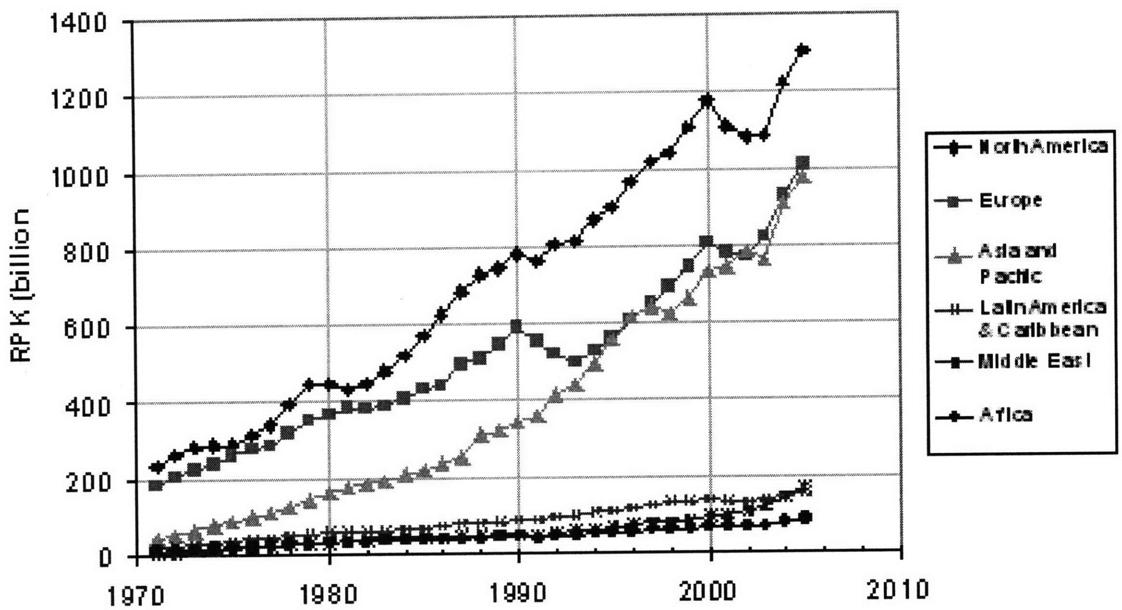

Figure 1-1: Traffic Increase in the NAS [22]

(NextGen). The current ATC system in the U.S. uses radar technology for surveillance.

The FAA hopes that ADS-B will enable new applications and procedures that will provide benefits in three areas- safety, airspace capacity, and operational efficiency. Key benefits include:

- Air-to-air surveillance capability.
- Surveillance in remote or inhospitable areas that do not currently have coverage with radar.
- Real-time traffic and aeronautical information in the cockpit.
- Reduced separation and greater predictability in departure and arrival times.
- Support of common separation standards, both horizontal and vertical, for all classes of airspace.
- Improved ability of airlines to manage traffic and aircraft fleets.
- Improved ability of air traffic controllers to plan arrivals and departures far in advance.
- Reduced cost of the infrastructure needed to operate the National Airspace System.

The FAA's Surveillance and Broadcast System (SBS) program office has been tasked with implementing ADS-B. [1] The SBS program is interested in encouraging voluntary early adoption of ADS-B by the airspace users. The SBS program would also like to ensure successful completion of the program in the long run. Early adoption is important because there is the perception of a pressing need for improvement in the current air transportation system. The long term success of the program is important to delivering improvements to the national airspace and for reaping a return on investment.

1.3 Background

1.3.1 ADS-B

ADS-B technology can be described by considering the components of its name. The system is automatic in that airplanes transmit data periodically, without interrogation. This is different from the radar system, which is based on interrogation-response. The system is dependent in that it receives signals from similarly equipped ground stations and aircraft. The surveillance portion of the system describes the intended use of the technology. The broadcast component comes from the fact that an airplane's message is sent to all receivers in its vicinity, including ground stations and other equipped aircraft. [1] Broadcast provides the potential for sending air to air signals, which can enable self-separation. A picture of the ADS-B system is shown in Figure 1-2.

There are two types of ADS-B functionality, which differ in required equipage and capability: ADS-B Out and ADS-B In. ADS-B Out is an airplane's ability to broadcast messages. ADS-B In is the ability of an airplane to receive ADS-B messages and display the information in the cockpit. ADS-B Out enables applications that require an air to ground link. ADS-B In enables air to air applications when used in conjunction with Cockpit Display of Traffic Information (CDTI), a method of displaying the messages received by the airplane in the airplane's cockpit. [2]

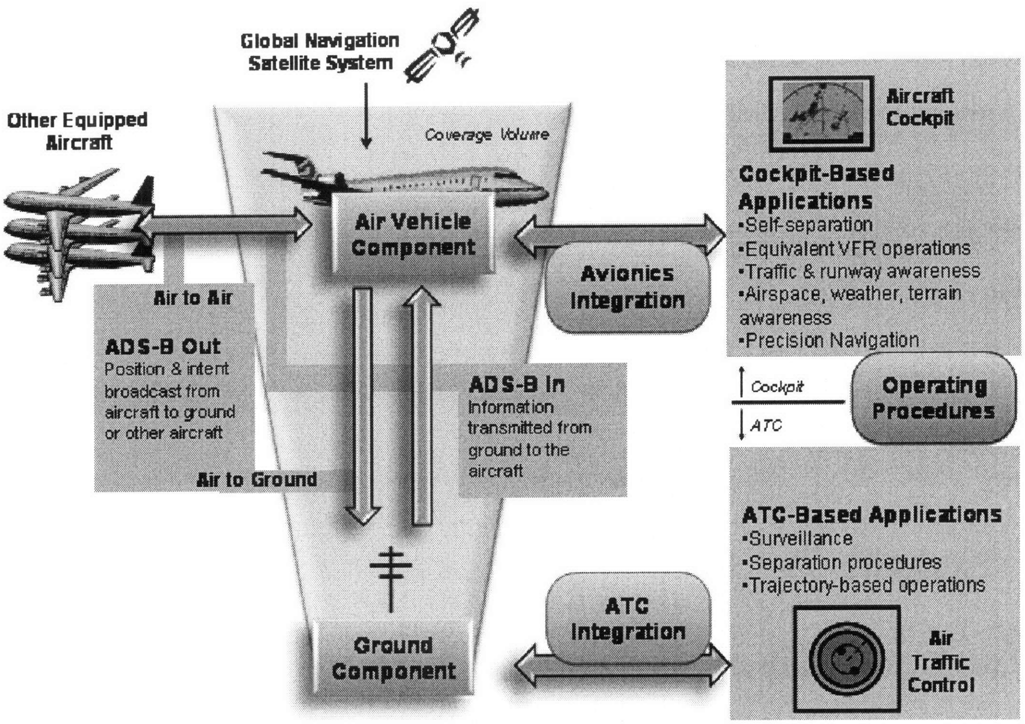

Figure 1-2: ADS-B System map [22]

Hardware

ADS-B hardware has both ground and aircraft components. On the airplane, a Mode-S Extended Squitter (ES) transponder, antenna, global positioning system (GPS), and a connection to the cockpit are required for ADS-B Out. CDTI would also be needed to enable ADS-B In on the airplane. The ground component of ADS-B consists of a ground station for receiving and processing ADS-B Out messages from aircraft. Ground infrastructure also requires a link between the ground stations and the ATC automation interface. [2]

1.3.2 Proposed ADS-B Rule in the United States

A notice of proposed rulemaking (NPRM) for ADS-B was issued by the FAA in August 2007. The NPRM proposes to mandate airplane equipage with ADS-B Out by 2020.

Airplanes in the United States will need to equip to technical standards specified in Radio Technical Commission for Aeronautics (RCTA) document DO260A. According to the NPRM, ADS-B ground infrastructure replicating current radar surveillance coverage in the national air space (NAS) will be installed by 2014. There is a seven year lag between completion of ground infrastructure deployment and mandated aircraft equipage to allow general aviation (GA) aircraft enough time to comply.

The U.S. has adopted a dual link standard for ADS-B, meaning that it will use both 1090 ES and universal access transceiver (UAT) links. 1090ES broadcasts in the 1090MHz frequency and is intended for use by commercial aircraft. UAT broadcasts on the 978 MHz frequency and is intended for use by GA aircraft. The 1090 link is the international standard for ADS-B. The FAA chose UAT in addition to 1090 because it wanted to offer a cheaper avionics package for GA. Furthermore, the extra bandwidth afforded by UAT can be used to offer airspace information and weather services to GA. The weather and information services come as part of a technology packaged called Flight Information Service-Broadcast (FIS-B). FIS-B will be deployed with ADS-B but is not an ADS-B technology. FIS-B will not be offered on the 1090 link because airlines already use commercial weather products. To bridge the 1090 and UAT link frequencies, the FAA will deploy automatic dependent surveillance rebroadcast (ADS-R), which will retransmit signals sent from one frequency via the second frequency. Furthermore, during the technology transition to full ADS-B equipage, a technology called Traffic Information Surveillance-Broadcast (TIS-B) will bridge the radar and ADS-B transmission frequencies. [2]

Rollout

The four services deployed as part of the ADS-B program are divided into two packages. The first package is for ADS-B, which consists of ADS-B and ADS-R. The second package is for data link services, including TIS-B and FIS-B.

The SBS program is also funding implementation of Airport Surface Detection Equipment Model X (ASDE-X) at major (OEP-35) airports. [25] ASDE-X is a ground surveillance program designed to improve visibility of airplanes on airport surfaces.

Although TIS-B, FIS-B, and ASDE-X are offered by the SBS program, they are not ADS-B functionalities.

The SBS program is deploying ADS-B across the nation in two segments. Segment 1 is a trial segment, occurring between 2009 and 2010. In Segment 1, TIS-B and FIS-B will be deployed throughout the NAS. In addition, ADS-B will be deployed at several trial sites, including Ft. Meyers, Philadelphia (PHL), Louisville (SDF), Gulf of Mexico (GoMex), and Ontario (ONT). [4] Ft. Meyers, Florida will receive information services as part of segment 1. This is part of a test program with Embrey Riddell's flight school to test these services for GA aircraft. Areas receiving an ADS-B connection to ATC include Philadelphia and Louisville airports, as well as the Gulf of Mexico. The Gulf of Mexico project is in collaboration with helicopter operators in the region and is intended to test ADS-B in non-radar areas. The Louisville site was selected because United Parcel Service (UPS), a cargo airline, is an early adopter of ADS-B. It is intended as a demonstration of ADS-B in low traffic density environments. The Louisville airspace is considered a low density traffic environment UPS is the dominant operator, with flights primarily at night. Philadelphia will be used to test ADS-B in high density, or mixed equipage airspace. There will also be an ADS-B ground station deployed at Ontario, California, another UPS hub. However, there will not be a connection to ATC at Ontario.

Segment 2 will deploy ADS-B ground stations across the nation. Ground station deployment will occur between 2010 to 2013, progressing from the East to West Coasts. A contract for the segment 2 rollout was awarded to ITT in August of 2007.

Applications

The SBS Concept of Operations (Conops) offers a set of applications for the initial round of applications. [3]

- ATC Surveillance
- Airport Surface Situational Awareness
- Final Approach Runway Occupancy Awareness

- Enhanced Visual Acquisition
- Enhanced Visual Approach
- Cockpit Display of Traffic Information/ Multifunction Display Assisted Visual Separation
- Merging and Spacing
- In-Trail Procedures and Application in Oceanic Airspace
- Conflict Detection
- Weather and NAS Situational Awareness

Conflict detection and Weather and NAS Situational Awareness benefit GA only. The Conops notes that conflict detection is not intended to be a traffic collision avoidance system(TCAS) replacement. Weather and NAS Situational Awareness are enabled through FIS-B, which is only available on the UAT link.

The ATC surveillance application affects air traffic control applications. Airport surface situational awareness, final approach runway occupancy awareness, enhanced visual acquisition, cockpit display of traffic information/ multifunction display assisted visual separation, and enhanced visual approach rely on ADS-B In because the applications utilize CDTI. Airport surface situational awareness, final approach runway occupancy awareness, and enhanced visual acquisition uses a cockpit display to provide situational awareness on the surface, on approach, and in airport airspaces respectively. Enhanced visual approach uses a cockpit display to continue the use of visual procedures in marginal conditions, such as haze, fog, ect. [3]

1.3.3 Airplane Equipage in the United States

Current airline equipage in the U.S. can be divided into four categories: not equipped, latent, latent for ADS-B Out, and latent for CDTI.

Not equipped aircraft lack upgradeable links, Multifunction Displays (MFDs) capable of ADS-B, and an acceptable GPS. These airplanes are likely to be analog airplanes. Also in this category are early ARINC 429 data bus airplanes, the first generation of digital bus airplanes, which might have an flight management system

(FMS) not capable of supporting ADS-B. These aircraft would need new displays and processors and a link to the FMS.

Latent aircraft have a GPS interface and display, but need a special type certificate (STC) for an ADS-B link. Generally, needing an STC indicates some level of hardware modification.

Latent for ADS-B Out aircraft have Mode-S transponders that can be upgraded to ES and can interface with the existing GPS receiver. Latent aircraft have integrated avionics, and a modern FMS with integrated functions that interface to electronic cockpit displays. Upgrading these aircraft for ADS-B Out would require software upgrades for the central processor and upgrades to certain line replaceable units (LRUs). For ADS-B In, these aircraft would need recertification of the software with CDTI.

Latent for CDTI airplanes have a transponder that can be upgraded for ADS-B, a MFD, and an interface to GPS. To upgrade to ADS-B In, these aircraft would need recertification of the software for CDTI.

About 5000 aircraft in the United States are equipped with the DO-260 version of ADS-B. However, some of these aircraft have an unacceptable horizontal protection limit (HPL) because some avionics manufacturers misinterpreted the DO-260 requirements.

The equipage and latency status of the airplanes do not necessarily correlate with the cost of equipage. Older airplanes might be easier to equip than newer airplanes. The integrated electronics of new planes might require recertification of software and may not be entirely compatible with ADS-B. Both these problems could add to the time and cost of the upgrade. By comparison, replacing the entire system of an older airplane may be easier than upgrading a newer plane. [17]

1.3.4 ADS-B Infrastructure in the United States

A legacy infrastructure of data link services (TIS-B and FIS-B) exists on the coasts of the United States, shown in Figure 1-3. [4] There have also been tests of ADS-B in Alaska and the Ohio Valley through the Capstone and Safe Flight 21 initiatives,

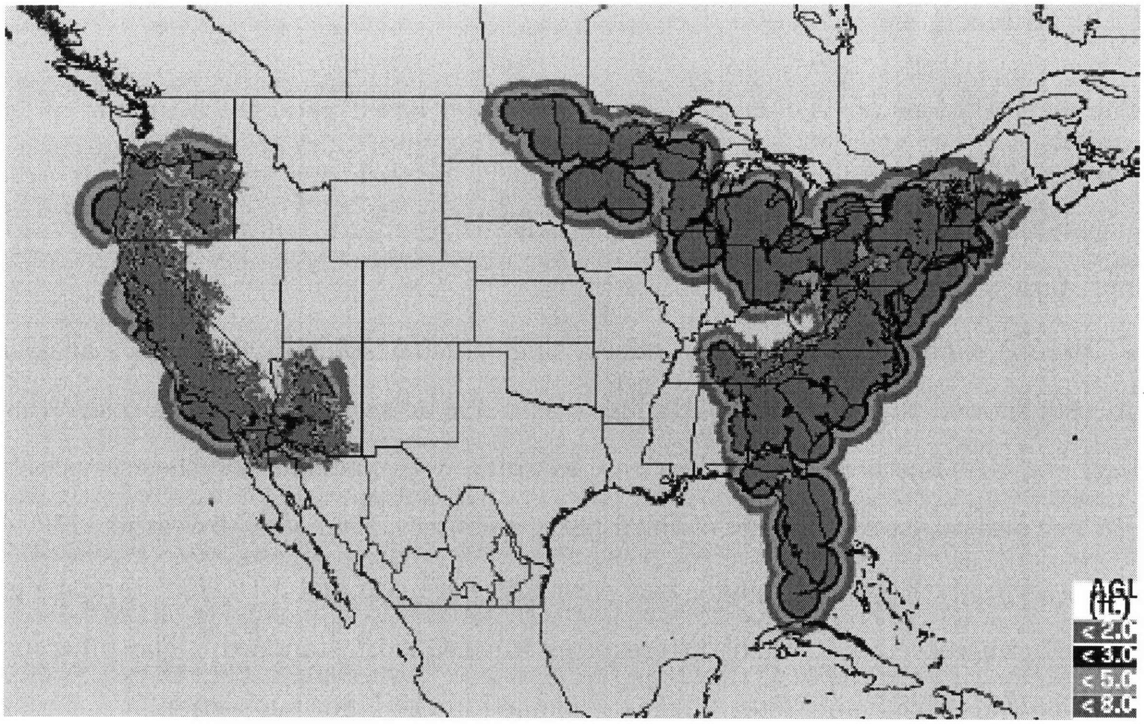

Figure 1-3: TIS-B and FIS-B Infrastructure[4]

respectively.

The Capstone program in Alaska was used to test and certify ADS-B in non-radar environments (ADS-B NRA). The Capstone trials showed ADS-B can offer capacity, efficiency, and safety benefits. [25]

1.4 ADS-B In a Global Context

ADS-B is gaining international momentum. Australia, Europe, Canada, Indonesia, and China have all begun ADS-B initiatives. Australia has implemented ADS-B in the Outback. Europe has begun ADS-B trials in several locations through its CASCADE program. The ADS-B initiative with the greatest influence on U.S. domestic operations is Canada. In particular, NavCanada has mandated ADS-B for operations over the Hudson Bay, an airspace traversed by many U.S. carriers on trans-continental routes. [15, 11]

Link Differences

The instantiations of ADS-B in each country differ based upon the structure of the country's ATC system. Key differences between international and U.S. ADS-B implementations are in the link offered, the ADS-B standard required, and the vision for a future control paradigm.

Europe, Canada and Australia offer a single 1090 MHz link. Australia's analysis of costs showed that the 1090 MHz link would not be significantly more costly than UAT for GA. Furthermore, Airservices Australia does not offer weather services to GA because of the availability of third party resources, such as XM weather. [7]

In addition, Europe, Canada, and Australia have adopted a DO260 standard for ADS-B, whereas the U.S. NPRM requires the DO260A standard. The difference between the DO260 and 260A links is explained in the following section.

A final difference between ADS-B programs in Europe and the United States lies in the control paradigm vision. While the United States envisions self-separation of air traffic, Europe sees control of air traffic remaining with ground controllers. It has been argued that this difference is minor because it pertains to applications at least twenty years in the future. It is assumed that there will be international collaboration on ADS-B development to ensure consistency in the global airspace.

DO260 v. DO260A

DO-260 differs from DO-260A in the type of quality message sent.

DO-260 requires quality information to be sent through the Navigational Uncertainty Category (NUC). DO-260A separates the quality information into integrity and accuracy. Integrity information is sent through the Navigational Integrity Containment (NIC) and Surveillance Integrity Level (SIL). Accuracy information is sent through the Navigation Accuracy Category (NAC). Accuracy information is not required for ADS-B Out if integrity information is known. However, for air-to-air applications, accuracy information might be necessary. Therefore, DO-260 compliant aircraft are ADS-B Out capable, but may not be ADS-B In capable.

There has been some controversy about weather DO-260 data is good enough to use for ADS-B Out. The issue lies in the source of integrity information for the GPS receiver. GPS receivers output HPL and Horizontal Figure of Merit (HFOM). The HPL is based on the GPS receiver's ability to detect a bad ranging signal from a faulty GPS satellite. The HFOM is based on the expected accuracy of the position data, assuming all satellites are working correctly. DO-260 allows the NUC to be based upon HPL, or HFOM if HPL is unavailable. However, because HFOM is based upon the assumption that satellite is working correctly, the user is not protected from satellite ranging errors. DO-260A requires that the NIC value be based upon HPL. If the NUC generated by DO-260 is based upon HPL, then it is the same as the data generated by the NIC in DO-260A. Since DO-260 change 1 requires the NUC to be based upon HPL, any avionics that comply with DO-260 would be ADS-B Out compliant. Air Services Australia has worked around the integrity problem by certifying each airframe for ADS-B operation. [8]

1.5 Stakeholders

There are several major stakeholders for ADS-B in the United States. One stakeholder group is the airspace users, which include GA, air cargo airlines, regional airlines, and major domestic carriers. GA encompasses a wide variety of airspace users, ranging from recreational airplanes to business jets. Air cargo airlines do not carry passengers. Regionals are airlines that contract flights for the major carriers. Passengers are generally unfamiliar with the names of the regional airlines. Examples include American Eagle and Comair. Major domestic carriers are the major passenger airlines that are fly domestic U.S. routes. Examples would include United and American.

Manufacturers are another stakeholder group. They include airplane manufacturers such as Boeing and Airbus. For the purposes of this thesis, avionics suppliers, such as Rockwell Collins or Honeywell, will also be classified as manufacturers.

The FAA is also a stakeholder in ADS-B. The FAA plays a unique role in ADS-B because it functions as both a regulatory body and as a market agent. The FAA regulatory role is accountable to the public for ensuring the safety of air transportation. The FAA fulfills its regulatory duties by controlling certification, making rules, and setting standards. The FAA market agent role comes from it function in ATC. By providing ATC, the FAA sells benefits and services to the airlines. Furthermore, the FAA purchases ground equipment from the manufacturers (ITT) in order to operate ATC.

1.6 Thesis Outline

This thesis will provide an examination of technology adoption problems specific to ADS-B using a market failure framework. Game theory is used to show where market failures are likely to occur in airspace user voluntary early equipage of ADS-B. Focused interviews with airlines provide the data for the game theoretic analysis. The thesis will also discuss and evaluate potential government actions for correcting these market failures. Figure 1-4 shows a map of inputs and outputs through the flow of the thesis. In the thesis map, the dashed lines represent the flow of data while the solid lines represent process and thought flows.

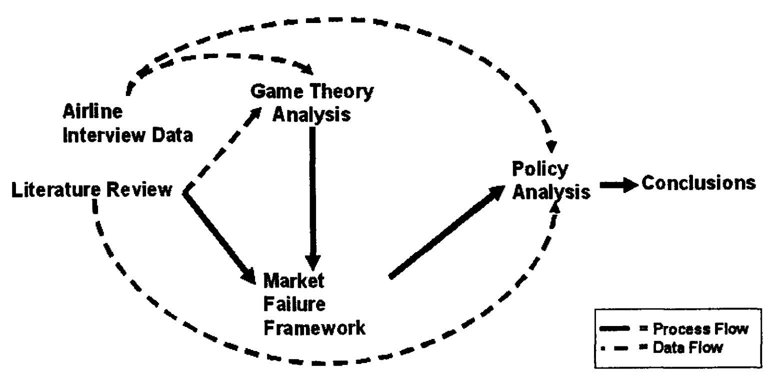

Figure 1-4: Thesis Map

Chapter one motivates the research. It provides background on ADS-B, introducing the technology and current regulations associated with the technology. There is also a discussion of international ADS-B efforts.

Chapter two reviews the literature pertaining to the analysis conducted in this thesis. It reviews work in economics and game theory regarding technology adoption.

It also reviews the applications of theory to problems with characteristics similar to ADS-B, such as transportation infrastructure problems. The chapter concludes with an overview of literature regarding government policy from the fields of political science, economics, and air transportation.

Chapter three lays out the framework for analysis used in this thesis. Market failure and game theory concepts are introduced. A definition and characterization of ADS-B used in the analysis is provided. Several games used in later analyses are set up.

Chapter four introduces the methodology for data collection through focused interviews with airlines. Information regarding the number and types of airlines and airline personnel interviewed is presented. Interview protocol is reviewed. An overview of the motivation and objective of each portion of the interview is provided. Methods for distilling the data are discussed.

Chapter five presents the results of the airline interviews. Data from each section of the interview is presented. Discussion of the results that address specific points made by individual airlines.

Chapter six analyzes the data presented in chapter five using game theory. Free market conditions are assumed for all games. Several forms of potential market failure in the implementation of ADS-B are identified. Sources of market failure are discussed.

Chapter seven examines the role of government in correcting market failures. Mechanisms through which government can act are presented. Implementation difficulties are discussed.

Chapter eight provides a summary of the findings and conclusions, contributions of the thesis, and future work.

Chapter 2

Literature Review

The problem of technology adoption has not been extensively studied in air transportation. Previous technology initiatives have either been mandated by the government or entirely market-driven. However, other fields have studied problems with characteristics that pertain to the ADS-B technology adoption problem. There is a substantial amount of economics literature on the theory of technology adoption. This literature presents general theories that can be adapted to a variety of problems. Particularly relevant to ADS-B is the study of technology adoption with externalities. More specifically, some economists have studied the effect of uncertainty on technology adoption. The economic theory has been applied to multinational transportation project and risk and security problems.

The role of government in technology adoption has been studied by both economists and political scientists. There is also literature on the role of government specifically in air transportation.

Finally, in air transportation, there have been studies of stakeholder views regarding ADS-B. These stakeholder studies have also explored incentivization policies for technology adoption.

2.1 Technology Adoption and Externalities

Technology adoption behavior has been studied by many economists, particularly in the context of innovation systems. Of particular relevance to ADS-B is the literature pertaining to technology adoption with externalities. Reinganum (1981) published a series of articles using game theory to analyze technology diffusion. In the first article, technology diffusion is modeled as a two-person non-zero-sum game. She assumes the firms are in direct competition and that one firm will gain at the expense of the other if they adopt earlier. Consequently, the analysis found that for identical firms, there will be a "diffusion" in technology adoption times, with one firm adopting relatively early and the other adopting relatively late. For non-identical firms, she found that an asymmetric Nash equilibria will exist. [29] The diffusion model was extended to multiple firm markets in a second paper. [30] These assumptions do not quite fit the problem of ADS-B, because the technology is dependent in nature.

Fudenburg and Tirole (1983) also pursued a game theoretic approach to technology adoption, analyzing the temporal aspect of adoption for multiple player games. They also assume that the first mover has a competitive advantage over later adopters. However, in contrast to the diffusion model, they found that when the gain from preemption is low, firms are likely to adopt later. Furthermore, Fudenburg and Tirole found that in games with more than two players, the gain from adoption is unlikely to be symmetric, even for identical players. [13]

An adoption model that matches well with ADS-B is the idea of technology adoption in network industries. Shy (2001) introduces the idea of market failures in network industries, and proposes using game theory to study these failures. Although Shy presents technology adoption in a network theory framework, his specific analysis is limited to technology replacement in time. [33]

Reignanum, Fundenburg and Tirole, and Shy all assume perfect information in their systems, a condition that does not apply for ADS-B. This means that firms understand the costs and benefits of adoption and all agents have the same information. As will be shown in the airline surveys, there is a tremendous amount of uncertainty regarding ADS-B benefits, which is a key factor in the airline's technology adoption decisions.

2.2 Technology Adoption and Uncertainty

Uncertainty has been factored into technology adoption with externalities models. Farrell and Saloner (1985) studied how standardization in industry can trap the industry in an inferior technology under incomplete information. [12] This is particularly relevant to ADS-B, since surveillance technology is necessarily standardized. Furthermore, there is incomplete information regarding ADS-B technologies.

The ideas of Farrell and Saloner are refined and formalized for general cases in the idea of risk dominance, introduced by Harsanyi and Selten (1988). Harsanyi and Selten show that strategic uncertainty in games with multiple equilibria can lead to the selection of Pareto inferior solutions. [16] Risk dominance plays an important role when considering the likely actions of stakeholders in ADS-B. Risk dominance was shown to be a factor in coordination failures by Straub (1995). [34]

2.3 Applications of Theory

The economic theory of technology adoption has been used to study multinational transportation projects and a class of problems called interdependent security problems (IDS).

Multinational transportation projects have many characteristics that parallel the ADS-B project. Both projects require heavy up-front investment and coordination of stakeholders with information and cost benefit asymmetries, have government as a stakeholder, and exhibit network externalities.

The network characteristics of transportation systems were characterized by Laird, Nellthrop, and Mackie (2005). [19] An analysis of multinational transport projects in Latin America was conducted by Caracamo-Diaz and Goddard (2007). They conduct a game theoretic analysis of market failures under different information and cost-benefit asymmetry conditions. They also investigated the role of government and the impact of government on system risk and benefit. [6] Fujimura (2004) conducted case studies of multinational infrastructure projects in Asia, showing the risks and coordination difficulties involved in these projects. [14]

Kunreuther and Heal (2003) used game theoretic techniques to examine how companies invest in protection from risk in a system with network dependencies. They incorporated probabilistic models of risk into the games, creating a method for analyzing IDS problems. This model contrasts with work done in transportation, which separates market effects from system risk. Kunreuther and Heal also investigated potential government policies by examining mechanisms through which governments can correct identified failures. [18]

2.4 Government Policies

Government policies have been studied in a number of disciplines. The field of welfare economics has studied stakeholder incentivization extensively. In welfare economics, the role of government is to correct market inefficiencies. However, the theory of welfare economics has somewhat limited application to ADS-B because it assumes a perfectly competitive market.

Government policies for technology adoption with network effects and public goods characteristics were studied by Dybvig and Spatt (1983). They described two types of public goods problems- early adopters and late adopters. Furthermore, they investigated the ability of government mandates and anonymous subsidies to push markets to Pareto-optimal equilibria. They found that mandates can be effective because they offer insurance to early adopters. Furthermore, they found that anonymous subsidies can be effective in encouraging technology adoption, but it may incentivize the wrong players to adopt. [9] The proof offered by Dybvig and Spatt is valuable because it offers insight into a counterintuitive phenomenon observed in practice. However, the analysis of government actions does not encompass all possible scenarios for air transportation technology adoption.

From a policy perspective, Sandler (2001) investigates the role of international organizations in encouraging adoption of international public goods. Sandler provides a taxonomy of types of public goods, noting that all goods have different amounts of public and private good characteristics. Government actions are proposed in accordance with taxonomic classification of the good. In particular, Sandler notes that for governments to achieve desired public goods benefits, the private goods characteristics of the good can be leveraged to induce stakeholders to adopt. [32] This idea is particularly interesting and applicable to ADS-B, which is a good with both private and public goods characteristics.

In the field of air transportation, Marais and Weigel (2006) have studied the role of government in air transportation infrastructure projects. They propose characterizing projects by stakeholder costs and benefits and deploying government action accordingly. They also provide a framework within which to study potential government actions for air transportation projects. [21] This thesis uses the government action framework of Marais and Weigel to study potential government policies for ADS-B.

2.5 ADS-B Stakeholder Studies for the Domestic U.S.

For ADS-B in the domestic United States, stakeholder views have been expressed by industry bodies representing airspace user groups. For example, the Air Transport Association (ATA), which represents the major domestic airlines, has published several opinion pieces that speak for the airline perspective on ADS-B. A key piece of literature is the ATA response to the NPRM for ADS-B Out, which summarizes the airline industry position regarding ADS-B. [5] The Aircraft Owner and Pilots Association (AOPA) has also written opinion pieces regarding the GA view of ADS-B costs and benefits. [27] In addition, it is likely that AOPA has submitted to a response to the NPRM for ADS-B Out, but it has not been published. Because both the ATA and AOPA represent industry groups, neutral party studies would be valuable in validating their conclusions and in helping frame their positions within a system-level view.

Lester (2007) has studied stakeholder opinions as a neutral observer. He examined stakeholder views ADS-B from an individual pilot perspective, with an emphasis on general aviation issues. Lester has also explored potential government policies based upon the results of the study. [20] However, because individual pilots do not represent the views of an airline, it is necessary to conduct a study of airline views of ADS-B.

2.6 Conclusion

This chapter presented a review of key literature pertaining to technology adoption and stakeholder views of ADS-B. The ideas presented can be applied to air transportation, studying problems of technology adoption, such as ADS-B. This thesis will use the market failure framework and game theoretic analysis technique introduced by Shy. Other works introduced in this chapter will inform the analysis of the games and help in interpreting the results. For policy analysis, the thesis will use the framework established by Marais and Weigel. The data presented in this thesis will offer a neutral observer reporting of airline views regarding technology adoption, with particular emphasis on ADS-B. The analysis presented in this thesis will serve to bridge the theory of technology adoption with the practice of air transportation technology implementation.

Chapter 3

Market Failures Framework

A market failure framework is used to study potential problems in adoption of ADS-B under free market conditions. The free market conditions represent the dynamics of ADS-B equipage without government intervention. This would be the case of voluntary early equipage by the airlines. The proposed mandate and other potential government actions will be evaluated in Chapter seven (Policies) of this thesis for their ability to correct problems identified by the market failure analysis.

ADS-B is a special type of market known as a network market. The network characteristics of ADS-B make it prone to market failure. Game theory can be used to illustrate market failures. Data for the game theory analyses were collected through stakeholder interviews, which are detailed in Chapters four and five of this thesis. Data from general aviation users was collected in a previous thesis by Lester. [20]

Government intervention may be effective in correcting market failures. Policy actions are suggested using a framework outlined by Marais and Weigel. [21]

3.1 Market Characterization of ADS-B

An economic market is defined as a social structure that facilitates the exchange of goods. The air transportation system has many markets. The characteristics of the markets vary with the nature of the technology and stakeholder interactions. ADS-B comprises a unique market within the air transportation system.

The ADS-B market good is the engineering system. It includes the ADS-B technology, as well as the services and benefits derived from the technology. Stakeholders in the ADS-B system include airspace users, the FAA/ATC, and the manufacturers/service providers. Airspace users include major airlines, regionals airlines, cargo, business jets, GA, ect. In the market, the role of the FAA/ATC is distinct from its role as a regulatory body. In essence, the FAA should be considered as two separate entities- a regulatory entity and a market agent. Figure 3-1 shows a schematic of the ADS-B market system.

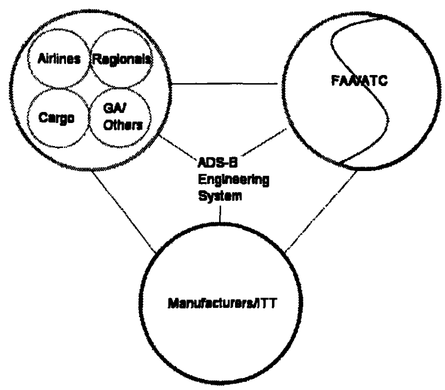

Figure 3-1: ADS-B Economic System

Airspace users are buyers in the market; manufacturers are sellers. The FAA functions as both a seller and a buyer. Airspace users buy avionics (airplanes) from manufacturers and services and benefits from the FAA. The FAA buys technology capability from the manufacturers so that they may sell the services to the airlines.

Network Market Traits

The main attributes of a network market are: 1) complementarity, compatibility, and standards; 2) consumption externalities; 3) switching costs and lock-in; and 4) significant economics of scale in production. [33] ADS-B exhibits all four of these characteristics.

Complementarity, compatibility, and standards mean that goods come as a system rather than as individual components. A classic example is the CD player, which would be useless to consumers without CDs. Likewise, ADS-B is a system product.

The avionics, ground stations, and ATC displays must all be coordinated. In addition, ADS-B needs procedures and applications to deliver benefits.

Consumption externalities refer to the phenomenon where the utility derived from a good is affected by the number of others using similar or compatible products. A commonly cited example is the telephone. A telephone's value to an individual increases as the network of users with compatible technologies increases. Likewise, due to the dependent nature of the technology, the value of ADS-B increases as more people equip. For example, having more airplanes equipped with ADS-B would enable procedures that allow for closer separation, thereby increasing airspace capacity or reducing delays. This would benefit both airspace users and the FAA. Furthermore, having more airplanes equipped would benefit airplane manufacturers because they would be able to manufacture more units, thereby employing economies of scale in production.

Lock-in occurs when the cost of switching to a new technology is high. There can be many types of switching costs, including training and learning time, data conversion, search cost, loyalty cost, and contracts. [33] For ADS-B, aircraft equipage is likely to impose a large switching cost on the airspace users. Aircraft owners must pay for avionics, which can be expensive. In addition, commercial carriers face added costs from lost revenue due out of service time and pilot retraining. The FAA must invest money in ground stations, applications development, and retraining air traffic controllers. Airplane manufacturers also incur switching costs by having to modify avionics production.

Economics of scale in production occur when the cost of manufacturing a product decreases as the number of units produced increases. Presumably, as more aircraft equip with ADS-B, the cost of the avionics will decrease. This can be attributed to the fact that manufacturers will be able to distribute their technology development and certification costs over a larger number of users. Also, presumably, the cost of ATC services might decrease as more users equip and controllers reap operational efficiency and situational awareness benefits.

3.1.1 Nature of ADS-B goods

The ADS-B engineering system has both public and private good characteristics. A public good is defined as being non-rival and non-exclusive. [32] This means that if one person purchases a good, the good will be available to all other users in the system as well.

Some benefits that come from ADS-B are private in nature. Examples would include potential fuel, efficiency, and cost savings for the airlines. For ATC, the private benefit would be a reduction in operating costs, since ADS-B is cheaper than radar.

ADS-B benefits also have public good characteristics, which arise from the network structure of the market. The externalities created by ADS-B equipage are examples of public goods. Increased safety and improved situational awareness can be considered public benefits because if only one user equips, all other users will also reap benefits. Furthermore, safety benefits are difficult to quantify and often do not factor into a company's business case. Some efficiency improvements are also public benefits. If one airline equips, non-equipped aircraft using sharing an operating environment (e.g. airports or airspace) will also reap efficiency benefit.

3.2 Market Failures Overview

Market failures are likely to arise in network markets with products with public good characteristics. By definition, a market failure is an inefficient allocation of resources. For ADS-B, a market failure can be defined as a case where users choose not to equip.

There are several sources of market failure. These include abuse of market power, externalities, public goods, and asymmetric information or uncertainty. Abuse of market power encompasses imperfect competition scenarios, such as monopolies and ogliopolies. In situations where a firm dominates the market, they may use their power to achieve certain market situations that are not optimal. Externalities refer to benefits produced by one market agent that may benefit other market agents. A public goods market failure occurs when system-wide benefits justify purchase of the good, but individual benefits are too diffuse for any one agent in the market to justify purchase of the good. Asymmetric information occurs when some information regarding the market is available to certain users but not to others. Having asymmetric information means that different users will not always act in accordance with rational choice theory. Uncertainty is when risk is added to the market and users have a probability distribution associated with their actions as opposed to a one or zero probability of making a particular choice. [10]

3.3 Institutional Failures Overview

Institutional failures are analogous to market failures. Institutional failures occur when government intervention in a market leads to inefficient allocation of resources. An example would be when the government regulates a less efficient technology standard.

Examples of institutional failures include bureaucratic interests and politics and organizational process failures. Bureaucratic interests and politics is an organizational interest in wealth and power. It can potentially lead to a lock-in to the existing distribution of rewards. Organizational process failures occur when the government's standard operating procedures do not fit into nonstandard or evolving situations. The government may fail to change their standard operating procedures to accommodate new situations. [28]

3.4 Game Theoretic Analysis Overview

Game theory is used to evaluate the existence of market and institutional failures in ADS-B.

Although there is an NPRM for ADS-B, free market conditions are assumed in the game theoretic analysis. Free market conditions model a situation where airspace users voluntarily equip. This assumption will allow for an objective assessment of all possible government intervention actions.

Under the free market assumption, several games can be played. Game situations arise at stakeholder coordination points. Therefore, there are games between 1) major domestic carriers; 2) major domestic carriers and other airspace users; 3) the FAA and airlines; and 4) airlines and the manufacturers. This thesis will analyze the first three interactions listed because the data collected pertains most to those games. In addition, game four is similar to game two.

The first game, between major domestic carriers, is an n-player game. A unique trait of n-player games is the ability to form coalitions through side payments, communication, and bargaining. Assume airlines are not allowed to form coalitions or collude because this would violate anti-trust laws. Furthermore, assume airlines make equipage decisions independently. The assumptions simplify the n-player game such that it can be represented as a 2x2 game. [26]

The game between major domestic carriers and other airspace users assumes that each airspace user group acts as a coalition. The 'other airspace users' coalition includes GA, regionals, and other smaller air carriers. Although the users in the 'other airspace users' coalition are quite diverse, they have similarities in their structure that make them a cohesive coalition for game theoretic analysis. In particular, other airspace users often do not have the resources to invest in new technologies proposed by the FAA, making them a group of relatively late adopters. Furthermore, the other airspace user group has a different set of benefits objectives than the major carriers. For this game, asymmetry of costs and benefits and asymmetric information are modeled.

The majors to FAA game is also asymmetric in costs and benefits. Furthermore, a dynamic game will be played between the majors and the FAA, simulating possible multiple steps to ADS-B equipage.

3.4.1 Static Games

All of the static games analyzed are 2x2 games that can be expressed as a normal form game. Figure 3-2 shows the 2x2 game setup.

Each user has two decisions, *equip* or *don't equip (invest or don't invest)*. One

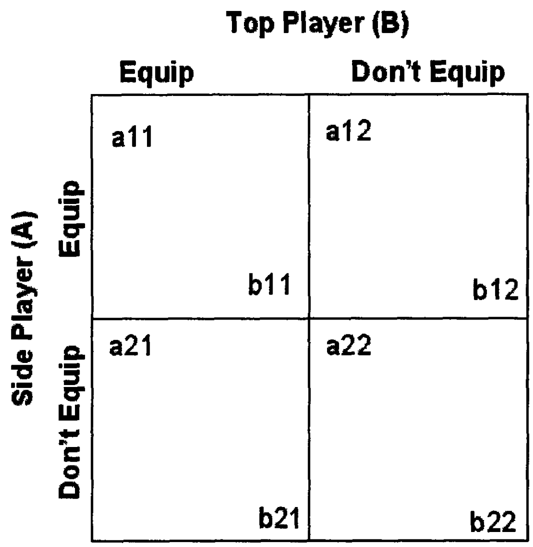

Figure 3-2: 2x2 Normal Form Game

player's decisions are shown across the top and the other player's decisions are shown along the side. Player payoffs are shown inside the squares. For purposes of clarity, payoffs for the side player (rows) will be shown in the top left hand corner of each square. Payoffs for the top player (columns) will be shown in the bottom right hand corner of each square.

3.4.2 Extensive Form Games

Extensive form games are used to analyze multiple-step decision making. Figure 3-3 shows an extensive form game.

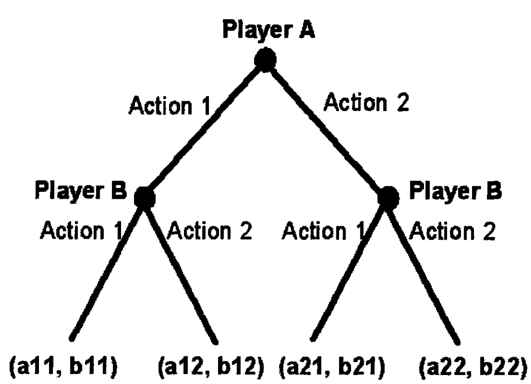

Figure 3-3: Extensive Form Game Structure

The game is formulated in a tree structure, with each node representing a decision point for the players. The branches of the tree represent the decisions available to the players. At each node, one player makes a decision. For the game in Figure 3-3, Player A makes the first decision and Player B makes the second decision. Payoffs are shown at the terminus of the tree. The branches of the tree may have associated probabilities to model the likelihood that a player will choose a particular action. The tree will have branches with probabilities when players make decisions based on factors other than simple payoffs. An example of another factor is risk.

3.4.3 Equilibrium Concepts

For every game, there can be a set of feasible steady-state solutions, or equilibria. The three equilibrium ideas used in this thesis are Nash equilibrium, Pareto optimality, and risk dominance.

A solution is a Nash equilibrium if no player can benefit by unilaterally changing their strategy while the other player keeps their strategy the same. Nash equilibria suggest that there exist solutions that will tend to attract players.

In games with multiple Nash equilibria, the equilibria can be Pareto ranked. Pareto optimality is the situation where no agent's position can be improved without making another agent worse off. [10] By definition, a Pareto optimal solution is also a Nash equilibria, although the converse is not true. For the case of ADS-B, the Pareto optimal Nash equilibria can be defined as *(equip, equip)*.

Risk dominance models player behavior under uncertainty. The risk associated with choosing a particular strategy is the cost to one player if they unilaterally deviate from that strategy. [16] If an equilibrium is Pareto optimal but risk dominant, players are not likely to select it. Intuitively, the strategy for which a player seeks to lose more in the face of payoff uncertainty is considered risk dominant. Therefore, the probability of a player choosing a particular strategy is not only influenced by pure payoff, but also by the amount of strategic uncertainty in the system. For a 2x2 game, the risk of a solution is its Nash product. The equilibrium with the higher Nash product dominates. [34]

3.4.4 Equilibrium Concept Example

To illustrate these equilibrium concepts, consider the game in Figure 3-2. Assume $a_{12} = a_{21}$ and $b_{12} = b_{21}$. Assume a coordination game, so the following conditions hold:

$$a_{11} > a_{12} \tag{3.1}$$

$$a_{11} > a_{22} \tag{3.2}$$

Analogous conditions hold for Player B.

Then, the game has two Nash equilibria: (a_{11}, b_{11}) and (a_{22}, b_{22}), the solution in the upper left and bottom right corners. Because of the condition in equation (3.2), (a_{11}, b_{11}) is the Pareto dominant solution.

The Nash product of the (a_{11}, b_{11}) solution is: $(a_{11} - a_{21}) \cdot (b_{11} - b_{12})$

The Nash product of the (a_{22}, b_{22}) solution is: $(a_{22} - a_{12}) \cdot (b_{22} - b_{21})$

The Pareto inferior solution, (a_{22}, b_{22}), would risk dominate if it has a higher Nash product. So, if $(a_{22} - a_{12}) \cdot (b_{22} - b_{21}) > (a_{11} - a_{21}) \cdot (b_{11} - b_{12})$, the Pareto inferior solution risk dominates.

3.5 Conclusion

The ADS-B technology adoption problem is formulated as a network market system. The stakeholders in the ADS-B market are defined to be airspace users, manufacturers, and the FAA. The good in the market is defined to be the ADS-B engineering system.

The network characteristics of ADS-B make it prone to market failures. Several types of market and institutional failures are described. Game theory is introduced as a tool for examining market failures. Two types of games are presented- a static game in normal form and a dynamic game in extensive form. In addition, the game theoretic equilibrium concepts of Nash Equilibria, Pareto Optimality, and Risk Dominance are introduced. The situation where all airspace users equip with ADS-B is defined as the market efficient, or Pareto Optimal, situation.

Chapter 4

Airline Interview Methodology

Airlines were interviewed to collect data for the game theoretic analysis of market failures. Airline interviews provide insight into how one stakeholder group thinks about ADS-B. This chapters outlines the method used for conducting airline interviews and analyzing the data.

4.1 Interview Participants

Airlines surveyed included domestic national carriers, regional airlines, cargo airlines, and business jet share programs. A total of fourteen airlines were interviewed. A distribution of interview participants by airline type is shown below in Figure 4-1. Airline type was determined by self-reported affiliation. In general, domestic national carriers are those that belong to the Air Transport Association, regional carriers belong to the Regional Airline Association, and general aviation are represented by the Aircraft Owners and Pilots Association.

Airlines asked to participate are those with the largest number of daily operations according to ETMS data from 2003. Additionally, airlines that have significantly expanded their operations since 2003 were interviewed.

Of the ten domestic national airlines asked to participate in the interview, eight responded, one chose to use the official Air Transport Association (ATA) response to the NPRM as a proxy for their views, and one chose to speak off the record. The data for the off the record interview is not presented, although the contextual information they provided did inform thinking in the analysis of results. Of the nine regional airlines invited to participate in the interview, three responded. All of the cargo carriers invited to participate in the interview responded. There was some difficulty finding contacts at the business jet programs, but one of the four major business jet share programs was interviewed.

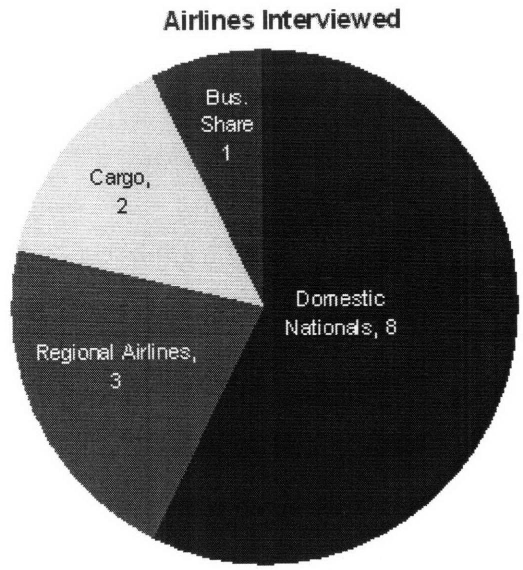

Figure 4-1: Airlines Interviewed

The interview participants were airline personnel familiar with ADS-B, either through operations or engineering (avionics). Interviewees included operations directors, avionics managers, flight technical pilots, and ATC liaisons for airlines. Some airline interviews were conducted with only one employee, while in other interviews, several employees were present.

4.2 Interview Method

Focused interviews were conducted via telephone with airline personnel. Answers were recorded on tape and by typing on a computer. In some cases, the taping mechanism did not work so only typed notes exist. Some interviewees prepared written responses in addition to their phone interview responses. These were collected by the interviewer via e-mail. The interview questions were sent to the participants for review at least one day before the interview.

Interviews were conducted between December 2007 and February 2008. Interviews usually lasted between one and two hours. The MIT Committee On the Use of Human Experimental Subjects (COUHES) protocol was followed for interviews. Several interview participants chose to keep their name and their airline name anonymous. Several other interviewees asked for permission to use quotations. Because a small pool of interview participants makes it easy to identify airlines if some data were attributed and others were not, all results are presented anonymously.

4.3 Interview Questions

The interview protocol covered general perceptions of ADS-B, ADS-B benefits, costs and barriers to equipage, current fleet status, equipage plans, and synthesis. A short overview of ADS-B was provided in the interview protocol introduction. A copy of the survey can be found in Appendix A of this thesis.

The background section was used to gage an interviewee's level of familiarity with ADS-B. It then probed for perceptions of the technology and the NPRM.

The benefits portion asked about potential benefits and benefit locations of ADS-B. In addition, it asked interviewees to judge the value of the benefits. A standard set of benefits was not given to interview participants. To ensure completeness in answers, the interview protocol provided a framework for thinking about possible benefit areas. The framework asked interviewees to think about benefits by flight regime (terminal, enroute, non-radar area, surface) and, within each flight regime, by function (ATC, AOC, cockpit). The benefits section also asked about the utility of services offered only on the UAT link and the impact of network effects on airline equipage decisions.

The costs and barriers portion of the survey asked about costs and barriers to ADS-B equipage. It specifically addressed upgrade costs and asked about airline confidence in the FAA. The costs and barriers portion also asked about incentives for encouraging adoption.

Current status questions were asked to gain a better understanding of how airlines use their fleets and to assess the current state of airline equipage.

The future technologies section asks about planned ADS-B In equipage and non-ADS-B technologies in which airlines might be investing. The purpose of the future technologies section is to understand other equipment airlines will have in the near future, competing constraints on airline budgets, and what technologies ADS-B will compete with in providing benefits. In addition, asking about future technologies gives insight into the criteria airlines use to make equipage decisions and how they value technology benefits.

At the end of the interview, airlines were given the opportunity to synthesize their views provide suggestions regarding the administration of the SBS program.

4.4 Analysis of Interview Data

Several methods were used to parse the airline interview data. The method used depended on how the questions were posed. Some questions had uniform answers that were distinctly categorizable For example, airline equipage and future technology investment questions yielded statistics or a finite set of discrete answers.

Responses to benefits and barriers questions were distilled using content analysis, which looked at the frequency and intensity of responses. General categories were designated to encompass more specific answers. These categories were determined based upon accepted standards in air transportation. In general, the categories are distinct in geography or phase of flight. For example, continuous descent arrivals (CDAs) and closely spaced parallel approaches fall into the broader category of arrival and departure procedures.

4.5 Conclusions

The methodology for airline interviews was presented. An overview of airlines and type of airline personnel interviewed is given. The interview protocol is introduced. The method for analyzing interview data is reviewed.

Chapter 5

Interview Results

The following chapter presents results of the airline interviews described in the Chapter four (Airline Interview Methodology) of this thesis. The sections in this chapter correspond to sections of questions asked in the airline interview.

The location of this chapter relative to the overall objective of this thesis is shown in Figure 5-1. The data presented in this chapter will be used in the game theory and policy analysis of later chapters.

5.1 Airline Perception of ADS-B

Airlines are supportive of the ADS-B concept because they view it as a necessary tool for modernizing the national air transportation system. The airlines have been impacted by increased congestion in the NAS through delays and are concerned about

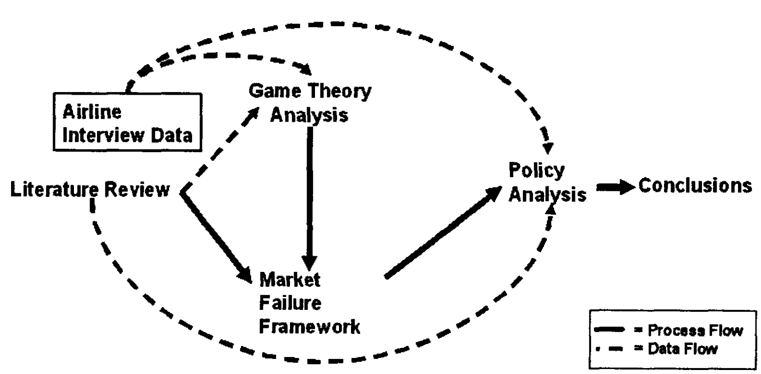

Figure 5-1: Thesis Map

increasing fuel costs. There is consensus amongst airlines that the air transportation system must be improved. International ADS-B programs lend further credence to the domestic technology initiative. However, some airlines are skeptical about the future success of the ADS-B program because of residual displeasure with past FAA technology implementation programs.

There is significant variation in the level of airline knowledge about ADS-B. Some airlines have employees closely involved with technical and procedures standards development, sitting on FAA and RTCA committees. For other airlines, knowledge of ADS-B is limited to press releases provided by the FAA. The range of familiarity with ADS-B led to a wide variety of answers regarding ADS-B benefits and equipage.

5.2 Benefits

Airlines are interested in benefits that will justify a business case for equipage. Airlines identified a variety of factors that contribute to a positive business case. Variation in responses aligned with differences in operations. Major airlines and cargo operators cite fuel savings, capacity increases, and overall operation efficiency as key factors to a positive benefits case. Regional airlines garner indirect benefits from fuel and capacity increases, since the majors pay for the fuel and set the schedule. However, more efficient operations would benefit the regionals by making them more competitive in bidding for contracts. Business jet owners are primarily interested in safety and efficiency benefits. Although all operators are concerned about safety, safety benefits alone are not sufficient to justify a business case for equipage.

There were a wide variety of benefits answers due to the diversity of knowledge and optimism among respondents. Some respondents based their answers on the applications listed in the SBS Conops. Others based their answers on the long term vision for ADS-B. Some respondents also constrained their answers to applications that they felt could be realistically accomplished by the FAA.

Despite differences in factors that contribute to a positive business case, there is agreement on the types of applications and procedures that would provide benefits to airlines. Operational differences seemed to modulate the intensity of some preferences.

Applications cited as beneficial by the airlines can be divided into two categories- high benefits and lower benefits. High benefits have a large direct impact on the company bottom line. Lower benefits might have an indirect or smaller magnitude impact on the company bottom line. High benefit applications tend to be in the early stages of development and require capabilities that have not yet been developed. Lower benefit applications tend to be available for immediate use. Often, these applications use technology or procedures that are already in place. Figure 5-2 shows the beneficial applications cited by airlines.

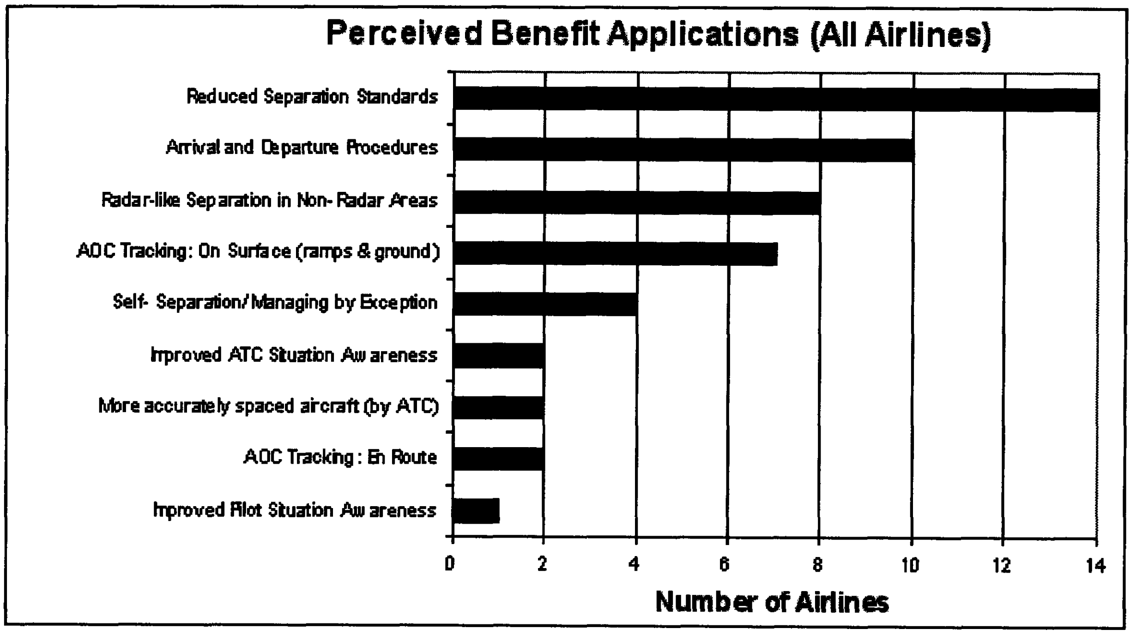

Figure 5-2: Benefits Applications

5.2.1 Primary Benefits

Reduced Separation Standards

All of the airlines mentioned reduced separation standards as the highest benefit application. Reduced separation standards would decrease queuing delays, reducing fuel costs. Theoretically, system capacity would increase as well. There is disagreement about whether reduced separation standards are achievable and there are many ideas about how to achieve separation standards. Some airlines believe that ADS-B Out alone will enable reduced separation standards. Other airlines believe that reduced separation standards will only come with ADS-B In and procedures development, so the benefit will be realized in the long term.

Some airlines believe reduced separation can be achieved with just ADS-B Out because ADS-B offers higher fidelity data than radar. Since it is a GPS-based system, ADS-B can offer a faster update rate and greater accuracy and integrity than radar. Some airlines believe that reducing error in the data will result in decreased actual airplane separation, leading to airspace capacity increases. Other airlines believe that better accuracy will provide sufficient justification for lowering separation standards. However, many airlines are skeptical that ADS-B Out can satisfy the requirements needed to reduced separation standards. Airlines expressed concern that the FAA's certification mechanisms will not be able to approve the reduced separation standards because they do not have precedent for such actions and are not equipped to make them.

Several airlines suggested that reduced separation standards might be achievable with ADS-B In. One idea is that ADS-B In will enable visual flight rule (VFR) procedures in instrument flight rule (IFR) conditions. This will require CDTI to aid the pilot in achieving visual awareness in instrument conditions.

Another idea is reducing separation standards as part of a change to the air traffic control paradigm. The new control paradigm would be based on either self-separation or control by exception. In both these paradigms, power and responsibility for separation is given to the pilots. Under the current control paradigm, controllers have the responsibility of maintaining separation. By contrast, in control by exception, controllers will intervene to issue commands only when necessary. Some airlines believe that decreasing controller involvement decreases latency in the time to make and issue decisions. This will allow airplanes to react more quickly to situations, thereby enabling reduced separation. Proponents of greater pilot control acknowledge that decision support tools are crucial to the self separation functionality. However, these decision support tools have not been developed or, in some cases, even envisioned.

About half of the major carriers are strongly opposed to self separation. Some argue that pilots will not want to shoulder the liability that comes with maintaining separation. Others argue that there is no reason to believe that pilots will separate airplanes at a lower distance than controllers. The concern of the opposition stems from experience and perceived difficulty in changing user mindset during technology transitions.

Arrival and Departure Procedures

Arrival and departure procedures is another application with the potential to deliver high value benefits. In particular, airlines would like to see capacity improvements on arrival. There are several ideas for approach procedures. Many of these ideas use required navigation performance (RNP) technology in conjunction with ADS-B to create new arrival routes. Two arrival procedures that were cited as very high impact are Continuous Descent Approaches (CDAs) and closely spaced parallel approaches.

CDAs are currently being tested by UPS at Louisville. Airlines like CDAs because they offer fuel savings. CDAs are also likely to receive operational approval because they do not require reductions in separation standards. Furthermore, airlines like the fact that the development work is being done by another airline (UPS). Some airlines, however, are skeptical that CDAs will provide benefits in a mixed equipage environment. Also, some CDA procedures might require ADS-B In, which is expected to be expensive.

Closely spaced parallel approaches would provide a high value benefit by increasing capacity and reducing delays at several busy and constrained airports. Examples include San Francisco (SFO), Seattle (SEA), Newark (EWR) and Boston (BOS). At SFO, for instance, low visibility due to fog can cut the operating capacity of the airport in half. However, closely spaced parallel approach would likely require CDTI to aid pilot navigation. Some airlines believe ADS-B is not needed for closely spaced parallel approaches because Precision Runway Management (PRM) procedures are already available.

Surveillance Coverage in Non-Radar Areas

An application related to reduced separation standards is surveillance coverage in current non-radar areas. Examples of non-radar areas include mountainous areas (e.g. airports in Colorado) and over water areas (e.g. Gulf of Mexico and the Western Atlantic). Because ADS-B is cheaper to install and maintain than radar, it presents an opportunity to extend the surveillance capability of the NAS. Putting ADS-B in current non-surveillance areas would allow operation under IFR rules instead of procedural standards. Because the application uses existing rules, a capacity increase can be achieved immediately with only ADS-B Out. One benefit is increased en route throughput, since IFR allows for closer spacing of aircraft than procedural standards. Another benefit is higher throughput at airports without radar surveillance. Increased throughput would occur as a result of switching from one-in one-out procedures to IFR procedures.

Although ADS-B NRA offers immediate benefits, the magnitude of the benefits is lower than the benefits from reduced separation standards. Legacy carriers and GA find ADS-B NRA beneficial, but regionals and low cost carriers (LCCs) do not. This is because the regionals and LCCs interviewed tend to serve major cities and do not usually operate in non-radar airspace. Furthermore, the economic value of remote locations to the regional airlines interviewed is low. Regionals worry that remote areas might not have the markets to support the increased frequency of service afforded by capacity improvements. For the major airlines, benefits from ADS-B NRA may be mitigated by investments in other technologies and the nature of the airspace. For example, the state government of Colorado has invested in multilateration because it has many mountainous airports and poor weather in the winter. Therefore, any airlines that would reap benefits from ADS-B NRA in Colorado might receive the same benefits sooner from multilateration. ADS-B NRA over water benefits may be constrained by neighboring foreign air traffic control areas. For example, one airline believes that ADS-B in the Gulf of Mexico will offer lower levels of benefits than those claimed by the FAA because it is constrained at one end by air traffic control in Mexico. Even if en route capacity through the Gulf were to increase, there is no guarantee that the air traffic controllers in the terminal areas in Mexico would be able to handle the additional traffic.

5.2.2 Secondary Benefits

Airlines mentioned several applications that could be implemented immediately because they only require ADS-B Out. However, these benefits are of lower value than the benefits that come from applications using ADS-B In.

Secondary benefits come mostly from ground operations applications, such as streaming ADS-B data into the Airline Operations Center (AOC). ADS-B data in the AOC is expected to provide operational efficiency and safety improvements. For example, airlines might be able to improve airplane turn around time at their hubs if they had more accurate arrival information and a better view of gate and surface activities. More accurate information would enable efficient dispatch of ground crew and gate assignment, resulting in faster overall turn-around. Other airlines envision being able to use the ADS-B data for push-back commands.

The locations where airlines derive surface benefits differs. Those operating at major hubs indicated that the service would be most be useful at the large hubs, since tend to the be system bottleneck. Airlines with more operations in remote outputs felt the system would be more useful at the smaller airports instead of the major airports currently with radar surveillance.

Not all airlines believe that AOC data will be beneficial. One airline contends that there is already the capacity to offer better data, but airlines have not asked for it, indicating the benefit offers little value. Data is currently fed into the AOC once every twelve seconds while radar data is updated every four seconds. Others airlines felt that Aircraft Communications Addressing and Reporting System (ACARS) communications were sufficient. Still other airlines have already invested heavily in ground multilateration systems and did not see a need for ADS-B. Some airlines did not find the application useful because they do not operate their own ground crew.

5.2.3 Benefits Locations

Figure 5-3 shows locations where ADS-B would be most beneficial to airlines.

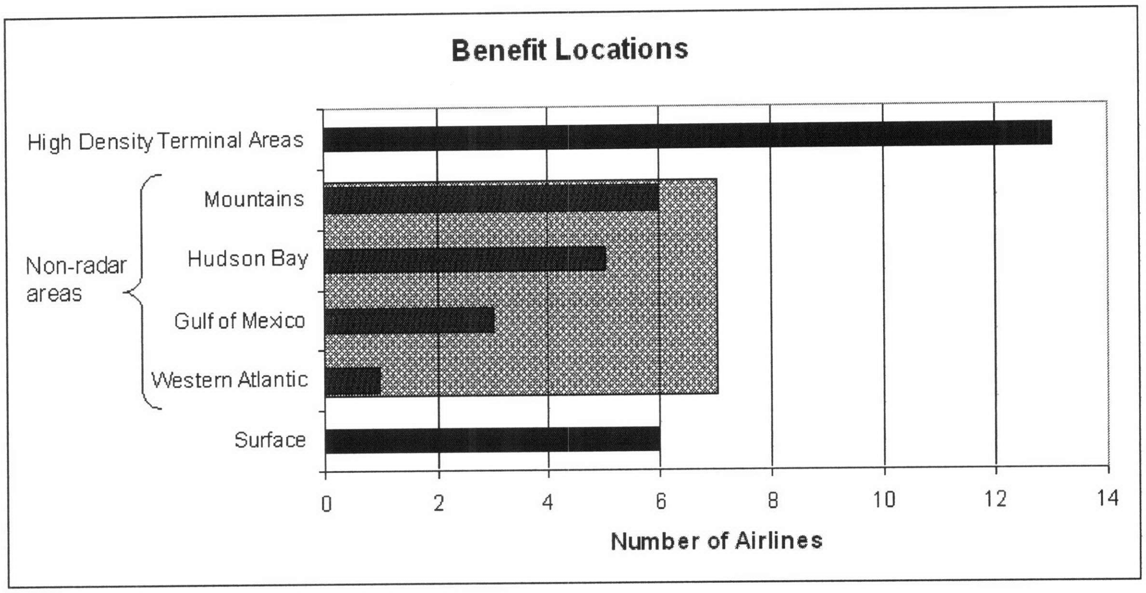

Figure 5-3: Benefit Locations

Differences in operating structure contributed to differences in locations where airlines would like to see benefits. For example, most LCCs and regionals interviewed do not operate frequently in non-radar areas. Therefore, they did not find non-radar area applications beneficial. Conversely, airlines that do not have high density operations in busy terminal areas did not find terminal area applications to be high value.

Terminal Areas

There is agreement amongst airlines that terminal areas are in need of capacity and efficiency improvements. Thirteen of fourteen airlines said ADS-B would have the biggest benefit in busy terminal areas, such as airline hubs. Airlines feel that terminal areas are especially constrained. Metropolitan areas cited include New York, Atlanta, Chicago, and Houston.

Non-Radar Areas

Non-radar areas were cited by seven of the fourteen carriers interviewed. In non-radar areas, there is the potential for immediate efficiency gains with ADS-B Out because it would enable the use of IFR procedures, as opposed to procedural standards. The airlines that did not find benefits in non-radar surveillance areas do not operate in that type of airspace. Within non-radar airspace, different types of airspace and different regions were cited by the airlines. Some airlines saw benefits at one-in one-out airports. Other airlines cited benefits en route. Non-radar regions where surveillance would be valuable include the mountains, the Gulf of Mexico, and the Western Atlantic. Five of the nine major carriers also mentioned that they are equipping for Hudson Bay in Canada.

Other than non-radar areas, airlines did not pinpoint specific en route areas where ADS-B would be beneficial.

5.3 Costs and Barriers

Airlines identified several barriers associated with ADS-B equipage. Because the primary concern of the airlines is getting a positive cost benefit case for equipage, barriers tended to fall into two categories- those due to direct cost and those due to uncertainty and risk. Figure 5-4 lists the issues of greatest concern for the airlines.

5.3.1 Costs

Cost of equipage is a large concern for most airlines. The primary costs stem from retrofitting existing fleets, not from changing existing orders. Airlines are concerned because many of them have old fleets that will potentially require extensive retrofits. Many airlines cited concerns about lack of available capital for avionics investments due to recent bankruptcies and rising operations costs due to the high cost of jet fuel. In addition, ADS-B faces competition for investment capital from other technologies that were on the FAA road map earlier and could provide immediate benefits, such

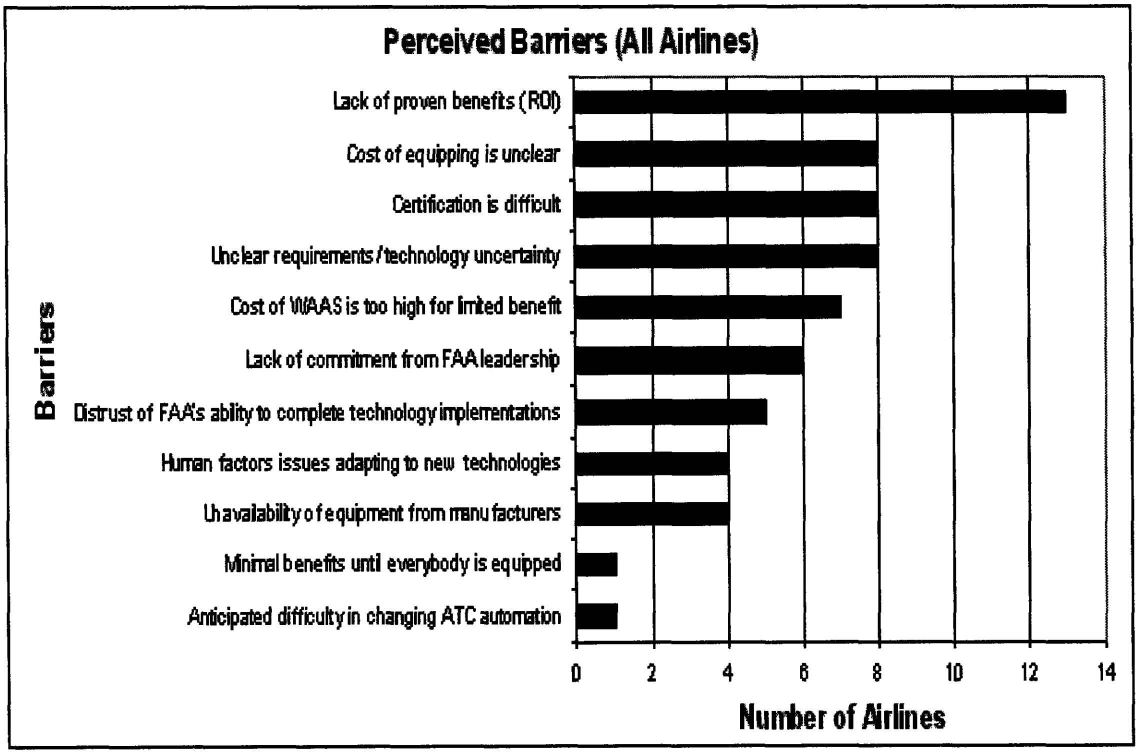

Figure 5-4: Barriers

as precision based navigation (RNP and RNAV). Airlines in better financial positions are less concerned about equipage than those that are cash poor and have older fleets.

For ADS-B Out, the largest up-front costs are expected to be for navigation (GPS), wiring changes, and additional transponders to meet DO260A standards. There is also cost associated with ground time and installation. Training costs are not expected to be significant for ADS-B Out.

A significant expenditure is expected for ADS-B In equipage. The displays needed for CDTI are expected to be very expensive. It is also unclear how the data needed for ADS-B In will be displayed.

Cost of fleet equipage will vary by airline. Airlines with relatively young fleets are likely to already have GPS, so upgrading will be relatively inexpensive and it will not take long to equip the entire fleet. Airlines with older and larger fleets will need significantly more time to retrofit their fleets unless they accelerate their heavy maintenance cycle, which would be a costly endeavor. Larger legacy carriers may also face significants costs from needing to do GPS upgrades on their fleets.

5.3.2 Uncertainties

Uncertainty and risk are major sources of concern for the airlines. Sources of uncertainty and risk include the FAA's track record with technology implementation, certification barriers, unclear information from the FAA, and difficulty in achieving system change.

FAA Technology Implementation Record

The airlines have been unhappy with past FAA technology implementation projects, leading to distrust of the FAA by the airlines. Airlines cited Future Air Navigation System (FANS) and Controller Pilot Data Link Communications (CPDLC) as examples of technology initiatives abandoned by the FAA. Airlines were left with expensive equipment that could not be used. Experience with FANS and CPDLC has made airlines wary of adopting technologies early for fear that investments will not garner returns. Airlines stressed the need to see commitment to ADS-B from FAA leadership. Airlines also want the FAA to commit to sustained funding for ADS-B to shelter their avionics investments from political risk. One airline interviewed believes the problems with previous technology initiatives are not a legitimate source of concern because the SBS program is being run by different people.

However, FANS and CPDLC do serve as reminders of the difficulties of achieving system change. In particular, difficulties come from the certification process and from changing system stakeholder mindset.

Certification Difficulties

Several airlines expressed concern about the FAA's ability to certify ADS-B avionics and to provide operational approvals for applications that will provide real benefits, such as reduced separation standards. The FAA does not have experience with certification and operational approvals for changes of the that is envisioned for ADS-B. Some airlines criticized the FAA's culture of safety for creating certification requirements that are too conservative and stringent. In particular, required level of safety to several nines may prove difficult without data. Airlines suggest that it may be better not to specify to the worst case, but instead to certify to the normal case and then find workarounds for anomalies.

Airlines are concerned that different regional offices have different standards for operational approvals. A configuration that has been approved for one airline may not be approved for another. This may also lead to discrepancies regarding how procedures are developed. For example, if one airline tests certain procedures, other airlines may not be able to use it because their specific regional office might not grant operational approval. The overriding concern with approvals and certification barriers is that they will increase the cost of avionics.

Human Factors Issues

Airlines are concerned about the human factors issues associated with technology transition. In particular, they mentioned it might be difficult to change controller mindset to accommodate and reap benefits from the new technology. Although airlines have not seen problems with controllers adapting to new procedures such as those for RNP, they are concerned about resistance to new procedures and an entirely new operating paradigm. Airlines that have tried to implement new procedures at specific airports report initial hesitation from the controllers, but little resistance after the controllers became accustomed to the new procedures. There is concern, however, that initial push-back will impede system change.

Related to the issue of stakeholder mindset is a concern about ATC's ability to handle mixed-equipage situations. Airlines say they are unwilling to equip early because benefits will be diminished by a mixed-equipage environment. Some airlines believe that the cognitive complexity of handling mixed equipage will make it difficult to institute early adopter incentives such as preferential treatment.

Lack of Information

Another source of uncertainty for the airlines is a perceived industry-wide confusion about ADS-B and lack of information from the FAA. Although some airlines closely involved with technology development know the exact technical requirements for ADS-B, airlines only peripherally involved with the technology complain of unclear technical standards. Airlines have mentioned that the NPRM has inconsistent technical requirements. Furthermore, the requirements for ADS-B In are unclear. One airline lambasted the ADS-B In portion of the NPRM for being more of a vision statement than a proposed rule document. Adding further to the confusion about technical standards is the fact that ADS-B is currently not available from the manufacturers. This compounds confusion about the cost of ADS-B, meaning that airlines cannot even begin to consider making a business case or planning for equipage.

In addition to confusion about technology standards, airlines are unclear about the FAA vision and ADS-B benefits. Airlines want to see the FAA leadership commit to ADS-B. The fact that ADS-B has not percolated to all the FAA vision documents contributes to the perceived lack of dedication to the program. Although it is in the NextGen and Operation Evolution Partnership (OEP) plans from 2008, ADS-B is not included in the FAA road map for precision based navigation. Airlines say that constantly changing technology initiatives from the FAA make it them to justify equipage cases to their finance departments.

Airlines are also unclear about what applications will be offered via ADS-B, compounding to the difficulty of making a business case for the technology. Although a list of applications is specified in the SBS Conops, some application descriptions are very vague and it is not clear how they will be implemented. Furthermore, it is difficult to quantify the benefits based upon the application descriptions in the Conops.

5.4 Equipment Usage

Most airlines do not designate planes for specific routes domestically. One exception is that some airlines designate planes for over-water operations. The implication is that airlines operate interchangeable fleets. Therefore, they prefer to institute equipage decisions for their entire fleets, instead of for specific subfleets.

For ADS-B, this means that benefits should either be available throughout the NAS or localized in areas accessed by the majority of the fleet. Examples of localized areas include airline hubs or a high density operations regions, such as New York. Airline hubs and high density operations regions would theoretically provide benefits with enough value to justify an entire fleet equipage.

Airlines report it will take between five and seven years to equip their fleets.

Most traditional carriers have a low percentage of their fleet equipped with GPS. Figure 5-5 shows the percent of GPS equipage in fleets of major airlines, including low cost carriers

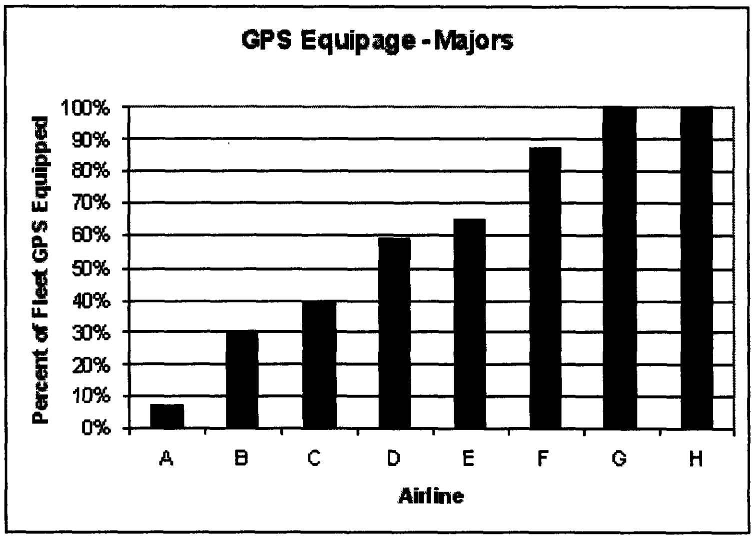

Figure 5-5: GPS Equipage at Major Airlines

Most carriers have plans to upgrade GPS on their fleets within the next five to ten years. LCCs and regional airlines participating in this interview tend to have a higher number of GPS equipped aircraft, because their fleets are younger than those of the legacy carriers.

Equipping with GPS is seen by the major airlines as method of laying the groundwork for ADS-B equipage. Furthermore, GPS is seen as an enabler of other technologies. With the exception of Horizon Airlines, airlines are not equipping with GPS with WAAS. However, according to the NPRM, WAAS is the only GPS system that will meet DO260A requirements. Airlines are opposed to WAAS because they believe that it will be expensive, it is not the global standard (since it is only available in the U.S.), and they believe that it is not necessary for ADS-B Out. WAAS is also not being offered by any airplane manufacturers. By the time WAAS is needed, some airlines hope that the Galileo system will be functioning in Europe, so the industry can move to a global GPS augmentation standard.

NavCanada's mandate for ADS-B over Hudson Bay has pushed some airlines to begin equipping with DO260. Of the airlines equipping with DO260, some claim to have sufficient equipage to make DO260A essentially plug and play. Other airlines do not know what is needed to be considered DO260A compliant. Airlines have suggested that the FAA should give credit for DO260 equipage because that is the European and Australian standard. In addition, they argue that DO260A is not needed for ADS-B Out. The airlines believe the FAA should implement less stringent equipage standards for ADS-B Out and specify requirements for ADS-B In later, when it is deployed. This is because airlines are concerned that current technology will be outdated by the time ADS-B In is implemented and do not want to spend money now for technology that will not be used.

Most airplanes that operate domestically do not have Mode S ES transponders. Those operating in Europe do have ES transponders. However, the data streams in those airplanes may not be correct for DO260A compliance.

No airplanes are currently equipped with DO260A. Some airlines mentioned that they have all the wiring in place for DO260A, but do not have the STC for 260A. UPS is expecting to receive the STC for DO260A very soon.

5.5 Incentives

Figure 5-6 shows the incentives that airlines reported they would like to see with ADS-B.

All of the airlines agreed that a mandate for ADS-B is a good idea. The airlines do not expect much objection to the mandate because the industry views ADS-B as inevitable. Airlines differed on the timing of the mandate. Some airlines suggested accelerating the current mandate because it would decrease their investment risk and

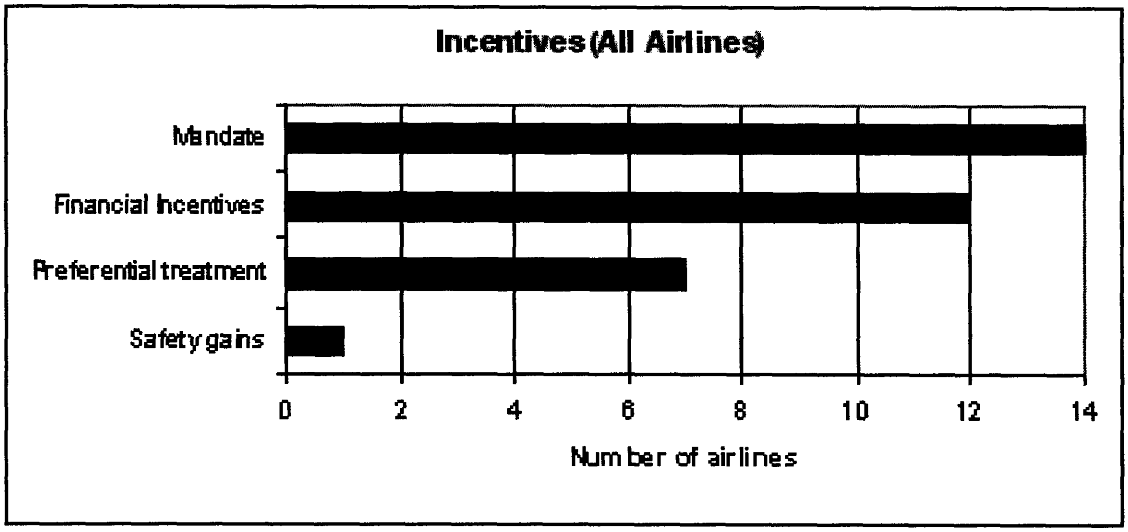

Figure 5-6: Incentives

would lead to an accelerate accrual of benefits. Other airlines felt the time frame for the current mandate was good. Airlines opposing the mandate caution that a mandate must accommodate airline maintenance cycles. Otherwise, the mandate could create significant disruptions to service and economic losses for airlines.

A mandate is viewed positively by many airlines because it creates a guarantee for system-wide equipage and reduces investment risk. It also shows that the FAA is committed to the project. Building trust amongst stakeholders is important for the FAA because of their poor track record with previous technology implementations. A mandate also ensures that airspace users who do not receive a positive cost-benefit from ADS-B (such as general aviation users) will equip. One potential problem of a mandate is that it may create difficulties in attracting early adopters, causing an effect where, if the benefit is low, everybody waits until the last minute to equip.

Beyond a mandate, airlines suggested direct financing would incentivize them to equip. One airlines said that if the benefits exist, monetary incentives would not be necessary. However, airlines with larger fleets believe that the FAA should fund implementation of ADS-B avionics out of fairness. They reason that if airplanes are considered part of the air transportation system, then avionics should be funded with the rest of the system. One airlines mentioned that federal funding would help them overcome all reservations about equipage. If the FAA were to fund their equipage, the airline would equip, regardless of their trust in the ultimate success of the project.

Preferential treatment garnered mixed support from the airlines. Those opposed to preferential treatment were concerned about the logistics of implementing it and were pessimistic about its feasibility. Airlines disliked an exemption system.

One airline suggested the FAA could internalize positive externalities created by early adopters.

5.6 Alternative Technologies

Many airlines mentioned that they were investing in technologies other than ADS-B. These technologies compete with ADS-B avionics for airline resources. Some of these technologies may provide benefits that overlap with ADS-B, further disincentivizing airlines from equipage. For example, RNP may enable new arrival routes that would ease the strain on some busy airports.

A graph of technologies in which airlines are currently investing is shown in Figure 5-7.

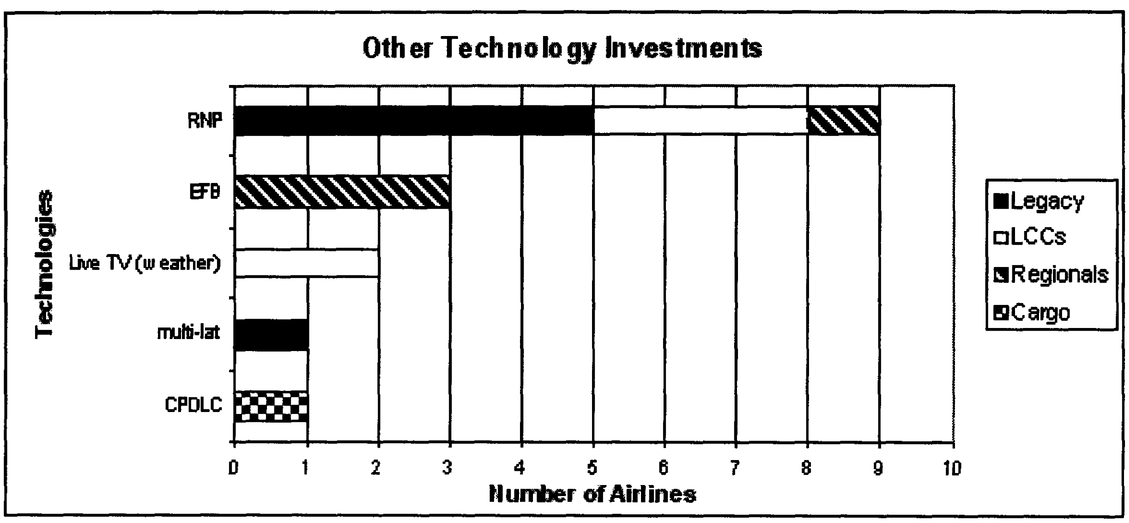

Figure 5-7: Alternative Technology Investments - All Carriers

It is interesting to view the breakdown of investment in alternative technologies by air carrier type. For reference, there were a total of five legacy carriers, three LCCs, three regionals, and two cargo carriers. All major airlines (legacy carriers and LCCs) are investing in RNP. The airlines mentioned that RNP is a higher funding priority than ADS-B because the technology is perceived as being more mature. In addition, RNP will offer some benefits similar to ADS-B. It will enable more precise spacing of airplanes, potentially opening more routes into congested airports. However, it should be noted that RNP is only a partial solution. ADS-B will be needed for lateral separation. In addition, PRM procedures may enable landings at airports with closely spaced runways. If these technologies are readily available and offer a limited version of ADS-B benefits, airlines may be less likely to adopt ADS-B early.

EFB investment comes primarily from regional carriers, which are interested in the weather functionality. Regionals are interested in investing in EFBs because one of the competitors in the group pioneered the use of the technology and has demonstrated benefits from using it. Regionals may be more interested in the weather functionality from EFBs than majors because majors already receive commercial weather services, either through ACARS or through proprietary systems. In addition, some low cost carriers are equipped with Live TV feeds and have been exploring the possibility of using these feeds for weather information.

Alternative technologies mentioned by a few of the airlines include CPDLC and multilateration. While CPDLC is lower priority than ADS-B for most airlines, it is a priority for airlines with extensive operations in Europe, where the technology is more mature.

Multilateration has been cited as an alternative to the surface application benefits of ADS-B. Some airlines have invested heavily in multilateration systems at their hubs. This detracts from the surface benefits of ADS-B. This hurts ADS-B because although surface benefits are small, they are easy to implement. Some local governments, such as the state of Colorado, have also been investing in multilateration systems. The multilateration system in Colorado may impact the magnitude of non-radar area benefit afforded by ADS-B if it is available sooner and for less of a cost to the airlines.

It is important to note that the only airline considering equipage with ADS-B In is UPS. ADS-B In is viewed as too far in the future and the technology standards are considered to be too uncertain to merit equipage consideration.

5.7 Synthesis/Recommendations

There was consensus on ways in which airlines would like to see improvements in the SBS program. Many airlines mentioned they wanted to see buy-in from the FAA leadership, particularly from the division responsible for operation procedures. Many airlines are dissatisfied with FAA progress toward delivering operational benefits, despite the fact the agency has concrete plans for ground infrastructure. Buy-in from FAA leadership is key because the airlines are seeking guarantees that their equipage investments will provide a return.

A second point pushed by airlines is the need for greater stakeholder involvement in the ADS-B program. To engage stakeholders, it was proposed that airlines, pilots, and controllers should be involved in the applications development. Airlines also wanted more transparent information about the cost of equipage and technical standards for ADS-B. Furthermore, airlines wanted proven benefits. Trials were suggested as a method for proving the benefits of ADS-B. The FAA has conducted limited ADS-B trials in the Capstone program in Alaska. However, airlines want trials with commercial carriers in more realistic operating environments. Airlines also stressed the importance of making the trial data available to all users.

5.8 Conclusion

Results of the airline interviews were presented. It was found that differences in airline operating structures led to different perceptions of benefits, barriers, and overall knowledge of ADS-B. Nevertheless, there was agreement on the highest value benefits and issues of greatest concern for the airlines. The three highest benefit applications for airlines are reduced separation standards, arrival and departure procedures, and surveillance in non-radar areas. The highest benefit locations are terminal areas. There was less agreement on benefits in non-radar and surface locations. Airlines are most concerned about cost of equipage, potential certification difficulties, FAA commitment to the program, and information about required equipage, costs, and benefits. the regionals interviewed have a higher proportion of their fleet GPS equipped than the majors. For incentives, all airlines support a mandate, while many also like cash. For alternative technologies, the majors are all investing in RNP while the regionals are all either investing in or intending to invest in EFBs.

Chapter 6

Analysis of Market Failures in Technology Adoption

This chapter presents a game theoretic analysis of the data presented in Chapter five (Interview Results). Free market conditions are assumed for all the games, representing the situation of voluntary early equipage of ADS-B by the airspace users. Market failures that occur in ADS-B implementation under free market conditions are identified as a result of the analysis.

The four games described in Chapter three of this thesis (Market Failures Framework) are played. These include three static games between: major airlines, major airlines and other airspace users, major airlines and the FAA. A dynamic game is also played between major airlines and the FAA.

The location of this chapter relative to the overall objective of this thesis is shown in Figure 6-1. Insights from the analysis in this chapter will inform evaluation of potential government policies in later chapters.

6.1 Airline to Airline Game

In the game between airlines, each agent has two choices, *equip* or *don't equip*. Each agent has a private monetary payoff (P) and a monetary cost (C) associated with equipage. If one agent equips but the other does not, the unequipped agent will still

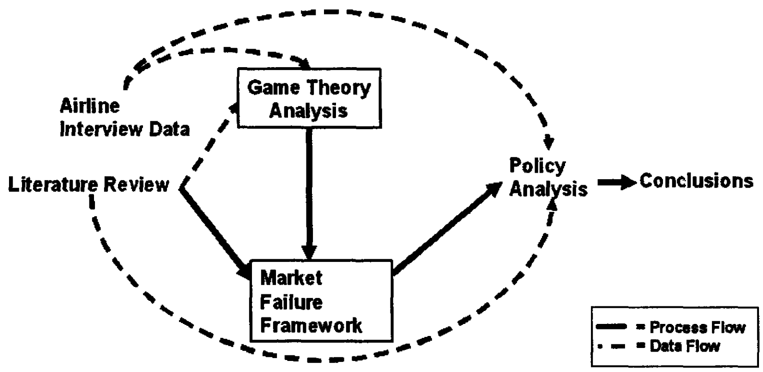

Figure 6-1: Thesis Map

Airline 1 \ Airline 2	Equip	Don't Equip
Equip	P_1-C_1+ε_2+γ ; P_2-C_2+ε_1+γ	P_1-C_1 ; ε_1
Don't Equip	ε_2 ; P_2-C_2	0 ; 0

Figure 6-2: Airline Game

garner a benefit (ϵ) even if they choose not to equip with ADS-B. This represents the externalities that arise from the network effects and the public goods characteristics of ADS-B. There is an additional benefit (γ) that arises when all agents decide to equip.

Based on the variable definitions, an airline's private benefit of equipping would be P-C. If all airlines equip, the payoff would be an individual payoff plus a net externality. So, in the *(equip, equip)* case, the net payoff would be $P - C + \epsilon + \gamma$.

The externality factors are defined to always be positive ($\epsilon > 0$ and $\gamma > 0$). The private benefit *(P-C)* can either be positive or negative.

Figure 6-2 shows the 2x2 game as defined for airlines.

Assume the game is symmetric between major airlines. This means that $P1 = P2$,

$C1 = C2$, and $\epsilon 1 = \epsilon 2$. A symmetry assumption is a fairly accurate representation of payoffs because there is a high level of agreement on benefits in the airlines survey. The assumption of symmetric costs might not be exactly accurate. The airline survey found significant variation in airline fleet equipage, particularly in GPS equipage. Since GPS comprises the bulk of the ADS-B Out equipage cost, this indicates costs of equipage may vary widely from airline to airline.

Under the symmetric assumption, the game changes to the one shown in Figure 6-3.

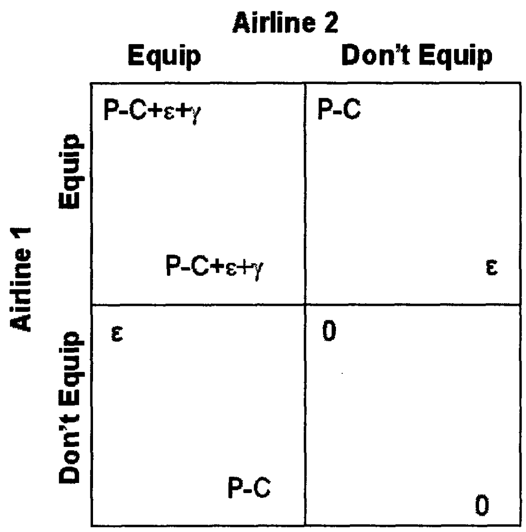

Figure 6-3: Symmetric Airline Game

According to the airline surveys, *P-C* is an unknown to many airlines and others consider it to be negative. For the game, assume $P - C < 0$. Although private benefits are negative, assume that ADS-B still benefits airlines as a group. Therefore, $P - C + \epsilon + \gamma > 0$. This game takes on the form of a coordination game, which has two Nash equilibria - *(equip, equip)* and *(don't equip, don't equip)*. The solution *(equip, equip)* is Pareto dominant. However, the responses from the airline survey indicate that, currently, airlines are more likely to select the *(don't equip, don't equip)* solution. This can be seen in the airline's insistence that the benefits must justify the costs before they will equip and that the applications currently offered by the FAA do not deliver sufficient benefits. Although the airlines are likely to receive a net positive value from equipping, the small private benefit of equipping makes it unlikely that airlines will want to equip. This is an example of a public good market failure.

Two major factors contribute to the public goods market failure. The first factor is that the value of private benefits is too low, creating a negative cost benefit case. This is reflected in the airline assertions that the current set of applications offered in the SBS conops do not align with airline criteria for highest benefit applications. The airlines would like applications that offer fuel, efficiency, and cost savings, which come from reduced separation standards and arrival and departure procedures. The current SBS conops applications primarily offer benefits in situational awareness and safety. While these benefits are important, they are public goods and do not contribute to creating positive business cases for individual airlines.

The second factor stems from the high cost of technology development faced by early adopters. Interview data and feedback from regionals indicates that major airlines likely to be early adopters of technologies championed by the government. The overwhelming concern regarding certification expressed by the major carriers reflects their role as early adopters. By contrast, none of the regionals were concerned about certification. Because major carriers tend to be early adopters, they are likely to incur costs from pioneering technology development in additional to simple equipage costs. In particular, for a nascent technology like ADS-B, airlines would likely test applications for approvals. In essence, as early adopters, major carriers are likely to create an externality that leads to low private payoffs, creating a situation where the non-Pareto optimal equilibrium is selected.

6.2 Airline to Other Users Game

The airline to other airspace user game is an asymmetric game. Figure 6-4 shows the airline to other airspace user game.

In this game, in contrast to the game between major carriers, major carriers are represented as a group, not as individual entities. Therefore P_{AC} represents the payoff to the large domestic carrier industry. As with the previous game, there are externalities that arise from mixed and homogeneous equipage situations.

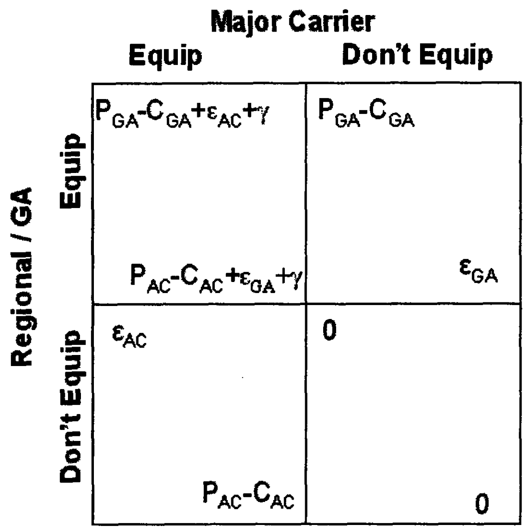

Figure 6-4: Airline to Other Airspace User

Data from the airline interviews shows a skewed distribution of costs and benefits between major carriers and other airspace users because the user groups value benefits differently. The regional airlines interviewed in this study fly only to major cities and do not spend a lot of time out of radar range. As such, they do not value the non-radar applications as highly as major carriers. In addition, regional carriers interviewed do not pay for gas or set their own schedules. The fuel costs and scheduling responsibilities are set by the majors for which they contract. As such, regionals do not value applications that provide fuel savings and increased airspace capacity as highly as the majors. Applications that offer fuel savings and capacity increases may make the regionals more competitive when bidding for contracts, but do not directly impact their bottom line. Based on the rate of regional equipage with EFBs, it seems that weather services might be more valuable to the regionals.

The operating structure of GA is drastically different from that of airlines. As shown in the interviews, airlines value efficiency and fuel savings. Recreational users, on the other hand, tend to value safety and information applications, such as weather services. [20]

Assuming the cost of regional and major airline equipage is comparable, there is a case of asymmetric payoffs. Because the type of benefits targeted by the ADS-B program do not strongly appeal to the regionals interviewed, they may prefer not equipping. In this case, only one Nash equilibrium may exist. If one agent has a strong preference for not equipping, the only dominant solution to the problem may be the *(don't equip, don't equip)* strategy.

An asymmetry in costs between majors and regionals can also be introduced to the game. The regionals interviewed have newer airplanes that would be easier to retrofit than the airplanes owned by the majors. In addition, as mentioned previously, majors often absorb development costs of new technologies and procedures. As such, the cost of equipage to regionals is likely to be lower than for the majors ($C_{AC} > C_{GA}$).

Therefore, assuming that the small payoff to regionals is balanced by the large cost incurred by the majors ($P_{AC} - C_{AC} \approx P_{GA} - C_{GA}$), two Nash equilibria may exist- either both players equip or they both do not equip. Based on the data, it seems that neither player is particularly keen on equipping. This can be attributed to information asymmetries, which make the non-Pareto optimal solution risk dominant.

In particular, regionals are generally less informed about a technology than the majors. As such, the airlines do not know what types of cost-benefit cases the regionals are likely to make. Therefore, uncertainty increases due to the information asymmetry, making the *don't equip* decision risk dominant.

6.3 Airline to FAA Game

Two games can be played for the airline to FAA interaction. First, there is a static game, representing the first equipage decision. An extensive form game is also played representing the multiple equipage process proposed for ADS-B.

6.3.1 Static Game

For the static game, the airline player represents airlines as a whole. The airlines have two decisions- *equip* or *don't equip*. The FAA also has two decisions - *invest* or *don't invest* in ADS-B. Define FAA investment in ADS-B to mean delivery of infrastructure, applications, and procedures. Define a payoff variable (P) and a cost variable (C) for each player. Furthermore, because payoff represents aggregate payoffs for the airline industry, assume that $P - C > 0$ for both airlines and the FAA. The condition for positive payoff is that both airlines are equipped and the FAA has invested in ADS-B. Assume that in the mixed solution case *(don't equip, invest)* and *(equip, don't invest)*, private payoff is zero ($P = 0$). For the *(don't equip, don't invest)* solution set, define the benefit to be zero. This assumes future possible negative consequences from not modernizing the air transportation system are neglected. The FAA game is shown in Figure 6-5.

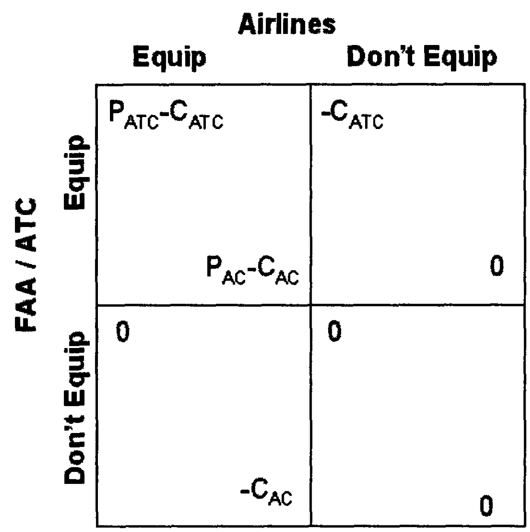

Figure 6-5: Airline to FAA

This game has two Nash equilibria - *(equip, invest)* and *(don't equip, don't invest)*. The solution *(equip, invest)* Pareto dominates. However, according to the airline survey, it is unlikely that airlines will choose the *(equip, invest)* solution under market conditions. If the airlines strongly prefer the don't equip solution, the game shows that the likely dominant equilibrium is *(don't equip, don't invest)*.

Airlines report the *(don't equip, don't invest)* may dominate because of a perceived asymmetry in costs and benefits. Airlines believe that they are generating a positive externality for the FAA by equipping with ADS-B. The argue that the FAA would receive cost savings by adopting ADS-B because ground stations are approximately one-fiftieth the cost of radar stations. [15] However, the FAA contends that ADS-B will provide airlines with operational benefits, which will result in significant cost savings.

Data from the FAA's draft regulatory impact analysis, shown in Figure 6-6 shows that both the FAA and airlines are correct.

	Undiscounted			Discounted by 7%		
Costs	ADS-B	Radar	Multilateration	ADS-B	Radar	Multilateration
FAA Total Cost	$2.26	$4.83	$2.70	$1.20	$2.15	$1.57
User Total Cost	$3.21	$4.56	$4.56	$2.24	$2.43	$2.43
Total Cost	$5.47	$9.39	$7.26	$3.44	$4.58	$4.00
Benefits						
Total Benefits	$16.25	$13.18	$10.10	$4.42	$3.11	$4.30
Net Benefits	$10.78	$3.79	$2.84	$0.98	-$1.47	$0.30

Figure 6-6: FAA Draft Impact Analysis Results [24]

The analysis shows that ADS-B will lower the cost of surveillance for both airlines and the FAA. Based on this FAA analysis, it seems that a market failure is unlikely to occur.

A market failure does occur because of a differences in expected time for return on investment and airline distrust of the FAA. While both parties make significant investments for infrastructure at the beginning of the project, they have very different time scales for return on investment. According to the airline survey, airlines have return on investment timeframes that vary between one and five years. Governments, on the other hand, can afford to wait longer for a return on investment. The FAA the estimate of benefits is based on a twenty year time frame, the lifetime of the project. Furthermore, the FAA impact analysis expects the majority of benefits at the end of the program, when all users are equipped and ADS-B In has been implemented. Considered in an airline return on investment (ROI) time frame, the high initial investments in avionics and minimal benefits in the early years of the program may indeed create a negative business case for the airlines.

The airlines distrust that the FAA will deliver the level of benefits claimed in their draft impact analysis. This distrust is due to a perception that the FAA has difficulty in completing technology initiatives. Therefore, the airlines are creating a business case on a shorter time scale and discounting the value of possible future benefits due to distrust of the FAA. Due to different time frames used for their respective individual business cases, there may indeed be a misalignment of costs and benefits

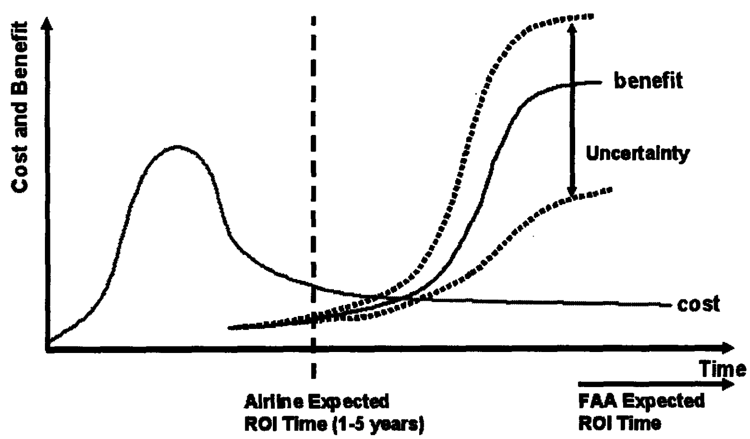

Figure 6-7: Differences in FAA and Airline Expected ROI Time

for airlines and the FAA that leads to market failure. This scenario is illustrated in Figure 6-7.

Risk Dominance

The long time frame to significant benefits makes the non-Pareto optimal solution potentially risk dominant. In particular, the condition for risk dominance is $P_{ATC}P_{AC} - P_{AC}C_{ATC} - P_{ATC}C_{AC} > 0$. Assuming payoffs and costs and symmetric between the FAA and air carriers as a whole, the condition for risk dominance becomes $2C \geq P$. This means that the payoff would need to be at least twice the cost of equipage in order for the Pareto optimal solution to be risk dominant. Based on airline feedback regarding benefits, it seems that the current set of applications offered by the FAA is unlikely to meet that criteria. Although higher levels of benefits may be offered in the future, those applications do not fall in the time frame necessary to create a business case for equipage in the immediate future.

The underlying cause of system risk stems from airline uncertainty about the FAA's ability to complete the project and deliver benefits. The uncertainty comes from perceived institutional failures in the regulatory arm of the FAA that affects the agency's performance as a market entity. In the case of ADS-B, one institutional failure that adds risk to the system is organizational processes.

Organizational Process Failures

Organizational process failures for the government stem from certification, as well as from management of system transition. Organizational process failures add risk and decrease the value of the airline equipage case by increasing the time needed to complete a project. With increased time to delivery of benefits, the benefits shift beyond a reasonable timeframe for return on investment for airlines.

Management of the system transition is difficult for the government because is has not recently implemented a change on the scale of ADS-B. The magnitude of the system change and the voluntary equipage aspect of ADS-B makes it unique. Previous wide-scale technology initiatives, such as TCAS, have been driven by a strong safety argument, which justified a mandate. Voluntary equipage means that the government must manage stakeholder needs and expectations while meeting its own performance objectives. Furthermore, the system-wide nature of the change means that there are many stakeholders with potentially different interests to balance. Because change of the magnitude and type of ADS-B is so rare, the government does not have well established standards and methods for balancing the demands of so many stakeholders, leading to organizational process failures.

Several airlines voiced concerns regarding FAA certification and operational approval processes. In particular, airlines fear that the constraints of the approvals process will prevent the implementation of ADS-B applications that will delivery high value benefits. Furthermore, airlines fear that the lengthy approvals process, coupled with the fast pace of technology development, will render technologies obsolete before they receive approval, creating wasted use of resources. Specific areas that concerned the airlines included meeting safety requirements with new procedures and avionics and receiving operational approval for individual fleet equipage. As a basis for their concerns, airlines cited the RNAV and RNP program, which have been slow to deliver beneficial procedures.

Analysis shows that the scope of changes envisioned for ADS-B would required complex coordination and intensive analysis to gain approval. In particular, analysis must be conduced in several operating performance areas, including avionics, ground infrastructure, air to ground interface of data integration, and operational procedures. For each operating performance area, safety analyses require technical expertise from from several stakeholder groups, including air traffic control and airspace users. It is noted that a large amount of analysis is required to prove systems meet performance requirements. [23] The complexity of operational approvals indicates there is a potential for organizational process failure.

6.3.2 Dynamic Game

The ADS-B program, as proposed by the FAA, has a minimum of two equipage steps- one to equip for ADS-B Out and one to equip for ADS-B In. More decision points may be added depending on whether the FAA will allow the DO260 standard, with equipment upgrades to DO260A for ADS-B In, and further equipment upgrades accommodate new capabilities. A dynamic game can be used to simulate multiple step equipages.

An extensive form game demonstrates why airlines are opposed to a multiple step equipage. Figure 6-8 shows a dynamic game between the FAA and airlines represented in extensive form.

Each node represents either an equipage decision point for the airlines or an investment decision point for the FAA. The game assumes four decision points- two by the airlines and two by the FAA. The FAA's first decision would represent their initial ground infrastructure deployment and first group of applications. The airline's first decision represents equipage with ADS-B Out. The FAA's second decision point represents implementation of ADS-B In applications. The airline's second decision represents a second equipage for ADS-B In. At each decision point, there is a probability that the user will choose to not equip or invest, thereby ending the program. Assume airlines will choose to equip with probability α. Assume the FAA will choose to invest with probability β. The probabilities of equipage and investment represent the coordination effort required at each decision point. Each coordination effort is analogous to playing the static games shown above. Payoffs are shown at the termi-

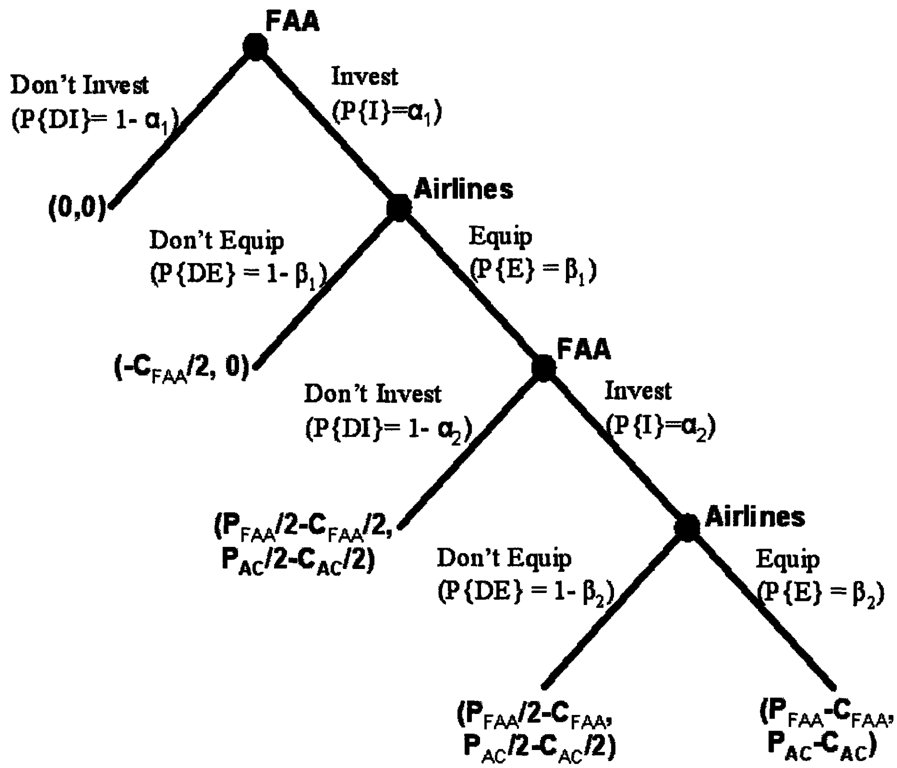

Figure 6-8: Dynamic Game: FAA v. Airlines

nus of branches of the tree. Full benefits cannot be achieved unless the full chain of positive investment and equipage decisions is followed.

The multiple step game shows that multiple equipages add risk and uncertainty to the system because probabilities associated with choices at each step are multiplicative. Because probabilities are less than one, the chances of achieving the optimal end state diminish with every additional branch in the decision tree. Initial investment risk is compounded at decision points because airlines are not certain that the final goal will be attained. Therefore, multiple decision points make it less likely airlines will make the significant up-front investment necessary to equip with ADS-B.

The risk at each decision point is particularly significant when considering the FAA is tied to a regulatory body that is also subject to institutional failures. An institutional failure likely to occur in the multiple step decision game is bureaucratic interests and politics.

In particular, sustained funding and government support for ADS-B is a significant concern of airlines. Airlines cite failures of technology initiatives such as CPDLC as a basis for their worries. Research of multinational infrastructure programs has validated airline concerns, showing the fragility of government funding for infrastructure type projects. Rogoff has shown in game theoretic analysis that when pressured with an election cycle, governments will choose to allocate resources to projects that can produce immediate results in order to win votes rather than to long term infrastructure projects. [31] Even discounting the effect of election cycles, sustained government funding is difficult to achieve in the face of competing interests, such as health care and education. The long time of an infrastructure project exposes it to greater risk of failure.

There is significant airline concern over the risk of program failure presented by funding cycles. The concern can be seen in airline responses that called for buy-in from FAA leadership and change being driven from the top. The sentiment amongst airlines is that having leadership champion the program will provide more stability and certainty for sustained funding. Some airlines suggested the FAA should accelerate the mandate for ADS-B, provided the benefits exist. Accelerating the mandate would decrease the risk of project failure because it would provide fewer funding decision points at which the project could fail.

6.4 Conclusion

Through a game theoretic analysis of airline interview data, several market failures were shown to exist for ADS-B technology implementation under free market conditions. Between major airlines, there is likely to be a public goods failure, where the individual benefit from equipage does not justify the cost. This can be attributed to the nature of applications offered by the current SBS Conops and the time frame during which airlines seek a return on investment. Between major airlines and other airspace users, there is likely to be a market failure resulting from asymmetry of costs and benefits and asymmetry of information. Asymmetries in costs and benefits come from different roles that the airspace users play in technology adoption, with the legacy carriers traditionally as early adopters and the regionals traditionally as late adopters. Between the airlines and the FAA, there is also a perceived asymmetry of costs and benefits, which stems from differences in acceptable time frames for return on investment. In addition, a market failure is likely to occur due to risk dominance. Risk in the system comes from institutional failures in organizational processes at the FAA regulatory arm. In addition, for a dynamic game, risk naturally arises from multiple equipage decision steps.

Chapter 7

Policies

Market failures suggest a need for government intervention. In theory, the role of government is to correct market failures, creating conditions that will drive the market to an efficient equilibrium. In this chapter, potential government actions to correct ADS-B market failures are suggested and evaluated. However, as shown in Chapter six (Analysis of Market Failures in Technology Adoption), government intervention may not always be effective because government is subject to institutional failures.

The location of this chapter relative to the overall objective of this thesis is shown in Figure 7-1.

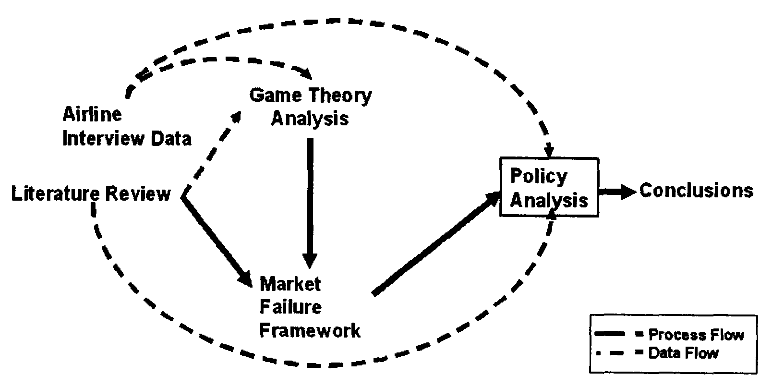

Figure 7-1: Thesis Map

7.1 Policy Mechanisms

A framework for studying government mechanisms pertaining to air transportation was developed by Marais and Weigel (2006). Government actions are grouped into four categories, which include infrastructure development support, increasing technology value, positive incentives, and mandates or putative measures. [21] Based on the feedback from the airline interviews, for ADS-B, it may be appropriate to separate mandates from putative measures, resulting in five categories of government mechanisms. The mechanisms are shown in Figure 7-2.

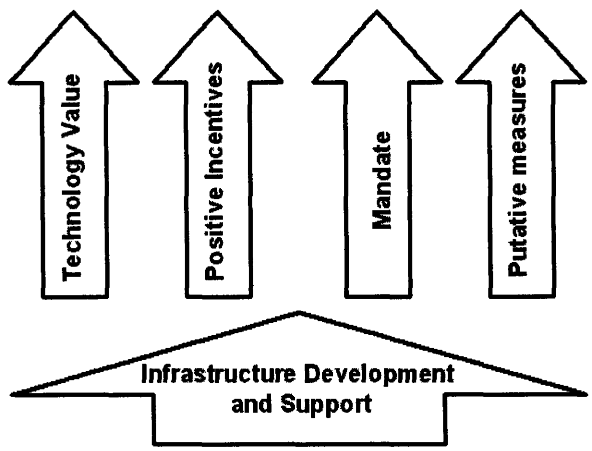

Figure 7-2: Mechanisms for Technology Transition [21]

Infrastructure development means ensuring that the technology is available and accessible to users. It includes physical deployment of ground infrastructure, certification, and development and testing of new procedures. For ADS-B, infrastructure would include ground stations, ATC controller interfaces, applications and procedures.

There are three ways to increase technology value. The public goods benefits can be increased, leading to an increased technology value across the system. Or, the private goods benefits of the technology can be increased, creating higher benefits for each individual user. In addition, the timeframe to accrual of benefit can be decreased, creating benefits within an acceptable time for return on investment for the airlines.

Positive incentives are tools available to the government that can be used to modulate the value of a technology. These tools offer benefits beyond the scope of benefits that can be provided by technology alone. Positive incentives can be used to deliver benefits in a return on investment timeframe acceptable for airline business cases if applications development takes too long. For ADS-B, positive benefits that have been suggested include cash payments to airlines, loans, tax credits, and preferential treatment measures.

Mandates are a way of guaranteeing full equipage and reducing investment risk. Mandates include rules requiring equipage of ADS-B. Mandates can be applied to either to the entire airspace or just to specific airspaces. For example, the FAA can choose to require ADS-B into all class B airspace, which would force most airlines into compliance. By decreasing risk, mandates may shift the airline cost benefit case to show returns within an acceptable time period.

Putative measures are a way to tax noncompliance. Putative measures can also include taxes for non-compliance, or exclusionary airspace restrictions. Putative measures can be used to shift the cost-benefit analysis for airlines by increasing the cost of noncompliance to an unacceptable level. It is interesting to note that putative measures and positive incentives acts in opposite ways. Positive incentives induce users to equip by adding benefit while putative measures induce users to equip to by increasing the cost of non-compliance.

The FAA has already implemented several policies that align with the Marais-Weigel framework. The FAA began infrastructure development through the contract for ground station deployment, awarded to ITT in August of 2007. Ground infrastructure deployment is expected to begin in 2010 and finish by 2014. In addition, the FAA has taken steps toward a mandate for ADS-B out by issuing a NPRM in August of 2007. According to the NPRM, a mandate for ADS-B Out in the NAS will take effect in 2020. The FAA has sought to increase technology value to GA users with a UAT link decision. Because GA find weather and information services most valuable, these services will be provided on through UAT. However, the ultimate value of the FIS-B services is debatable because of the development of alternative commercial services, such as XM radio.

Despite the actions of the FAA, data from the airlines shows the system is still prone to market failures. This suggests the FAA should take further steps to correct these sources of market failure. This conclusion is validated by airline survey data, which indicates airlines believe the FAA has not done enough to advance the deployment of ADS-B technology.

7.2 Policy Selection Criteria

The market failures identified in Chapter six present criteria for objectives of government policy. The market failures identified include:

- Public Goods Failure
- Asymmetry of Costs and Benefits
- Asymmetry of Information
- Risk Dominance
- Organizational Process Failures
- Bureaucratic Interests and Politics

To correct the public goods failure, the government could ensure delivery of private benefits. Although it is important that the government deliver the public goods offered by ADS-B, private benefits can be used as a vehicle for encouraging airspace user equipage and attaining implementation of the public goods. Through careful selection of benefits and incentives, the government can realign asymmetries of costs and benefits. Asymmetry of information can be corrected by encouraging stakeholder involvement and working to effectively disseminate information. Risk can be reduced by correcting information asymmetries and institutional failures.

7.3 Policy Actions

In the synthesis portion of the interviews, airlines suggested several policy actions that would encourage them to equip. These are categorized according to the modified

Marais-Weigel framework.

Although the FAA has begun infrastructure development with ground infrastructure deployment and initial applications and procedures development, they can extend their use of this mechanism through flight trials. Airlines believe that trials are necessary to demonstrate the real benefits of ADS-B applications and to ensure safety and certification approval for the applications and procedures. Several airlines have expressed eagerness to collaborate with the FAA on ADS-B trials. To a limited extend, the FAA begun trials of ADS-B, focusing their work in Alaska and Louisville. The Alaska trials were part of the Capstone program. However, the trials only demonstrated ADS-B via UAT, so the scope of the study only applies to GA aircraft. In addition, airlines feel the data from the Capstone trials is not transparent and accessible. Therefore, the results cannot be independently validated. Trials with UPS in Louisville demonstrating CDA procedures have been more effective. Airlines laud the achievements of these trials and they have been effective in providing proof of ADS-B benefits and garnering support for the program. Airlines would like to see this type of trial program expanded to more applications.

To increase technology value, airline interview data shows the best action may be to deliver benefits with high private value. Applications with high private value to the airlines can be accelerated through the development and approval process. Examples of high benefit applications for the airlines are ADS-B in non-radar areas, arrival and departure procedures, and allowing reduced separation standards. The FAA has already tried to increase technology value for general aviation users by offering weather and information services through the FIS-B link. However, with the emergence of satellite weather services, it is unclear if FIS-B services will provides as much of a benefit as previously calculated.

There many ways to offer positive incentives, including direct financing (cash), tax credits, and preferential treatment. Of these incentives, airlines preferred direct financing. Some airlines liked preferential treatment, while others did not feel that it would be feasible. Another potential positive incentive is guaranteeing benefits to the airlines by a certain date. If the FAA is unable to deliver benefits by a certain date, they could offer to pay for lost benefits. This would insure the airlines against institutional failures.

The FAA already has a mandate for ADS-B Out. Airlines like the mandate because it provides insurance for their investment decisions and standardizes the technology. However, airlines suggested considering alternative instantiations of the mandate. To encourage early equipage amongst a particular group of airspace users, the FAA could impose a mandate in select airspace, such as the airspace around New York, or around class B airports. Some airlines suggested the FAA could accelerate the mandate for ADS-B Out for airlines. A decrease in the program cycle length would decrease investment risk for the airlines. Lastly, some airlines suggested a need for a mandate for ADS-B In.

Putative measures include taxation and exclusionary airspace. Taxation would tax anybody who is not equipped. Exclusionary airspace is the inverse of preferential treatment. It would not allow anybody not equipped to enter certain airspace. Before putative measures are levied, the reason for stakeholder non-compliance should be considered. Some airspace users, particularly recreational GA, may be unwilling to equip because they cannot afford to do so. In such a case, putative measures would unfairly inflict a double tax on these users. One particularly innovative program employed by AirServices Australia uses the ATC services savings from ADS-B to fund GA equipage. While the airlines do not reap financial benefits from the savings, they benefit indirectly from having a higher percentage of equipped planes in the airspace.

7.4 Policy Evaluation

Figure 7-3 shows a summary of the policy options, evaluated against the policy selection criteria.

As seen in Figure 7-3, no single measure sufficiently satisfies all the policy selection criteria. Instead, a combination of policies will likely be adopted to achieve the goals of the FAA and meet the criterion of the stakeholders. The wide variety of stakeholders

Policy Mechanisms to Correct Market Failures		Market Failures: Public Goods Failure	Market Failures: Asymmetry of Costs and Benefits	Market Failures: Information Asymmetry	Risk Dominance: Organizational Processes Failure	Risk Dominance: Bureaucratic Interest and Politics
Infrastructure Development and Support	Trials			X	X	
Increasing Technology Value	High Private Value Applications	X	X			
Positive Incentives	Direct Financing	X	X			
Positive Incentives	Tax Credits	X	X			
Positive Incentives	Preferential Treatment	X	X			
Mandate	Full Mandate					X
Mandate	Accelerate Mandate					X
Mandate	Location-Specific Mandate					X
Puntative Measures	Tax		X			

Figure 7-3: Policy Mechanisms for Correcting Market Failure

does not make this a trivial problem. One way to package policies is by program phase. Survey results show that different stakeholders are likely to equip at different phases of the program. In essence, each stakeholder group reacts to a slightly different set of market conditions.

According to the surveys, major domestic carriers are likely to be the earliest adopters. Once the technology has become more mature, regionals, business jets, and other GA aircraft who can afford to equip are likely to equip. Recreational general aviation users are likely to be the last to equip due to a lack of benefits and inability to afford new the new technology.

Amongst early adopters, the market failures were public goods failures and cost-benefit asymmetries due to short timeframes for airline ROI. The failures arise due to externalities from pioneering development costs, a long technology deployment time, and higher risk of program failure. Policies such as preferential treatment, offering high private benefits, and financing would likely encourage early adoption. Preferential treatment and financing serve to internalize externalities produced by the early adopters. High private benefits helps the airlines make a positive cost-benefit case for equipage.

Two types of early adopters seem to exist for ADS-B. One type of early adopter is airlines that would equip if they could accumulate benefits from existing equipage and technologies. This type of early adopter plays a key role in moving industry momentum toward the new technology. Therefore, they are strategically important for the FAA. For type one early adopter airlines, it is important to accelerate benefits.

To accelerate benefits to early adopters, it may be beneficial to first find applications that offer private benefits using existing technology. For example, the FAA could find applications that use ADS-B in conjunction with RNP or DO260 to provide benefits. Existing technologies offer the advantage of having already gone through the certification process. When thinking about benefits for early adopters, it is important that the benefits are independent, to allay fears about the impact of a mixed equipage environment.

A second type of early adopter is airlines willing to invest in future concepts.

They are extremely useful to the FAA because they present an opportunity for the FAA to conduct trials of new avionics, such as DO260A, and to test new procedures. Because development work in future concepts requires heavy investment and the airlines produce significant positive externalities, it is important that the FAA help them internalize these externalities. Potential actions for the FAA include financing equipage and offering preferential treatment.

For later adopters, market failures that arise are information asymmetries and cost-benefit asymmetries stemming from a lack of benefits. These market failures stem from the fact that late adopters may have a relative paucity of resources and the program does not offer them private benefits. If the goal is to encourage late adopters to equip earlier, it may be beneficial to provide information and accelerate applications that will provide high benefit to them. Conducting trials to prove benefits may help them establish a more compelling individual cost-benefit cases. These trials will likely follow naturally from early adopters equipage. As a last resort, putative measures and mandates may be appropriate. However, these measures should be instituted cautiously because they may act as a double tax for users who could not afford to equip in the first place. For a small subset of late adopters who cannot accord to equip (i.e. likely some recreational GA owners), direct financing might be appropriate.

Meeting the benefits demands of all stakeholder groups will be challenging. However, overlaps in preferred benefits amongst stakeholder groups provides opportunities for government action. For example, all types of airlines are interested in benefits that alleviate congestion in busy terminal areas. Non-radar areas provide an opportunity to provide benefits to both GA and legacy carriers.

In addition to targeted policies, some policies would be beneficial for the duration of the program. These policies are targeted at market failures that affect many stakeholder groups. Examples of these market failures are risk and institutional failures. Risk can be reduced throughout the program by getting support from FAA leadership and eliminating organizational processes failures.

All stakeholder groups were also concerned about a potential lack of benefits from

ADS-B. This suggests a need for user-driven development of benefits. The data presented in this thesis offer a starting point for thinking about applications designed to offer high user benefit. As the program progresses, the users suggest that the FAA should provide them with data from technology trials and offer a transparent process for the users to offer input and suggestions.

7.5 Implementation Difficulties

Policy selection is only part of the work. There may be tremendous difficulty in implementing some of the policies suggested in this chapter due to institutional failures. In particular, institutional failures may inhibit the government's ability to act as a coordinating body through the reallocation of resources.

One example is airline skepticism about the FAA's ability to offer early adopter incentives. The airlines reason that if the incentives offered are truly valuable, lobbying groups will ensure the benefits are available to all users, regardless of equipage. Lobbying is an example of a bureaucratic interest and politics institutional failure. Lobbyists makes it difficult for the FAA to shift benefits from one user group to another. They also make it difficult for the FAA to offer incentives that apply only to a subset of stakeholders, such as incentives for early adopters. A potential way around this failure is making the stakeholders understand the reasoning for the action and creating an atmosphere of perceived fairness, as Airservices Australia did for their general aviation equipage plan.

The FAA may also be limited in its ability to partner with airlines for trials of technology under development and future airspace concepts. In particular, they may be accused of favoritism for partnering with specific airlines. One airline suggested that a way around this problem is for the FAA to solicit information about potential early adopters through the Air Transport Association, the airline industry trade group.

7.6 Conclusion

Government policies for correcting market failures are presented and evaluated. The Marais-Weigel framework is used to categorize government actions. Potential policies were evaluated for their ability to correct market failures. It is suggested that a combination of policies be adopted, depending upon the phase of the program and the airspace user's resources and needs. Implementation difficulties associated with some suggested policies are discussed.

Chapter 8

Conclusion

This thesis presented an analysis of the problem of market driven technology transition in the air transportation system, focusing specifically on ADS-B. Technology transition problems arise because of the network characteristics of ADS-B, which make it prone to market failure. A market failure framework was used to identify potential sources of problems in ADS-B technology implementation. Market failures were illustrated using game theoretic analysis. Data for the analyses was collected through a series of airline interviews. Policy actions were evaluated for their ability to correct market failures.

8.1 Summary of Results

Fourteen airlines were interviewed to gather data on airline views of ADS-B costs and benefits, airline perception of ADS-B, and airline investment decisions. For benefits, airlines are primarily interested in applications that provide efficiency improvements, fuel savings, and increase airspace capacity. Benefits that provide high value to airspace users include reduced separation standards, arrival and departure procedures, and surveillance in current non-radar areas. Barriers identified by airlines fall into two categories - cost and uncertainty. Costs are associated with cost of equipage. GPS is expected to account for a large proportion of the cost for ADS-B Out. Uncertainties are associated with institutional failures that result from the FAA role as both a regulatory and market agent. Uncertainties serve to increase investment risk for airlines.

It was found that different types of airspace users have different preferences and priorities. This could make it difficult to deliver equal benefits to all stakeholders.

Regional airlines participating in this study have a higher percentage of fleet GPS equipage than legacy airlines, indicating it may be easier for regionals to implement ADS-B. However, regionals are likely to act as late adopters while major carriers are likely to act as early adopters. This is because regionals do not pay for their own fuel or set their own schedule, resulting in less emphasis on the types of benefits offered by ADS-B.

Market failures identified to occur for the ADS-B technology implementation under market conditions include:

- **Public Goods Failure** due to low private benefits in the current set of proposed ADS-B applications.
- **Asymmetry of Costs and Benefits** due to differences in stakeholder preferences.
- **Asymmetry of Information** due to different levels of stakeholder knowledge and access to information regarding ADS-B.
- **Risk Dominance** resulting from difficulties in certification and perceived past problems with technology implementations.
- **Organizational Process Failures** which make it difficult to fit existing procedures to evolving situations, such as accommodating the level of changes needed to approve ADS-B avionics and procedures.
- **Bureaucratic Interests and Politics** which can inhibit government from making a sustained commitment to the project and taking necessary actions to correct market failures.

Government intervention can be effective in correcting market failures. Government policies can work through many mechanisms, including infrastructure development and support, increasing technology value, offering positive incentives, issuing mandates, or levying putative measures. It is suggested that governments should adopt a combination of policies and vary them according to the phase of the project.

In particular, it is important for the government to deliver private benefits, balance costs and benefits to stakeholders, give stakeholders more information, and correct institutional failures. Private benefits incentivize users to equip and provide a vehicle for ensuring the delivery of public benefits. For early adopters, the government should focus on internalizing externalities. For late adopters, the government should focus on delivering information and insuring they have the resources to equip. A mandate was considered a good idea by all airlines.

8.2 Contributions

This thesis presents two types of contributions. First, a method for analyzing potential problems in air transportation technology initiatives is presented. The method applies economic ideas of market failure and game theoretic analysis to analyzing stakeholder interactions in air transportation. In this thesis, the method is used for the case of ADS-B technology adoption.

The second contribution of this thesis is a body of knowledge regarding domestic airline views on ADS-B technology in particular and equipage investments in general. This knowledge will potentially be useful for government agencies thinking about technology transition in the future. By using the method presented to analyze the ADS-B program implementation, this thesis bridges the gap between technology adoption theory and the practice of implementing infrastructure technologies in air transportation.

8.3 Future Work

Specific to ADS-B, a rigorous analysis of policy options presented in this thesis should be conducted to provide further guidance for government actions. Furthermore, as data regarding costs, benefits, and risk, becomes available, the game theoretic analysis of market failures can be refined. It may be necessary to do further analyses for ADS-B In equipage or if conditions changes in the ADS-B project.

The methods and ideas used in this thesis can be used to analyze other coordination problems in air transportation that present network features. In addition, it would be interesting to extend the application of the method to other problems with similar characteristics.

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Appendix A

Interview Instrument

ADS-B Airline Industry Survey

Professor John Hansman, Professor Annalisa Weigel, (Jenny) Xiaojie Hu
MIT International Center for Air Transportation (ICAT)

Carrier Name:

Interviewee: **Date:**

The MIT International Center for Air Transportation, in the Department of Aeronautics and Astronautics, is working with the FAA to investigate applications and benefits of ADS-B technology and user equipage. This data will be valuable in informing strategies for the deployment of ADS-B ground infrastructure and applications. We are surveying airlines to identify their views on benefits from ADS-B applications and costs and barriers associated with adoption of ADS-B. Thanks for your participation.

For the purposes of this survey, ADS-B services are divided into two types - 1) Surveillance and 2) Broadcast services. Broadcast services refer to TIS-B and FIS-B. Surveillance services refer to all other ADS-B functionalities on both 1090 and UAT.

Part I. Background:

1.1 What is your role in your airline?

1.2 In what capacity have you been involved in ADS-B?

1.3 What is your airline's view of ADS-B?

1.4 What is your airline's view of the NPRM for ADS-B Out?

Part II. Benefits Questions:

We are considering ways to deploy the ADS-B infrastructure and would like feedback on applications and geographies for the rollout plan. Infrastructure can be rolled out in three types of service volumes: 1) Surface, 2) Terminal, and 3) Enroute. The surface service volume refers to the airport traffic area and surface. The terminal service volume is equivalent to a TRACON. The enroute service volume is equivalent to an ARTCC.

ADS-B information can be linked to three locations: the air traffic control center, the airline operations center, and airplane cockpits.

2.1 Surveillance services: For your airline, what benefits/applications can be derived from linking ADS-B surveillance data to the following locations. Please consider benefits associated with surface, terminal, enroute, and non-radar coverage airspaces.

a) ATC
b) Airline operations centers
c) Airplane cockpits
d) Other

Are there specific locations where these benefits apply?

Are there locations where it would be beneficial to install ADS-B ground stations early in the rollout process? Which locations? Why?

2.2 Broadcast services: Do you think there are any broadcast services that provide benefits your airline? (i.e. graphical weather information, NOTAMS, ect.)
Yes No

If yes, what benefits?
Are there specific locations where the benefits apply?

2.3 How do the equipage decisions of other airlines or users influence your decision to equip with ADS-B?

2.4 At the national level, what do you see as the main obstacles for obtaining the ADS-B applications you mentioned?

2.5 Are the benefits/applications you have mentioned enough to incentivize your airline to equip with ADS-B? Why or why not?

Part III. Costs and Barriers

3.1 For your airline, what do you see as the main barriers or concerns regarding the adoption of ADS-B? How do these costs and barriers compare in the way that they influence your decision to equip with ADS-B?

3.2 What is your confidence that the benefits/applications you mentioned in Part II for ADS-B will receive operational approval by the FAA?

3.3 What incentives, or mandates beyond operational benefits would be most effective in encouraging your fleet to equip?

Part IV. Current Status

4.1 What is your airline's philosophy towards fleet operation? (i.e. Do you operate separate fleets for certain routes?)

4.2 What level and type of ADS-B equipment is on your current fleet? How much of your fleet is GPS equipped?

4.3 Are your new aircraft delivered with ADS-B?

Yes No

What level of ADS-B equipage do they have? (i.e. DO 260 v. DO260A)

4.4 What type of equipment upgrades would be needed to make your fleet NPRM (for ADS-B Out) compliant? (i.e. DO260A, GPS with WAAS, TSO-C166a)

Part V. Future Plans

5.1 The NPRM suggests a mandate for ADS-B Out only. Does your airline have plans to equip with ADS-B In? Why or why not?

5.2 Is your airline planning any other modernization efforts? (i.e. RNP, CPDLC, etc.) What is the relative priority of these technologies compared with ADS-B ?

Part VI. Synthesis

6.1 Have you been involved with other modernization efforts?

Yes No

What lessons learned from those experiences can be applied to ADS-B?