GAME THEORY ANALYSIS OF AIRCRAFT MANUFACTURER INNOVATION STRATEGIES IN THE FACE OF INCREASING AIRLINE FUEL COSTS

James K.D. Morrison, Sgouris Sgouridis and R. John Hansman

This report is based on the Master Thesis of James K.D. Morrison submitted to the Engineering Systems Division in partial fulfillment of the requirements for the degree of Master of Science in Technology and Policy at the Massachusetts Institute of Technology.

Report No. ICAT-2011-4
June 2011

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

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by

James K.D. Morrison, Sgouris Sgouridis, and R. John Hansman

Abstract

The air transportation system is a vital infrastructure that enables economic growth and provides significant social benefits. Future increases and volatility in crude oil prices, as well as environmental charges, are likely to increase the effective cost of fuel. We investigate the impacts of effective fuel cost increase on the US air transportation system historically and perform a game theory analysis of the impact of manufacturer competition on the introduction of new, more fuel efficient aircraft.

The cost of jet fuel increased 244% between July 2004 and July 2008, providing a natural experiment to evaluate how fuel price increase affected continental US networks and fleets. It was found that non-hub airports serving small communities lost 12% of connections, compared to a system-wide average loss of 2.8%. Increased effective fuel costs will provide incentives for airlines to improve fleet fuel efficiency, reducing the environmental impacts of aviation, but may cause an uneven distribution of social and economic impacts if small communities suffer greater loss of mobility. Government action may be required to determine acceptable levels of access as the system transitions to higher fuel costs.

Technology innovation may act as a long-term hedge against increasing effective fuel costs, enabling mobility to be maintained. The single aisle commercial aircraft market segment is the largest, but has the longest running product lines. We hypothesize that competition has important effects on manufacturers' decisions to innovate that must be considered when designing policies to reduce fleet emissions. An aircraft program valuation model is developed to estimate expected payoffs to manufacturers under competitive scenarios. A game theory analysis demonstrates how the incentives to innovate may be altered by subsidies, technology forcing regulations, increased effective fuel costs, the threat of new entrants, and long-term competitive strategies. Increased competition may result in incumbent manufacturers producing re-engined aircraft while increased effective fuel costs may result in new aircraft programs. Incumbents' optimal strategies may be to delay the entry of new single aisle aircraft until 2020-24, unless technology forcing regulations are implemented.

Acknowledgements

This work was supported by the MIT/Masdar Institute of Science and Technology under grant number Mubadala Development Co. Agreement 12/1/06. The authors wish to thank PARTNER for access to the Piano-X software package and Robert M. Peterson from the Boeing Corporation for his valuable feedback on the aircraft program valuation model. Any errors are the authors’ alone.

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Acronyms and Abbreviations

Acronyms		Description
ASM	:	Available Seat Mile
ASK	:	Available Seat Kilometre
ATA	:	Air Transport Association
BEA	:	Bureau of Economic Analysis (United States)
BTS	:	Bureau of Transportation Statistics (United States)
CASM	:	Cost per Available Seat Mile
CDF	:	Cumulative Distribution Function
CO_2	:	Carbon Dioxide
DOT	:	Department of Transportation (United States)
EAS	:	Essential Air Service (United States DOT Program)
EIA	:	Energy Information Administration (United States)
E(NPV)	:	Expected Net Present Value
EPA	:	Environmental Protection Agency (United States)
ERA	:	Environmentally Responsible Aviation (NASA Project)
EU ETS	:	European Union Emissions Trading Scheme
FAA	:	Federal Aviation Administration
GAO	:	Government Accountability Office (United States)
GDP	:	Gross Domestic Product
GHG	:	Green House Gas(es)
GTF	:	Geared turbofan (Engine)
HHI	:	Herfindahl-Hirschman Index
IATA	:	International Air Transport Association
ICAO	:	International Civil Aviation Organization (United Nations)
IPCC	:	Intergovernmental Panel on Climate Change (United Nations)
IRR	:	Internal Rate of Return
LCC	:	Low Cost Carrier
MAC	:	Marginal Abatement Cost
MDO	:	Multidisciplinary Design Optimization
NASA	:	National Aeronautics and Space Administration (United States)
NLC	:	Network Legacy Carrier
NPV	:	Net Present Value
NTSB	:	National Transportation Safety Board (United States)
OEW	:	Operational Empty Weight
RASM	:	Revenue per Available Seat Mile
RDT&E	:	Research, Development, Testing, and Evaluation
RPM	:	Revenue Passenger Mile
TAROC	:	Total Aircraft Related Operating Cost
TFUC	:	Theoretical First Unit Cost
WACC	:	Weighted Average Cost of Capital

CHAPTER 1

1.0 Introduction

1.1 Motivation

The air transportation system is a vital infrastructure that enables economic growth and provides significant social benefits. To access larger markets, businesses locate near airports. Families pursue global career and leisure opportunities that are only enabled by aviation. Hospitals require time sensitive diagnostic materials transported by air. There is a correlation between GDP and passenger traffic growth, as shown in Figure 1:

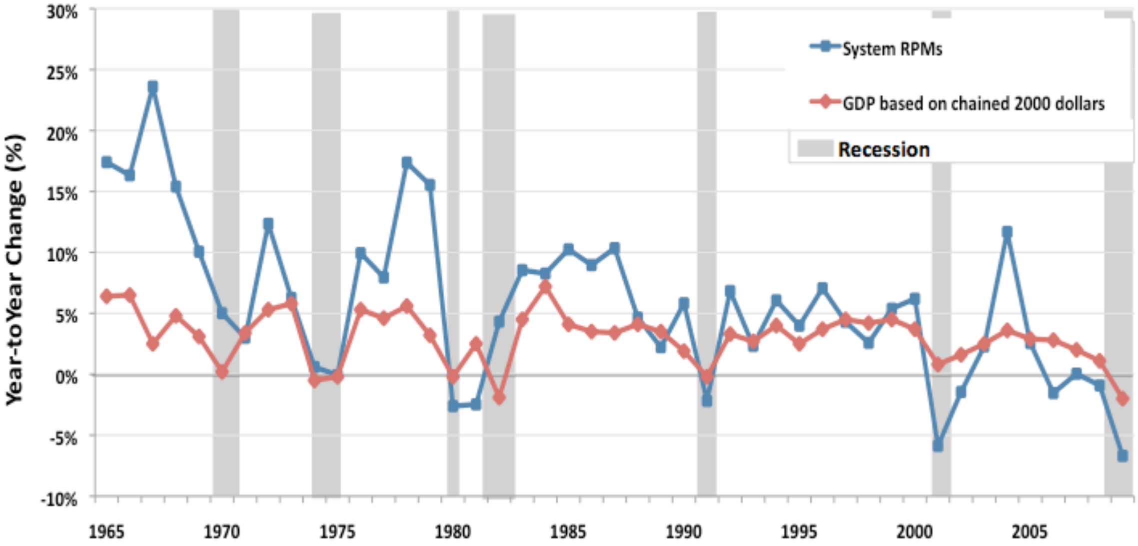

Figure 1. Correlation Between GDP and Passenger Traffic in the US. Data Source: BTS, 2009; Bureau of Economic Analysis, 2009; National Bureau of Economic Research, 2009. Courtesy of Dr. P. Bonnefoy.

As developing economies grow, the demand for air transportation will increase. Passenger traffic is expected to continue to grow at a rate of 4-6% annually while jet aircraft fuel efficiency has historically improved at a rate of 1.2-2.2% per year on a seat-km basis. Fuel efficiency improvements have not been sufficient to counter increased emissions due to rising demand for air transport (Lee et. al., 2001).

Future increases and volatility in crude oil prices, as well as environmental charges (e.g. CO_2 cap and trade, carbon taxes), are likely to increase the effective cost of fuel. As the supply of crude oil tightens, without significant reductions in worldwide demand, prices will increase. Geopolitical events and acts of nature may result in price surges that shock industries reliant on fossil fuel energy sources. Further, as climate change concerns mount, governments will face increasing pressure to take action to reduce the emission of carbon dioxide and other greenhouse gasses. Aviation will be included in the European Union's Emissions Trading Scheme (ETS) in 2012, putting a price on carbon for all flights with origins or destinations in the EU. In the United States, the Supreme Court ruled that the Environmental Protection Agency (EPA) has the authority to regulate greenhouse gasses under the Clean Air Act, including CO_2 emissions from transportation (Massachusetts et. al. vs. EPA, 2007). The International Civil Aviation Organization (ICAO) has resolved to achieve an annual average fuel efficiency improvement of 2% until 2050 (ICAO, 2010) while the International Air Transport Association's (IATA) 2050 aspirational goal is to reduce CO_2 emissions from aviation by 50%, compared to 2005 levels (IATA, 2010). The key challenge for the air transportation industry is to reduce carbon emissions while sustaining mobility for passengers and meeting future demand in developing countries.

In this report We investigate the impacts of effective fuel cost increase on the US air transportation system historically and perform a game theory analysis of the impact of manufacturer competition on the introduction of new, more fuel efficient aircraft that may act as a long-term hedge against effective fuel cost increase.

1.2 Macroeconomic Model of the Air Transportation System

Air transportation has substantial economic benefits, directly employing 5.5 million and generating an estimated 31.9 million aviation related jobs globally. Aviation's 2007 global economic impact was estimated to be $3,557 billion or 7.5% of world GDP (IATA, 2010). The economy and the air transportation system are interconnected, as shown by the feedback loops in the conceptual model in Figure 2. While the economy creates demand for travel, the air transportation system has direct, indirect, and induced employment effects on the economy. Increased access to people, markets, ideas, and capital create economic enabling effects that can catalyze economic growth. The effective cost of fuel is influenced by crude oil prices as well as domestic and international market-based carbon policies. Changes in the effective cost of fuel affect the air transportation system on: (1) the supply-side, through pricing and scheduling, networks and fleet; and (2) the demand-side, through the economy. Governments can take action to reduce declines in air service by providing subsidies to airlines for essential routes that would otherwise not be served.

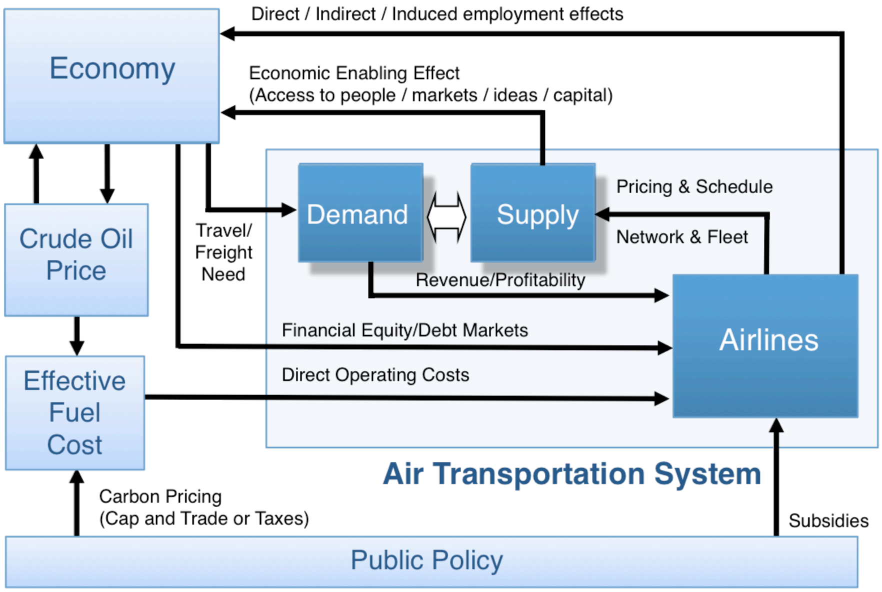

Figure 2. Air Transportation System and Effective Fuel Cost Macroeconomic Interaction Model. Adapted from Tam and Hansman, 2003.

Peak oil theory predicts continued volatility and increasing costs of fossil fuels while new environmentally driven charges are expected to further add to fuel costs, impacting airlines' financial performance, technology and operational change uptake, as well as the provision of air service nationwide. These future scenarios motivate the need to understand how air transportation networks and fleets will evolve with increasing effective fuel costs.

1.3 Reducing Commercial Aviation's CO_2 Emissions

Sgouridis, Bonnefoy, and Hansman (2010) highlighted five levers to reduce CO_2 emissions from aviation:

- ***Technological Efficiency Improvements:*** improving aircraft fuel efficiency.

- ***Operational Efficiency Improvements:*** improving airline and air traffic control operations.
- ***Alternative Fuels:*** transitioning aircraft energy supply to fuels that have lower lifecycle CO_2 emissions than traditional oil-based jet fuels.
- ***Demand Shift:*** reducing demand for air transportation, or shifting demand to other modes.
- ***Carbon Pricing:*** increasing the effective price of fuel and reducing demand through the price-demand elasticity relationship (i.e. market-based incentives).

Kar (2010) identified 41 CO_2 mitigating measures and estimated the potential reductions in US fleet emissions based on published data of the availability and magnitude of each measure, as shown in Figure 3. Although operations improvements and technology retrofits can be implemented in the short-term, technology improvements on new aircraft represent the largest source of potential carbon emission reductions in the long-term.

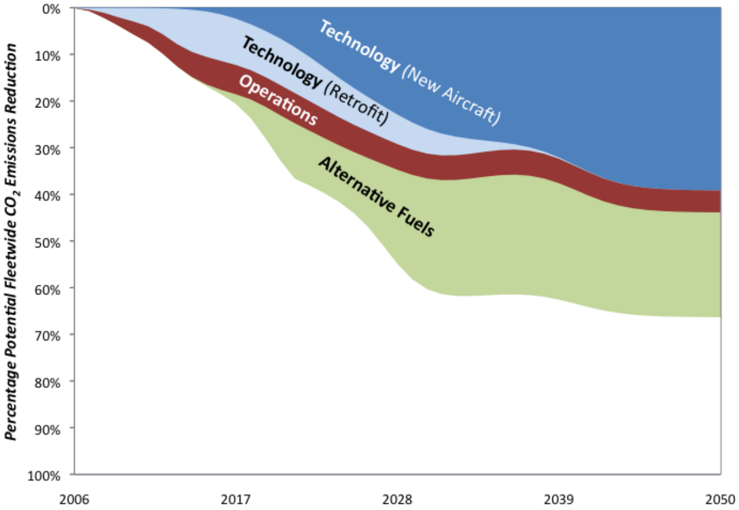

Figure 3. **Cumulative Potential Reductions in CO_2 Emissions from 2006 to 2050.** Source: Kar, 2009.

Before technology improvements are implemented in new aircraft, manufacturers must have the incentives to innovate. New aircraft programs offer the largest potential gains in fuel efficiency, but are risky and require large capital investments. Re-engining existing airframes reduces risk and capital requirements but offers lower potential fuel burn improvements. Maintaining existing aircraft with incremental improvements may entail the lowest risk. We hypothesize that competition has important effects on manufacturers' decisions to innovate that must be considered when designing policies to reduce fleet emissions. Therefore, to understand what policies are likely to be effective at reducing new aircraft fuel intensity, the effects of competition must be understood.

1.4 Thesis Outline

Chapter 2 outlines this report's research questions and approach. An empirical analysis of the 2004-08 fuel price surge is used as a case study in Chapter 3 to demonstrate the impacts of effective fuel cost increase on the US air transportation system. These impacts are extrapolated to further understanding of the potential short- and mid-term consequences of effective fuel cost increase. The introduction of new, more fuel-efficient aircraft is a primary option to adjust to higher effective fuel prices without reducing air service. Chapter 4 provides the background of how aircraft manufacturer competition impacts fleet emissions and how fuel efficiency improvements can be accelerated through changes in the single aisle aircraft market structure. An aircraft program valuation model is developed in Chapter 5 that is used to estimate the rank ordering of aircraft manufacturer payoffs under different competitive scenarios. A game theory analysis of aircraft manufacturer competition is performed in Chapter 6, furthering understanding of how technology innovation can be accelerated to initiate a long-term hedge against effective fuel cost increase that reduces the environmental impacts of aviation. Chapter 7 concludes the report and outlines future work.

CHAPTER 2

2.0 Research Approach

2.1 Research Questions

The air transportation system provides significant economic and social benefits to the communities and nations it connects. But the burning of fossil fuel impacts climate. Pressure will mount for aviation to reduce CO_2 and other greenhouse gas emissions. Without safety certified alternative energy sources available in the required quantities, increasing effective fuel costs and political pressure will compel commercial aviation to adapt – either through reductions in service or improvements in efficiency. Reductions in service will diminish the economic and social benefits of aviation to some communities while efficiency improvements will require technology innovation and operational changes.

The first question posed in this report is:

- **Question 1:** If the effective cost of fuel increases, what are the potential impacts on the US air transportation system?

This question is answered by performing a historical analysis of the 2004 to 2008 fuel price surge in Chapter 3.

Given the expected impacts of future fuel price surges and permanent increases in the effective cost of fuel, fuel efficiency and CO_2 mitigating measures are investigated in the remaining chapters. Previous work has determined that technologies on new aircraft could be the largest non-alternative jet fuel lever in reducing CO_2 emissions from aviation. Single aisle, 150-seat jets form the backbone of the world's fleet and are expected to continue to be the largest market segment. But the incumbent large commercial aircraft manufacturers Boeing and Airbus have not made significant improvements to their 737 and A320 single aisle families for a decade. We hypothesize that in a duopoly market where both manufacturers have existing single aisle aircraft families and fuel prices are low, neither competitor has an incentive to produce a clean sheet design aircraft that offers significant performance improvements. New aircraft lines require significant research, development, testing and evaluation investments, are technically risky, and may cannibalize the sales of existing overlapping product lines. Production learning curves require manufacturers to produce and sell initial aircraft at a net loss in order to gain the experience required to improve production processes and reduce unit costs. Profitability is only achieved as volumes rise (Benkard, 2000). As the effects of the learning curve are negated with the introduction of a new product line, the incentive to introduce a new aircraft is reduced. To explore the impacts of aircraft manufacturer competition on introducing new, more fuel-efficient product lines, the second research question posed is:

- **Question 2:** What scenarios are likely to result in the development and production of new single aisle aircraft with significant fuel efficiency improvements?

This research focuses on the factors or policies that may change the dynamics of aircraft manufacturer competition to incentivize the development of a new aircraft and to compare these factors on the basis of expected impact on fleet carbon emissions. Understanding how competition impacts the decision to invest in new aircraft designs may assist policy makers in developing regulatory mechanisms to improve aviation's fuel efficiency and can inform expectations of the introduction of new aircraft for global aviation emission models. This question is answered by performing a game theory analysis of single aisle manufacturer competition in Chapters 4 through 6.

2.2 Research Approach

This section outlines the approach used to answer the research questions posed.

Question 1: Impacts of Effective Fuel Cost Increase

The 2004-08 period provided a natural experiment that is used as a case study in Chapter 3 to evaluate how fuel price increases affected air transportation networks and fleets. Comparative analyses were performed over two time periods: (1) July 2004-08, and (2) July 2007-08. The July 2004-08 time period was selected to demonstrate medium-term trends in airline decisions when facing increasing fuel costs, while the July 2007-08 time period was selected to examine short-term trends. Primary focus was placed on the July 2007-08 period, as the rate of fuel cost increase was greatest and airline decisions were likely to have been made under forecasts of continued high, or increasing, fuel costs. Comparing network and fleet changes between the same months in subsequent years avoided introducing seasonal effects in the analysis. By July 2004, US domestic supply (as measured in available seat miles, ASM) had recovered to pre-September 11, 2001 levels and one year had passed since the SARS pandemic of May-July 2003. Also, US gross domestic product (GDP) was increasing during this time period, peaking in nominal terms in Q3 2008. Therefore, the effects of the demand shift due to the 2008-2010 financial crisis do not impact the analysis.

The air transportation system is influenced by multiple factors. Between Q3 2007 and 2008, real GDP remained relatively constant. There were no major US air safety or security incidents during this period, and US passenger carrier operations did not result in any fatalities. Airline competition (as measured by the Herfindahl-Hirschman Index[1]) changed from 0.082 to 0.083, indicating a marginally less competitive industry. Airline labor costs, as reported by the Air Transport Association (2010), decreased 3.9% between Q3 2007 and 2008. As the rate of change of these factors was dwarfed by the escalation of fuel costs, it was assumed that fuel cost increase was the dominant causal factor during the July 2007-08 time period. During the July 2004-08 time period, several major US carriers entered Chapter 11 bankruptcy, three accidents occurred involving passenger fatalities,[2] and real GDP increased 8.6%. This time period is used to put changes observed July 2007-08 into historical perspective and to identify medium-term trends in airline behavior. This study does not account for the effect of changes in economic activity, or other exogenous variables, on the air transportation system.

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[1] Herfindahl-Hirschman Index (HHI) was calculated as the sum of the squares of the domestic revenue passenger mile (RPM) market share of all US passenger carriers reported in BTS Form 41 Schedule T2.

[2] US carrier accidents involving passenger fatalities, July 2004-08: (1) 0/19/04 Kirksville, MO, Corporate Airlines, British Aerospace Jetstream 32, (2) 12/19/05 Miami, FL, Chalks Ocean Airways, Grumman G-73T, (3) 08/27/06 Lexington, KY, Comair, Bombardier CRJ-100 (National Transportation Safety Board, 2010).

Many airlines dampen fuel cost volatility by adopting financial fuel price hedging strategies. Over the time frame of this study, successful hedging strategies likely provided significant cost advantages to individual airlines. The magnitude of the fuel price increase implies that, in the future, hedging prices will increase and will account for such extremes in volatility. Therefore, fuel price hedging cannot be considered a sufficient measure of protection against systemic fuel price increases. Actions other than hedging are the subject of this report, including changes to airline network and fleet assignments.

The data used for these analyses was obtained from the Bureau of Transportation Statistics (BTS) Form 41 databases. For data consistency and availability reasons, the analysis was generally limited in scope to the continental US domestic air transportation system. Data was filtered to exclude cargo service, military flights, repositioning flights (i.e. departures performed with zero passengers reported), and sightseeing (i.e. departures performed whose origin and destination were the same airport). Based on these datasets, a comparative analysis of the continental US air transportation network and fleet at the airport and route levels was conducted. In addition, the effect of changes in air service provision on population access was evaluated.

To provide potential causal explanations for the observed effects on network and fleet from the case study, complementary analyses were conducted, including: the evaluation of aircraft fuel intensity, airline economics, and airfare time series analyses. Finally, effects observed in the case study were extrapolated to various scenarios in which effective fuel cost increases are expected to discuss their potential consequences.

Question 2: Game Theory Analysis of Single Aisle Aircraft Manufacturer Competition

To answer the second question posed, a three-staged approach was used. First, static and dynamic game structures for a two- and three-player market are constructed in Chapter 4. Second, an aircraft program valuation model is developed to estimate payoffs to manufacturers under different market share, fuel price, and demand scenarios in Chapter 5. Third, a game theory analysis is used to model competitive forces impacting manufacturer decisions in Chapter 6. Policy options are tested to determine their outcomes in a competitive market, based on the assumptions in the valuation model.

We chose a game theoretic framework to investigate the dynamics of aircraft manufacturer competition as it accounts for the presence of multiple actors, all of who make rational decisions in accordance with their own best interests. It was further assumed that all players act with the knowledge that all other players make rational decisions. This framework enables the discovery of each player's best response to the predicted strategy of all other players.

The purpose of this analysis is *not* to determine aircraft manufacturer profitability, but rather to estimate the rank ordering of payoffs to determine how changes in the market structure may alter the equilibrium game outcome using a consistent framework for comparison. Unfortunately, such analysis is hindered by the proprietary nature of aircraft program economic data. Reasonable assumptions, based on publicly available data sources, are used as proxies while a sensitivity analysis demonstrates the extent to which these assumptions impact the findings. The aircraft performance parameter of interest in this report is fuel intensity - the energy consumed per unit of output. As a proxy, the fuel burn per seat mile is used. Efficiency improvements are meant to indicate reductions in fuel intensity.

Both Airbus and Boeing have complete product lines that span all 100+ seat market segments. Decisions within one market segment are constrained by the state of products in other market segments. Limited engineering resources and capital have historically prevented manufacturers from undertaking more than one major aircraft design program at any one time. This analysis neglects this complexity, assuming manufacturers make decisions regarding the single aisle market without constraints imposed by decisions regarding the twin aisle markets. Benkard (2004) developed an empirical dynamic oligopoly model of the wide-bodied commercial aircraft industry used to analyze industry pricing, aircraft production costs, aircraft performance, and policy. He assumed that unobservable aircraft characteristics that are known to buyers (i.e. quality) could be represented with a stochastic Markov process that he empirically estimated to determine that they do not affect production costs. Benkard's quality parameter and engine number were used as proxies for fuel efficiency. My approach does not follow an empirical econometric analysis. We focus on assumed fuel efficiencies under varying external conditions to estimate the expected demand preference among aircraft product lines offered by competing manufacturers.

CHAPTER 3

3.0 Impacts of Effective Fuel Cost Increase

The cost of aviation fuel increased 244% between July 2004 and July 2008, becoming the largest operating cost item for airlines (Air Transport Association (ATA), 2010a). Figure 2 depicts a conceptual model showing the linkages between the air transportation system and economy. Changes in the effective cost of fuel affect the air transportation system on: (1) the supply-side, through pricing and scheduling, networks and fleet; and (2) the demand-side, through the economy. A key contributor to the effective cost of fuel is the price of crude oil. As shown in Figure 4, jet fuel prices surged from an average of \$0.72/gallon in January 2000 to a peak of \$3.82/gallon in July 2008, trending closely with crude oil prices. During the period of the highest rate of increase, July 2007-08, jet fuel prices climbed 82%. It is expected that increases in the effective cost of fuel impact the balance of supply and demand in the system, resulting in changes in airline supply (i.e. network and fleet). To prepare for higher oil and carbon prices in the future, there is a need to understand how fuel price increases have historically impacted the air transportation network and fleet assignment decisions, and the effectiveness of government policies in meeting socioeconomic and environmental objectives.

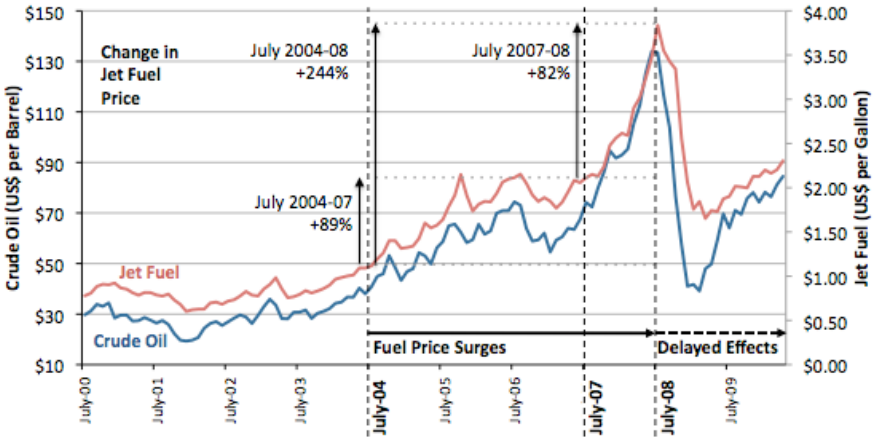


Figure 4. Trends in Crude Oil and Jet Fuel Prices During the Time Periods of Study. Data Source: ATA, 2010a.

In Section 3.1, the continental US system during the 2004-08 fuel price surge is analyzed to improve understanding of how air transportation networks and fleet may evolve under volatile and upward trending effective fuel costs in the future. We use two time periods – July 2004-08 and July 2007-08 - as natural experiments to understand short- and medium-term effects of fuel cost increase and volatility on the behavior of airlines in a competitive system. Potential explanations of the effects of the fuel price surge are described in Section 3.2. Future effective fuel cost increase scenarios, possible long-term consequences of the evolution of the system observed in the time periods of the study, and potential fuel efficiency measures are discussed in Section 3.3. Section 3.4 outlines the role of government in mitigating negative impacts resulting from uneven reductions in air service while conclusions are drawn in Section 3.5. To mitigate negative social and economic impacts from future fuel price surges, action is needed to improve fuel efficiency of the air transportation system. Chapters 4 through 6 examine how aircraft manufacturers may be incentivized to develop fuel-efficient aircraft.

3.1 Historical Case Study: 2004-08 Fuel Price Surge

Fuel became the greatest expense for the aviation industry in 2006 when it surpassed labor, the second largest airline cost component, as shown in Figure 5:

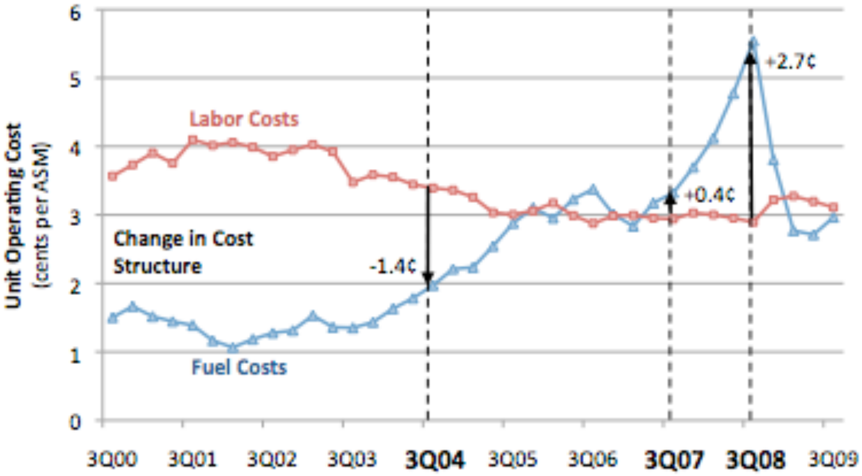
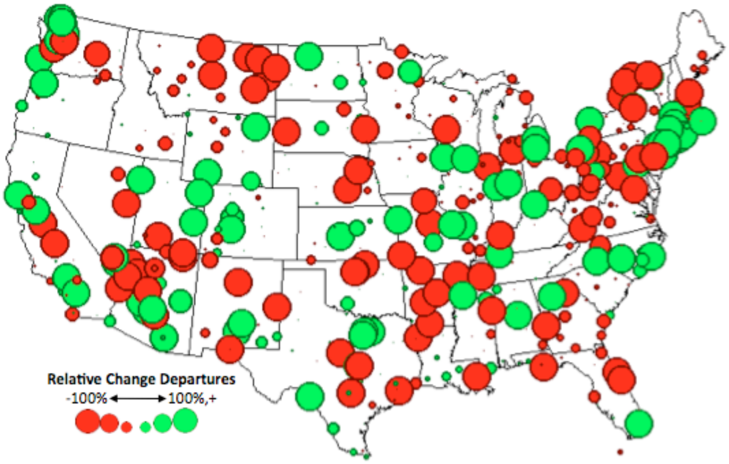


Figure 5. Trends in US Airline Industry Unit Operating Costs.
Data source: ATA, 2010b.

A combination of increasing fuel costs and decreasing labour costs due to industry restructuring led to this change in share of direct operating costs. As fuel costs have become a larger share of industry revenue, changes in the effective cost of fuel have had a greater impact on airline decisions and profit margins. The impacts on network structure, changes to passenger access to the air transportation system, and the impacts on airlines will be discussed in this section.

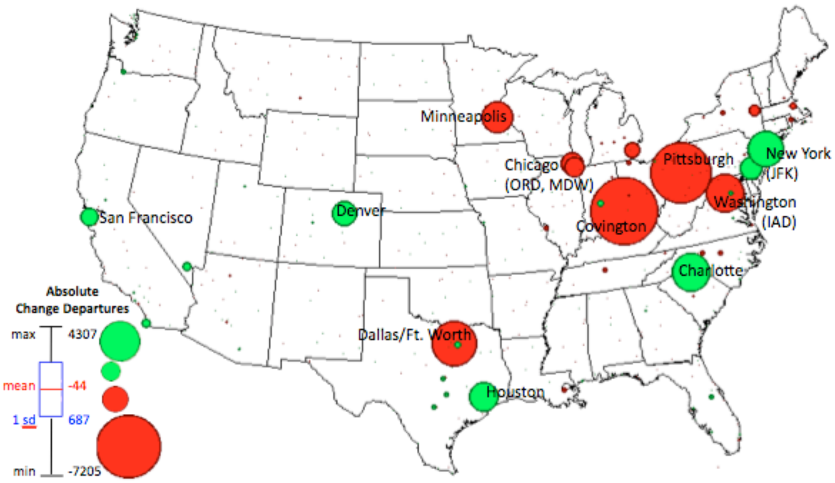
Impacts on Network Structure

Comparative analysis of the network structure in the periods July 2004-08 and July 2007-08 showed that a reallocation of resources throughout the continental US air transportation network occurred. July 2004-08, the aggregate number of departures performed were reduced by 2.8%, while this number dropped by 1.6% July 2007-08. Some airports experienced greater reductions in service than others. Figure 6 and Figure 7 show relative and absolute changes in passenger departures performed at continental US airports July 2004-08. Changes in departures at individual airports are used as a proxy for access to the national air transportation system. A reduction in access to the system is expected to have social and economic impacts in the airport catchment area as passengers and businesses are forced to find alternative modes of transportation, likely resulting in increased travel time. The relative and absolute changes in airport traffic demonstrate volatility at small and large airports throughout the country.



	Airport	HubClass	ΔDepartures	
1	Kenmore, WA	NonHub	271	∞
2	Santa Rosa, CA	NonHub	182	∞
3	New York, NY	NonHub	137	∞
4	Plattsburgh, NY	EAS	116	∞
5	Phoenix, AZ	NonHub	90	∞
6	Del Rio, TX	NonHub	84	∞
7	Alamogordo, NM	NonHub	59	∞
8	New York, NY	NonHub	57	∞
9	Palmdale, CA	NonHub	57	∞
10	Vernal, UT	EAS	56	∞
		.....		
466	Columbia, MO	EAS	-109	-100%
467	Enid, OK	NonHub	-124	-100%
468	El Dorado, AR	EAS	-130	-100%
469	Watertown, NY	EAS	-152	-100%
470	Hot Springs, AR	EAS	-155	-100%
471	Prescott, AZ	EAS	-156	-100%
472	Trenton, NJ	NonHub	-161	-100%
473	Lake Havasu City, AZ	NonHub	-166	-100%
474	Peach Springs, AZ	NonHub	-227	-100%
475	Killeen, TX	NonHub	-409	-100%

Figure 6. July 2004-2008 Relative Changes in US Airports' Continental US Passenger Departures and Top 10 Relative Gains and Losses. Data Source: BTS, 2010b.



	Airport	HubClass	ΔDepartures	
1	Charlotte, NC	Large	4307	27.8%
2	New York, NY	Large	3933	50.5%
3	Houston, TX	Large	3336	19.0%
4	Denver, CO	Large	2812	12.3%
5	Philadelphia, PA	Large	2467	16.5%
6	San Francisco	Large	2069	18.5%
7	Las Vegas, NV	Large	1150	7.7%
8	San Diego, CA	Large	1128	14.7%
9	Indianapolis, IN	Medium	849	17.0%
10	Dallas/Ft. Wrth (DAL)	Medium	805	21.8%
		.....		
466	Boston, MA	Large	-901	-5.8%
467	Albany, NY	Small	-1245	-38.3%
468	Detroit, MI	Large	-1803	-9.1%
469	Chicago, IL (MDW)	Large	-2261	-21.8%
470	Chicago, IL (ORD)	Large	-2566	-7.0%
471	Minneapolis, MN	Large	-3411	-16.9%
472	Washington,DC (IAD)	Large	-4287	-27.6%
473	Dallas/Ft.Wrth (DFW)	Large	-4872	-16.0%
474	Pittsburgh, PA	Medium	-6551	-53.5%
475	Covington, KY	Large	-7205	-38.1%

Figure 7. July 2004-2008 Absolute Changes in US Airports' Continental US Passenger Departures and Top 10 Absolute Gains and Losses. Data Source: BTS, 2010b.

Figure 8 categorizes airports by the number of departures per day in July 2007. Small airports, with fewer than an average of 300 departures per day, lost relatively more traffic than larger airports July 2007-08. These small airports correspond to non-hub, small hub, and medium hub classes, as defined by the FAA (2008) based on the number of passenger boardings in the year 2007, as shown in Table 1.

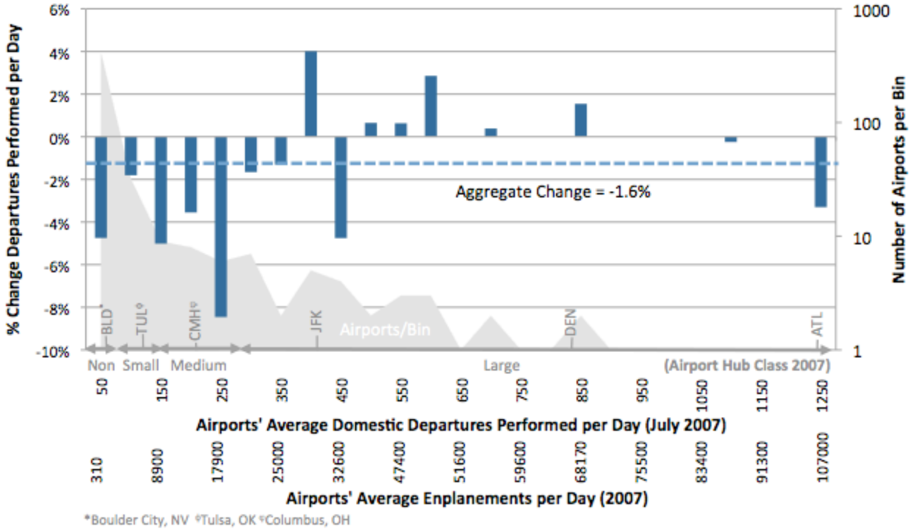


Figure 8. July 2007-08 Relative Changes in Airports' Continental Passenger Departures per Day, Binned by Airports' Size.

Table 1. Number of Airports by Class with Continental US Passenger Departures.

Airport Hub Class	Boardings	July 2004	July 2007	July 2008
Large	≥1%	32	32	32
Medium	0.25-1%	37	37	37
Small	0.05-0.25%	63	63	63
NonHub	0-0.05%	245	276	257
EAS*	0-0.05%	98	95	76
	Total:	475	503	465

Airport classes held constant from the full year 2007 for analyses.

**Indicates airports serviced by Essential Air Service (EAS) subsidized routes. All EAS airports were NonHub airports.*

Data Source: BTS, 2010b; FAA, 2008; Office of Aviation Analysis, 2010.

Table 1 also shows that small airports were disproportionately affected. July 2007-08, 70 airports lost all service and 32 airports gained service, resulting in a net loss of 38 airports. The net change July 2004-08 was a loss of 10 airports with service. Airports that lost all service were generally small airports with fewer than seven domestic departures performed per day in July 2007. GAO (2009) reported that 38 airports with routes receiving Essential Air Service (EAS) subsidies lost all service July 2007-08 (as discussed further in Section 3.4). It is expected that the social and economic effects of reductions in access to the national air transportation system would be greatest at airports that lost all service or experienced a prolonged period without service.

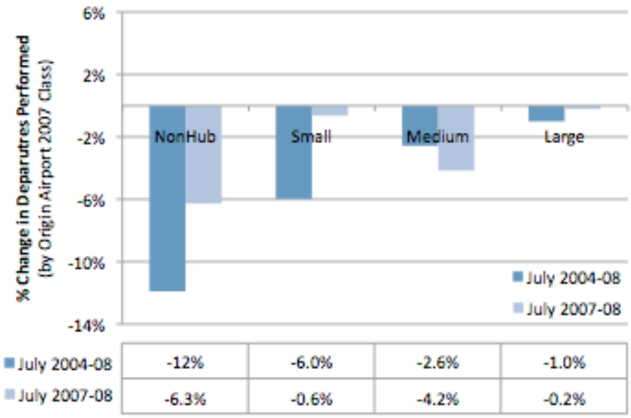


Figure 9. Origin Airport Class Change in Departures. Data Source: BTS, 2010b.

Table 2. Changes in Continental US Passenger Departures by Airport Class, July 2007-08. Data Source: BTS, 2010b**.**

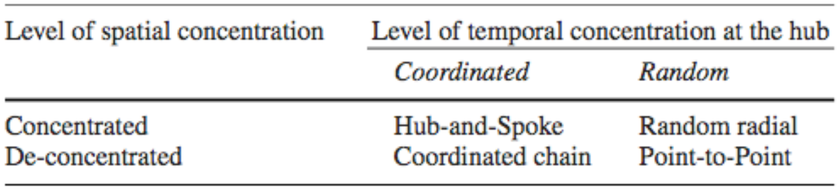
	NonHub	Small	Medium	Large
NonHub	-2922 -18%	-358 -20%	-2549 -24%	-359 -0.4%
Small		132 15%	420 2.6%	-1365 -1.0%
Medium			-3633 -11%	-3787 -1.7%
Large				1849 0.7%
			Total:	-12572 -1.6%

Percentage values represent the relative change in number of departures performed from each connection class in July 2007.

The July 2007-08 comparative network analysis was also performed at the origin-destination flight segment level. During this period, continental US departures were reduced by over 12,500. Table 2 shows the changes in departures between airport classes. Large-to-large hub connections increased while Figure 9 demonstrates that non-hub airports lost relatively more departures over both of the study periods. Small communities, serviced by non-hub airports, lost relatively more access to the national air transportation system than large communities.

The level of spatial and temporal concentration can be used to describe airline networks. Networks with a high number of flights into and out of one airport are spatially concentrated while flights that are organized to make connections with other flights are temporally concentrated. While hub-and-spoke networks are spatially and temporally concentrated to facilitate connections, point-to-point networks are generally temporally disperse, but not necessarily spatially concentrated due to the organization of maintenance and operational bases. Burghouwt (2005) describes four extreme network configurations, between which many intermediary networks may exist, as shown in Table 3 and Figure 10.

Table 3. The Airline Network Configuration Matrix. Source: Burghouwt, 2005.



Level of spatial concentration	Level of temporal concentration at the hub	
	Coordinated	*Random*
Concentrated	Hub-and-Spoke	Random radial
De-concentrated	Coordinated chain	Point-to-Point

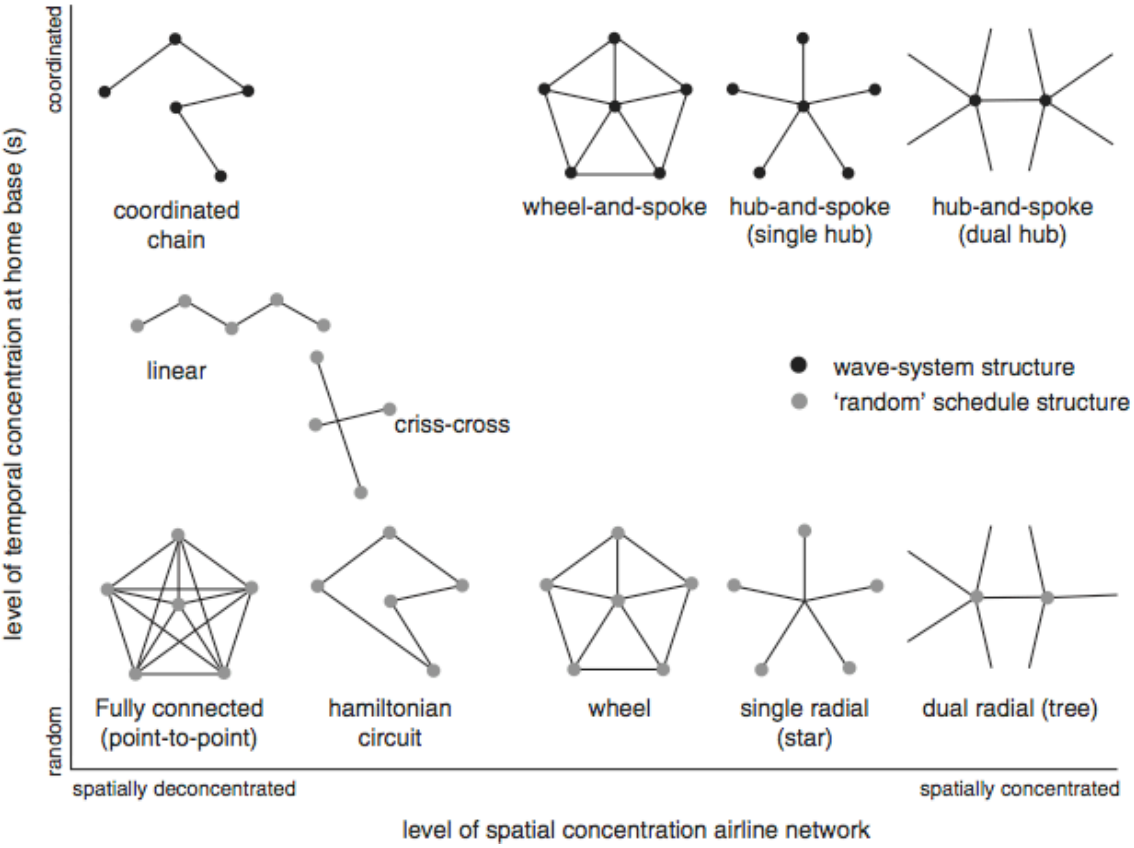


Figure 10. Airline Network Configurations. Source: Burghouwt, 2005.

Cento (2009) proposed using the Freeman network centrality index to measure the strength of hub-and-spoke vs. point-to-point networks. In a pure hub-and-spoke network, all airports are connected through one hub. In a pure point-to-point network, all airports are connected directly to every other airport in the network. The Freeman network centrality index uses the weighted average of paths through each airport connecting every other airport in the network, normalized by the maximum value achieved by a pure hub-and-spoke network. Therefore, for a pure hub-and-spoke network the Freeman index is 1, while for a fully connected point-to-point network the Freeman index is 0. The reduction in the number of non-hub airports, as well as the reductions in connections originating in non-hub and medium hub airports, led to a strengthening of hub-and-spoke networks July 2007-08. System-wide, the Freeman index increased from 0.17 to 0.26 - its largest change in the decade - as shown in Figure 11.

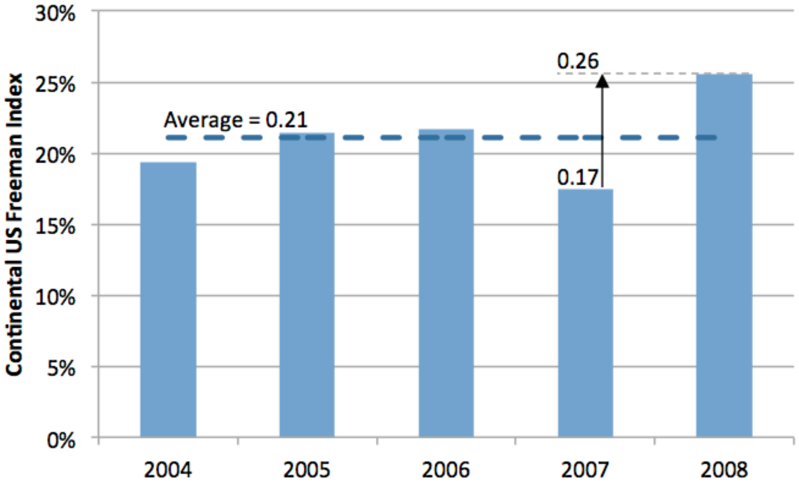


Figure 11. Continental US Air Transportation Network Freeman Index, 2004-08. All Airlines

Airlines employed different network strategies. An analysis of the two largest airlines (by July 2007 ASM) in each category (as defined in the Appendix), demonstrates differing trends, as shown in Figure 12:

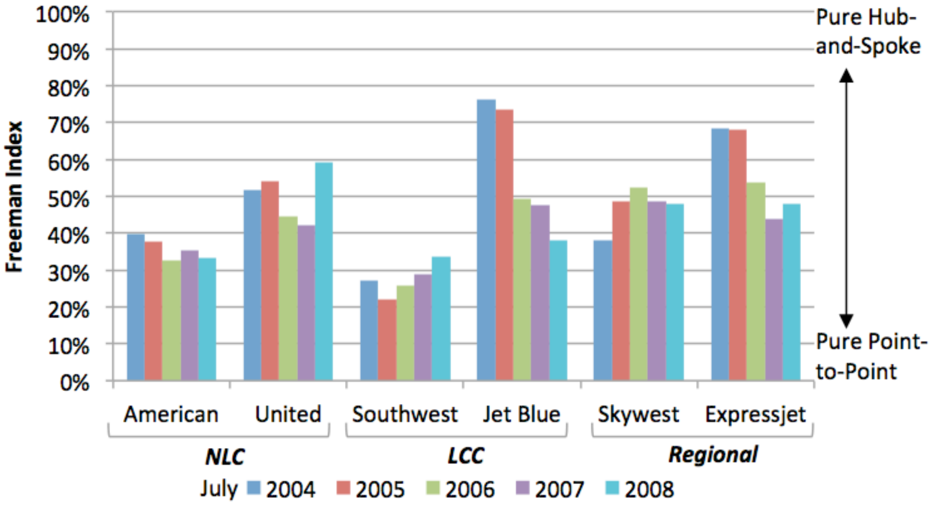


Figure 12. Continental US Airline Network Freeman Indices, 2004-08
Top Two Category Airlines, by July 2007 ASM

July 2007-08, United Airlines significantly strengthened its hub-and-spoke network against the trend of the previous three years. American Airlines' network remained more spatially disperse. Over the period investigated, Southwest Airlines trended towards a more concentrated hub-and-spoke network while its LCC peer, JetBlue, moved towards a point-to-point network as it expanded to routes away from its New York JFK base. While

ExpressJet moved towards a point-to-point network in the first years of this analysis, this trend reversed during the peak of the fuel price surge, July 2007-08.

A relative shift towards longer haul flights occurred during this time period. The average stage length[3] of continental US passenger departures increased from 609 miles in July 2004 to 626 miles (July 2007) and 632 miles (July 2008) due to the addition of long haul connections and reductions in the number of short-haul connections.

Impacts on Access to the Air Transportation System

During the period of steepest increase in fuel prices, July 2007-08, service was reduced for small and remote communities. For each of the airports that lost all service, the distance to the next nearest airport with traffic was calculated using Google Maps (2009), as shown in Figure 13. The average driving distance to the next nearest airport with service was 57 miles, corresponding to an average driving time of 75 minutes. The maximum driving distance was 208 miles, from Miles City, MN to Sheridan, WY.

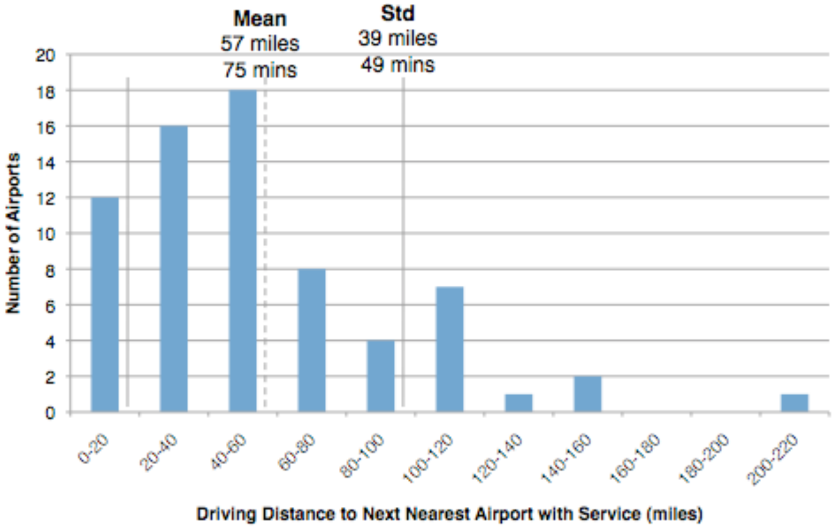


Figure 13. Next Nearest Airport with Passenger Departures to Airports that Lost All Service, July 2007-08. Data Source: Google, 2009.

The percent of continental US population living within 40 miles of an airport with regular service dropped 1.4% to 88.9% July 2007-08, as shown in Figure 14. This was determined by calculating the great circle distance from year 2000 US census SF3 tract internal coordinates to the nearest airport with at least one reported passenger departure

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[3] Stage length is a flight leg's great circle distance from the origin to destination airport.

per week, and summing the cumulative percent of the population. The number of airports with regular service increased July 2004-07, largely due to increases in EAS funding, as discussed in Section 3.4. The drop in the number of airports with regular service July 2007-08 resulted from a number of airlines serving small communities suffering financially. The selection of new air service providers for EAS subsidized routes restored service to most airports by July 2009. Access to the national air transportation system for a significant portion of the population is sensitive to the financial viability of regional and commuter airlines, as well as government subsidies.

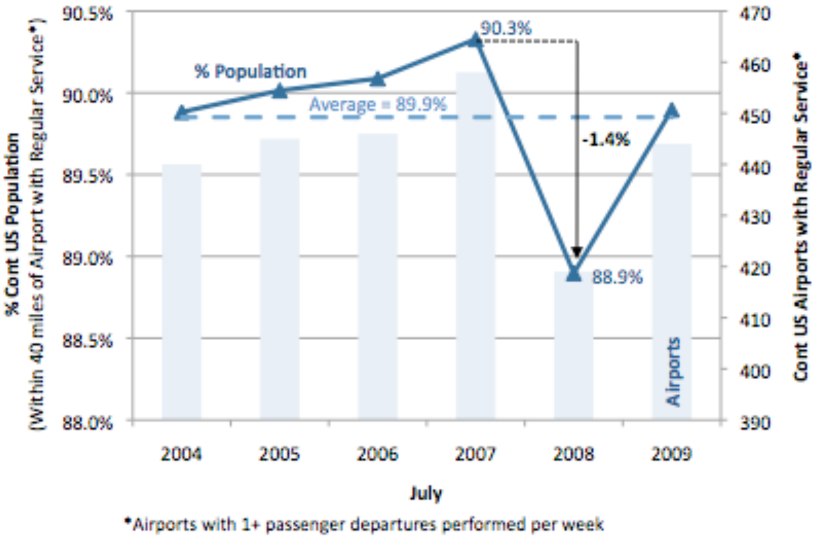

Figure 14. Continental US Access to Airports with Regular Service.
Data Source: BTS, 2010b; GeoLytics, 2000.

Impacts on Airlines

Airlines suffered financially during the fuel price surge, although regional and commuter airlines suffered relatively more in the July 2007-08 period. 11 of 107 (10.3%) US passenger carriers ceased operations July 2007-08, of which ten were regional or commuter airlines. Virgin America and Lynx Aviation commenced operations during this time period. Although representing a large percentage of total airlines, airlines ceasing passenger operations accounted for only 1.5% of domestic ASM in July 2007. Thirteen passenger carriers declared bankruptcy in 2004-2005, including legacy carriers US Airways, Delta Air Lines and Northwest Airlines, although many of these carriers continued operations. The fuel surge of July 2007-08 demonstrated that smaller, regionally focused airlines tend to have less ability to handle the financial stress caused by fuel price increase and volatility.

Grouping US carriers as Network Legacy Carriers (NLC), Low Cost Carriers (LCC), Regional, and Commuter (as defined in the Appendix), Table 4 shows that NLCs reduced domestic capacity most aggressively while LCCs added domestic available seat miles (ASM) market share, which increased from 18% in July 2004 to 26% in July 2008. Regional airlines were slower to cut capacity July 2007-08, with a 3.1% drop in ASM, but suffered a larger relative drop in demand with a 6.8% drop in revenue passenger miles (RPM).

	July 2004-08		July 2007-08	
	RPM	**ASM**	**RPM**	**ASM**
NLC	-2.1%	-2.9%	-4.5%	-2.8%
LCC	12.4%	12.1%	2.3%	5.9%
Regional	1.1%	0.8%	-6.8%	-3.1%

Table 4. Annualized Changes in US Carrier Domestic Supply and Demand, by Airline Class. Data Source: BTS, 2010b.

Much of the volatility in the number of airports with service was due to the cessation of operations of Air Midwest and Big Sky Airlines. These airlines were the sole carriers serving 20 communities of the 70 that lost all service. Small community access is sensitive to the operations of individual airlines, especially regional airlines that may not have the same access to financing as larger airlines.

While US carriers reduced domestic capacity, NLCs increased international capacity 6.6% July 2007-08, as shown in Table 5. Although LCCs showed large relative gains in international traffic July 2004-08, LCCs provided less than 3% of US carrier international ASMs in July 2008 while NLCs provided 94%. This increase in international capacity is part of a longer-term trend: NLC international ASMs increased 28% July 2004-08. These figures indicate a change in the primary provider of air transport in continental US as LCCs increase their market share, NLCs transfer capacity to international routes, and regional carriers focus on domestic routes.

	July 2004-08		July 2007-08	
	RPM	**ASM**	**RPM**	**ASM**
NLC	7.1%	7.1%	4.5%	6.6%
LCC	18.4%	16.9%	-2.3%	-7.0%
Regional	-5.4%	-6.0%	-25%	-24%

Table 5. Annualized Changes in US Carrier International Supply and Demand, by Airline Class. Data Source: BTS, 2010

3.2 Potential Factors Influencing Airline and Passenger Decisions under Increasing Effective Fuel Prices

This section proposes possible explanations of the observed effects on the air transportation system during the fuel price surge. The US domestic aviation industry is highly competitive and numerous exogenous factors influence stakeholder decisions in addition to fuel prices, including: economic activity, financial markets, competing modes of transportation, competition among airlines, airport construction, regulations, foreign affairs, terrorist events, and security concerns. We focus on the impacts of increases in the effective cost of fuel.

Increases in the effective cost of fuel impact the air transportation system through the supply-side and the demand-side of the market for air transport. Supply-side effects include increases in direct operating costs of airlines, resulting in changes to networks and fleet assignments. Demand-side effects are due to reductions in economic activity, as well as passenger and freight sensitivity to fare increases.

Bruekner and Zhang (2010) explored the effect of airline emission charges on airfares, airline service quality, aircraft design features, and network structure by developing a theoretical model of competing duopoly airlines. Emission charges were included as an increase in the effective cost of fuel, although the volume of passengers was kept fixed, avoiding the complexity of the price elasticity of demand. Their research showed an increase in fuel price will lead to higher fares, lower flight frequency, a higher load factor, more fuel efficient aircraft, and an unchanged aircraft size. Further, using a simplified network model, they showed that hub and spoke networks are strengthened by increases in effective fuel cost, except under certain conditions. This report provides empirical findings that support the conclusions of the theoretical model

Supply-side

Changes in the share of direct operating costs require airlines to alter their resource allocation. As fuel costs per ASM exceeded 5¢ (as shown in Figure 5), airlines altered their fleet assignments and network structures. While decreases in short-haul connections to thin demand markets were discussed in the previous section, two other trends in airline decisions during the fuel price surge were observed: (1) a reduction in the utilization of fuel intensive aircraft, and (2) increased costs passed through to passengers.

Operating Fleet

Aircraft fuel intensity, measured in gallons of fuel per ASM varies by aircraft type and engine due to differences in design, weight, operations, and level of technology. Figure 15 shows variations in fuel intensity within and between aircraft classes.[4] Regional jets are generally more fuel intensive than turboprops of the same seat size when adjusted for operating range. With increasing effective fuel costs, the economic incentive for airlines to reduce utilization of fuel intensive aircraft increases. The number of regional jets in US carrier fleets has increased dramatically since introduced in the 1990s. Increased fuel cost and changes to pilot scope clauses[5] arrested this trend in 2006. The number of regional jets operated by US carriers increased 27% between Q3 2004-2006 to 1605, but declined 3.6% to 1548 in Q3 2008. When fuel prices spiked in 2008, airlines increased utilization of turboprops and reintegrated parked turboprops into their fleet. The number of operating turboprops increased by ~41% from Q3 2007 to 274 (BTS Form 41 T2, 2010).

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[4] Aircraft fuel intensity derived from Piano-X aircraft database. Fuel burn was calculated using the aircraft's maximum payload at each R1 range quintile. The R1 point indicates the range at which aircraft must sacrifice payload to increase range. Fuel intensity was calculated as the weighted average of fuel burn per available seat mile (ASM) at each R1 range quintile, based on 2006 operating range frequencies.

[5] 'Scope clauses' are included in pilot union labor contracts to specify the maximum number and/or size of aircraft that mainline airlines can utilize in their low-cost operations or regional alliances (Gittell et. al., 2009).

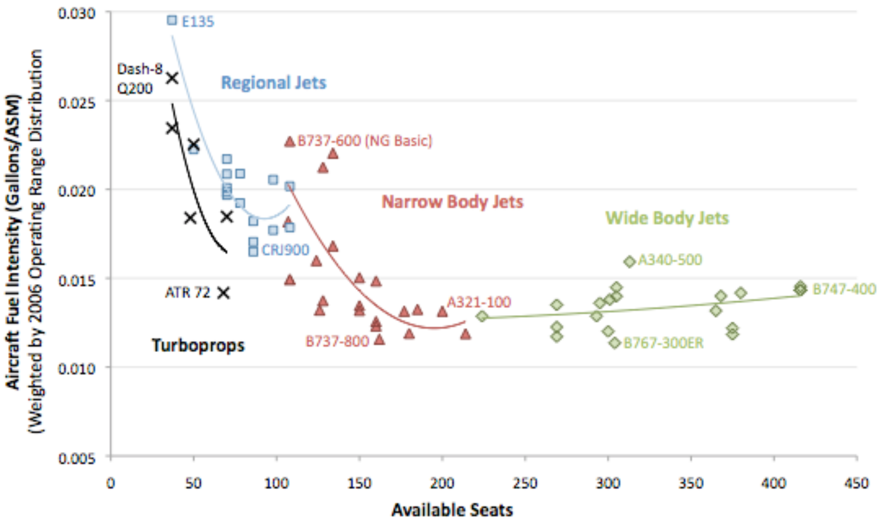

Figure 15. Aircraft Type 2006 Operating Fuel Intensity. Data Source: Piano-X Aircraft Database.

Figure 16 shows that airlines increased the miles flown for fuel-efficient aircraft while decreasing the miles flown for fuel inefficient aircraft July 2004-08. With a permanent increase in fuel cost, airlines are likely to replace fuel intensive aircraft with newer, fuel-efficient models. These decisions could lead to a renewed interest in turboprop technology, reduced regional jet purchases, and will likely lead to substantial interest in next generation fuel efficient aircraft such as Boeing's 787, Airbus's A350, and Bombardier's CSeries.

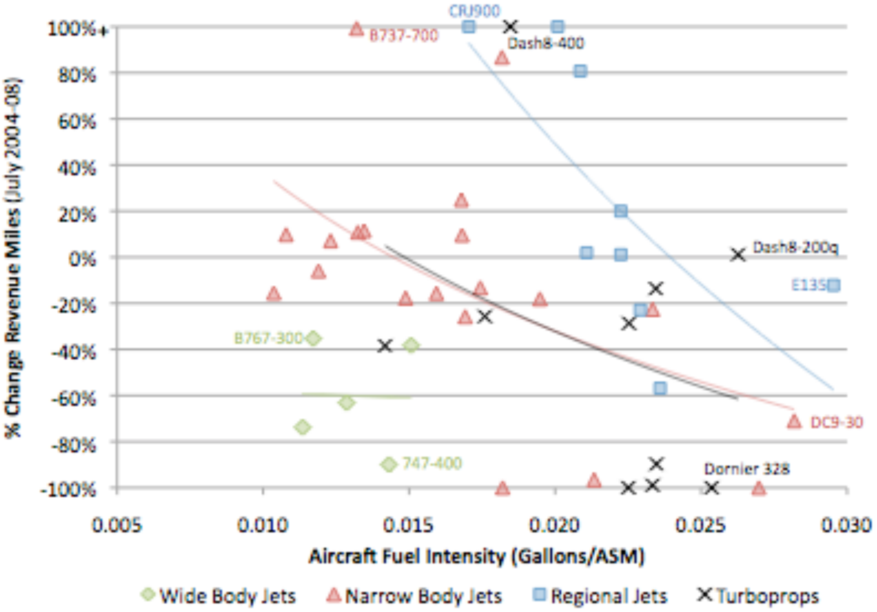

Figure 16. Change in Revenue Miles Flown by Aircraft Type Fuel Intensity
Aggregated for all US Airlines, July 2004-08.

Fuel Cost Passed on to the Consumer in the Form of Airfare Increases

Competition in the airline industry has resulted in a reduction in real fares since deregulation in 1978. Increased fuel costs have resulted in increased costs passed through to passengers in the form of fuel surcharges, increased fares, and unbundling of services, such as checked bags and onboard meals. BTS (2009) reported average domestic air fares in the third quarter of 2008 to be $362, up 10.4% from the third quarter of 2007, and up 22% from the post-September 11, 2001 third quarter low of $297 in 2004. Increased airfares were not distributed evenly across the system. Passengers originating in non-hub airports experienced a 3.9% increase in average airfares to $479 in Q3 2008 (BTS, 2010). Although passengers originating in non-hub airports generally face higher fares, they experienced a relatively smaller increase in airfares, likely due to these passengers' shorter average segment stage lengths. Non-hub airports are generally connected to medium and large hub airports by short-haul connections flown in turboprops and regional jets. As stage length decreases, fuel cost as a percent of operating cost decreases, overtaken by maintenance and labor costs. Thus, short-haul fares are less sensitive to fuel cost increase (Babikian, 2002).

Figure 17 shows changes in US airline's cost per available seat mile (CASM) and revenue per ASM (RASM) between the third quarters of 2007 and 2008. CASM increased 3.00¢, of which 2.20¢ was due to the increase in fuel costs. This increase in cost was only offset by a 0.73¢ increase in RASM, eliminating the 2007 positive profit in the US airline industry (ATA, 2010b). Between Q3 2004-08, fuel cost per ASM increased 3.57¢ while revenue per ASM increased only 2.48¢.

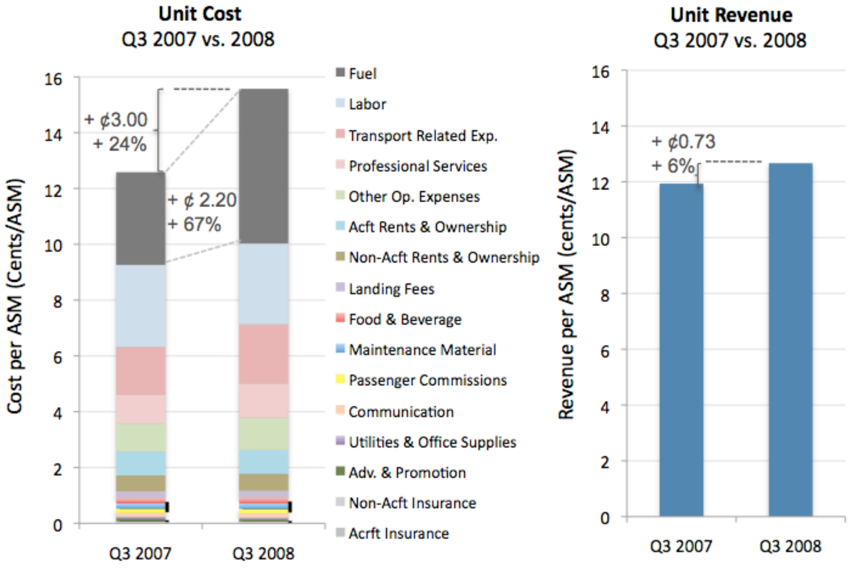

Figure 17. Cost and Revenue per ASM (Excluding Taxes) - Q3 2007 and 2008 Comparison. Data Source: ATA, 2010b.

Increased costs impact supply through airfare pricing. Increased prices impact demand through the price elasticity of demand for air transportation. In the short- and medium-term time periods of this analysis, all of the increases in fuel costs were not passed through to passengers. In the long-term, with increased effective fuel costs, airfares will need to increase and/or non-fuel related costs will need to be trimmed to compensate for the change in direct operating costs, or the industry will not be financially sustainable.

Demand-side

The amount of fuel cost increase passed on to the consumer has an effect on demand for air transport through the price elasticity of demand. In general, when other influences on demand remain unchanged, a higher price for a product results in a lower quantity demanded. The price elasticity of demand measures the sensitivity of demand to changes in the price. If the change in quantity demanded is greater than the change in price, the demand is said to be elastic. If the change in quantity demanded is less than the change in price, the demand is said to be inelastic.

Gillen, Morrison, and Stewart (2008) compiled multiple studies on the price elasticity of demand for air transportation, as shown in Figure 18. The price elasticity of demand was found to differ between short-haul and long-haul travel, domestic and international, as well as between leisure and business travel. Short-haul, leisure travel was found to be the most price elastic while long-haul international business travel was found to be the least. Alternative modes of travel, such as rail, bus, and automobiles, are close substitutes to short-haul air transportation, whereas there are no close substitutes to long-haul air travel. It is expected that demand for air transport is less elastic for longer flights. As international travel is generally spread over more time than domestic travel - making airfare a smaller proportion of the overall trip cost - international travelers are generally less sensitive to changes in ticket prices.

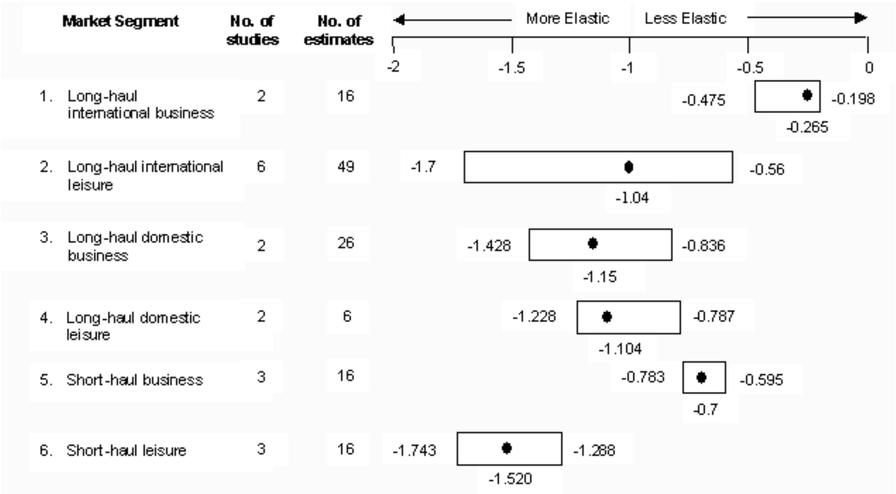

Figure 18. Price Elasticities of Demand for Air Transportation
Source: Gillen, Morrison, and Stewart, 2008.

During the periods of study it was found that connections to short-haul markets were reduced, average stage length increased, and international traffic grew. Airlines made strategic decisions on how to maintain revenues while facing higher operating costs. This led to reductions in service to markets in which passengers are more sensitive to airfare increases, and increases in international traffic for passengers less sensitive to airfare increases. Further, Airbus (2010) forecasts North American domestic passenger traffic to grow at 1.6%/year for the period 2009-2018, while passenger traffic to international destinations is forecasted to grow at a rate of 4.5%/year over the same period. As the continental US market approaches saturation, airlines are seeking higher growth markets on which they are able to maintain higher yields (i.e. unit revenue).

3.3 Extrapolating Findings to Future Scenarios

Future increases in the effective cost of fuel could have significant long-term social and economic consequences, and could increase the rate at which commercial aviation adopts fuel-efficient technologies that reduce carbon emissions. In this section, behaviour observed in the case study time periods is extrapolated to discuss potential future trends in the US air transportation system and their potential consequences.

Factors Influencing the Effective Cost of Fuel

Two scenarios would result in increased effective fuel costs for commercial aviation: (1) government policy, and (2) crude oil markets.

Government Policy

International accords or national governments may act to curtail carbon emissions by instituting emission taxes or cap and trade policies. This would increase direct operating costs associated with fuel burn through the need to purchase offsets on carbon exchanges or pay increased fuel taxes. It is expected that such measures would be phased in over a number of years, providing an adjustment period, and would not lead to a similar spike in fuel costs as experienced during the fuel price surge.

The American Clean Energy and Security Act, H.R. 2454 (commonly referred to as the Waxman-Markey Climate and Energy Bill) passed the United States' House of Representatives in July 2009, but did not become law. The EPA (2009) estimated a permit to emit one ton of carbon dioxide would be worth \$11-\$15 in 2012, increasing to \$22-\$28 in 2025 under Waxman-Markey (2005 US\$). Assuming a system fuel intensity of 0.016 gallons/ASM, emission permits would result in increased unit costs in the range 0.2-0.5¢/ASM for airlines, representing 8-21% of the unit cost increase that occurred Q3 2007-08. This cost increase is significant and would be in addition to the cost of any increase in market prices for crude oil. Secondary effects of carbon pricing policies through the broader economy would further reduce demand for air transport.

Crude Oil Markets

International markets may continue to provide high volatility in the price of crude oil and jet fuel. Under peak oil scenarios, the worldwide supply of oil would decrease, resulting in increasing fuel costs if demand for oil does not slacken. Without economical, technologically mature, and safety certified energy substitutes, commercial aviation would continue to rely on oil derived jet fuel at increased prices. EIA's Annual Energy Outlook (2010) reference case forecasts jet fuel prices to reach $2.93/gallon by 2020 and $3.58/gallon by 2035 (2008 US$) as shown in Figure 19. The low/high oil price case provides forecasts depending on more optimistic/pessimistic assumptions for economic access to non-OPEC resources and for OPEC behaviour. In the high oil price case, jet fuel is forecasted to climb to $4.72/gallon by 2020 and $5.33/gallon (2008 US$) by 2035. It is likely that jet fuel prices will remain volatile and events similar to the fuel price surge examined in this paper may be repeated.

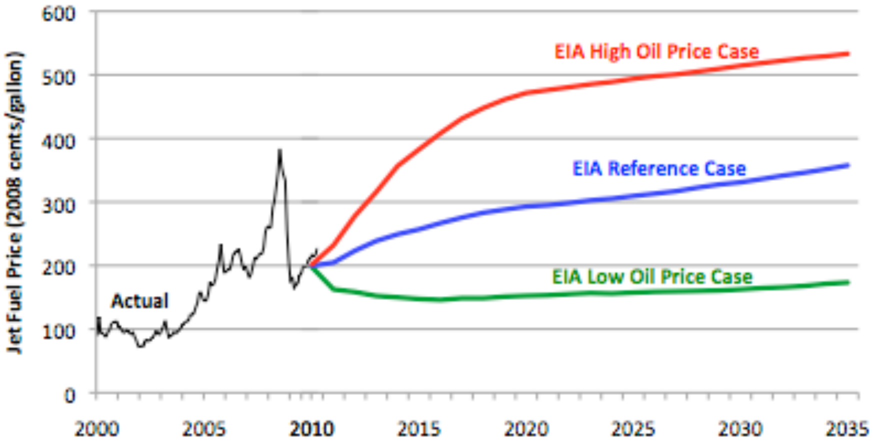

Figure 19. Jet Fuel Price Forecast. Data Source: ATA, 2010; EIA, 2010

Increased oil-based fuel costs would create an incentive to transition to long-term purchase agreements of alternative fuels and to reduce fuel burn through the implementation of efficiency measures in aircraft design, operations, and air transportation networks.

Fuel Efficiency Measures

In order to reduce the effects of increasing effective fuel costs, airlines can adopt fuel efficiency improvements using a portfolio of measures that include technology improvements, operation optimizations, and alternative fuels (Sgouridis, Bonnefoy, and Hansman, 2010). Engine and aerodynamic efficiency have historically improved at average rates of 1.5% and 0.4% per year, respectively (Lee et. al., 2001). This trend in operational data continued in the past decade, as shown in Figure 20. US domestic passenger carrier fuel intensity decreased an average of 1.6%/year 2000-2009, as calculated by fuel issued and ASM reported on BTS Form 41 Schedule T2.

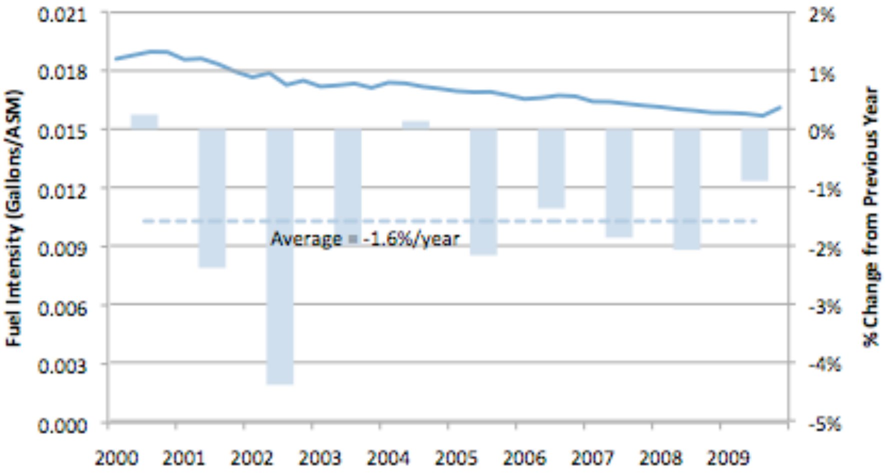

Figure 20. US Passenger Carrier Domestic Operations Fuel Intensity, 2000-09.
Data Source: BTS Form 41 T2, 2010b.

Aircraft require long research and development times and the turnover time for the global aviation fleet is approximately 20-25 years. It is unlikely that efficiency improvement rates will increase dramatically fleet wide in the near future. In the short-term, new operational procedures may reduce fuel burn, although infrastructure changes have significant lead times (Lee et. al., 2009). Fuel efficiency measures are unlikely to buffer airlines from volatility in crude oil prices and increases in the effective cost of fuel, motivating the need to understand how air transportation systems will adapt and what the potential social and economic consequences are from increases in the effective cost of fuel. In the long term, the introduction of new, more fuel efficient aircraft will reduce the economic impacts of effective fuel cost increase and enable aviation to transition to higher fuel costs.

Social and Economic Impacts of Reductions in Air Service

Goetz and Sutton (1997) used a core-periphery structure to explain the geographic effects of deregulation on the airline industry from 1978-1993. Their findings showed that core centers (the large hubs and international gateways, such as Chicago, Atlanta and New York) benefited more than the periphery spoke cities from increased air transportation employment, frequency of service, passenger flow, and lower fares, except where one or two airlines dominated a hub. If the observed impacts of the fuel price surge were to become permanent, lasting social and economic effects could occur, continuing the geographic trends of deregulation.

Airports provide numerous benefits to their region of service, including: reduced travel time and cost, enable businesses and healthcare procedures requiring time sensitive shipments, civil defense, stimulation of regional business, access to the national airport system, and recreation. Economic impacts are described as direct, indirect, induced, and catalytic. The direct and indirect regional economic impacts of airports can be estimated using FAA guidelines. These impacts scale with the number of commercial passengers and airport-based aircraft. In 1992, Butler and Kiernan estimated an airport with 50 based aircraft induced an annual benefit of $615,500 and provided annual payroll of $304,500, while an airport with 50 based aircraft and 50,000 annual commercial customers induced $1,672,500 of annual benefit and $1,827,000 of annual payroll (1992 US$). Reductions in service and the accompanying passenger traffic to small airports could limit the financial viability of many airports, depriving inhabitants in the airport's catchment area of these benefits.

Malina, Schwab and Wollersheim (2007) used a contingent valuation approach for a secondary airport in Germany and its catchment area to quantify the catalytic effect for regional economies that are induced by airports. Their study provided insights as to which industries benefit the most from the airport and the value companies place on airports. Ishutkina and Hansman (2008) described the interaction between air transportation and economic activity in regions throughout the world. By examining links between economic development and air transportation, they showed how different regions have developed air transportation systems to generate comparative advantages. For example, United Arab Emirates' has diversified its oil-based economy to include logistics operations, tourist attractions, and the fresh flower industry - which are all enabled by air transportation. Jamaica is dependent on air transportation to bring tourists to the island whose spending promotes economic growth. If a large number of communities in the United States were to lose access to the air transportation system, economic opportunities that parallel those experienced at the international level could be lost at the local level. This potentiality could warrant government action.

3.4 Policies to Reduce Social and Economic Impacts

To ensure small communities maintained a link to the national air transportation system, Congress established the Essential Air Service (EAS) program when it passed the Airline Deregulation Act in 1978. EAS provides subsidies to airlines for otherwise unprofitable routes between communities that had air service prior to deregulation and hub airports. A reduction in the financial viability of service to small communities may result in increased government subsidies to commercial aviation in attempts to maintain regional benefits. Figure 21 shows that continental US EAS subsidies have doubled from \$79.5 million in 2003 to \$163 million in 2010. The largest annual increase occurred between 2007 and 2008 when subsidies increased \$34.5 million to \$131 million. The recent trend has been for more communities to require more subsidies as the number of continental US communities receiving subsidized service increased 19%, from 90 in 2003 to 107 in 2010. In July 2007, the population in the catchment areas[6] of the communities with regular service provided by EAS subsidized routes averaged ~170,000, for a total of ~6% of the continental US population, based on year 2000 census data. EAS subsidies improve access to the national air transportation system for a significant portion of the population. Historically, governments have intervened to provide subsidies to commercial aviation proceeding calamitous events, such as 9/11. Industry adjustment to permanent increases in the effective cost of fuel could result in further government subsidies.

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[6] Catchment area defined as the area of shortest great circle distance to the airport, as calculated using Thiessen polygons in ESRI's ArcGIS™.

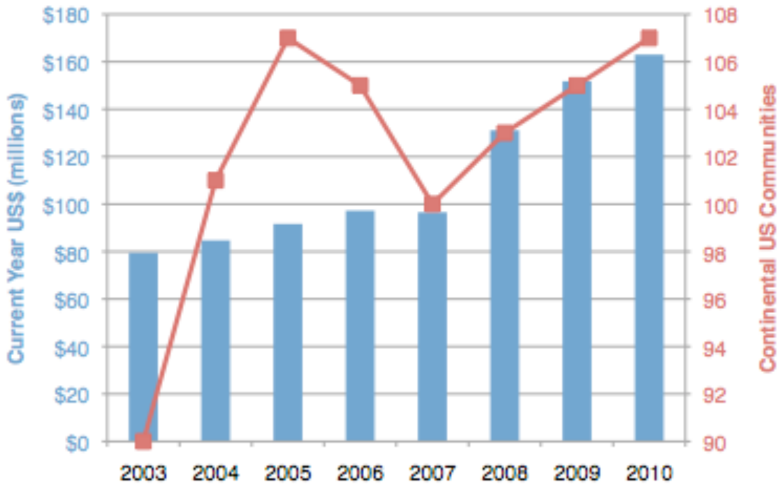


Figure 21. EAS Subsidies and Continental US Communities Served by EAS. Data Source: Office of Aviation Analysis, 2010.

In 2008, three EAS carriers serving 37 communities ceased operations. 30 EAS communities were temporarily without air service for up to 10 months, and 6 for a longer period of time (GAO, 2009). Although the EAS mechanism was able to return service to these communities, this prolonged interruption likely resulted in social and economic effects. The number of carriers providing EAS service has declined from 34 in February 1987 to 10 in May 2010. In the event of future shocks to the airline industry it is likely that small communities will face interruptions in air service. Changes to the EAS mechanism may be required to mitigate negative impacts.

Nolan, Ritchie, and Rowcroft (2005) examined various schemes to attract air service in smaller markets, including: direct subsidies, protected route packages, and guaranteed revenue approaches (e.g. airline travel banks). Using a small network simulation model, they evaluated each option in terms of social welfare and underlying agency costs. They found that using revenue guarantees, as opposed to direct subsidies, reduces the agency problems of adverse selection, opportunism and regulatory capture. Adverse selection occurs when communities lobbying for regulatory support have an inherent interest in overstating their need. Cases in which one or more of the parties abrogates the terms of an agreement demonstrate opportunism (e.g. an air carrier refusing to provide as many flights as originally promised). Regulatory capture results in the politician, the regulator, or the firm capturing the control and benefit of the regulatory process at the cost of the community.

GAO (2003) recommended more flexibility to be built into the EAS program, including eliminating subsidized service to certain communities that are relatively close to other larger airports, providing eligible communities with grants to allow them to tailor air service to unique local needs, and allowing carriers to operate smaller aircraft that are more suited to local levels of demand. If small communities continue to require subsidies to maintain air service, Congress will need to decide what level of access to air service is acceptable and what level of subsidies it is willing to provide. In March 2011, future funding for EAS was in question. The House version of the FAA Reauthorization and Reform Act of 2011 proposed phasing out funding for EAS over four years while the Senate version included reduced funding levels (Darson, 2011). Although non-hub airports account for 72% of continental US airports with commercial service, they account for only 9% of departures, which are generally performed in smaller aircraft over shorter stage lengths, resulting in smaller aggregated environmental impacts than large jets from large airports. When considering climate change and energy legislation, Congress will need to weigh the social and economic benefits of air service in small communities against the limited potential for reductions in environmental impacts.

3.5 Summary

Using the 2004-08 fuel price surge as a natural experiment, it has been shown that connections to non-hub airports serving small communities were most sensitive to effective fuel cost increases. It was found that non-hub airports lost 12% of connections, compared to an average loss of 2.8%, July 2004-08. The complete loss of service July 2007-08 at 70 non-hub airports, representing 14% of continental US airports with commercial service, resulted in an average driving time of 75 minutes to the next nearest airport with service for passengers relying on airports no longer with service. It is believed that reduced access to the national air transportation system had social and economic effects for small communities. The cessation of operations of Air Midwest and Big Sky Airlines, the sole carriers serving 20 communities in July 2007, resulted in much of the volatility in airports with service 2007-08. Regional and commuter airlines were less able to handle fuel cost volatility during this period as ten declared bankruptcy. To maintain historic levels of access to the air transportation system, funding for EAS subsidized routes has doubled since 2003 while the number of continental US communities serviced by subsidized routes has increased 19% to 107 in 2010. Even though subsidies have increased, 36 airports were without service for 10 months or longer following the 2008 fuel price surge. If small communities continue to require increasing subsidies to maintain air service, Congress will need to decide what level of access to air service is acceptable, what level of subsidies it is willing to provide, and how flexibility can be designed into programs to reduce interruptions in air service to small communities in the future.

Increases in the effective cost of aviation fuel could result from escalating crude oil prices and environmental driven costs (i.e. from cap and trade schemes or taxes). Complementary analyses of aircraft fuel efficiency, airline economics, and airfares provided a basis for understanding some airline decisions during the fuel price surge that can be extrapolated to examine future trends. Increased effective fuel costs will provide incentives for airlines to improve fleet fuel efficiency, reducing the environmental effects of aviation, but may cause an uneven distribution of social and economic impacts as airline networks adapt. As fuel costs increased 2004-08, use of aging, fuel inefficient aircraft was reduced while the number of operating turboprops increased. Permanent effective fuel cost increase will likely lead to increased adoption rates of CO_2 mitigating measures which reduce fuel burn, such as aircraft technology innovations, optimized operational procedures, and network changes. Benefits due to reductions in the environmental impacts of aviation may be balanced by social and economic costs. Government action may be required to determine acceptable levels of access to service as the air transportation system transitions to higher fuel costs.

CHAPTER 4

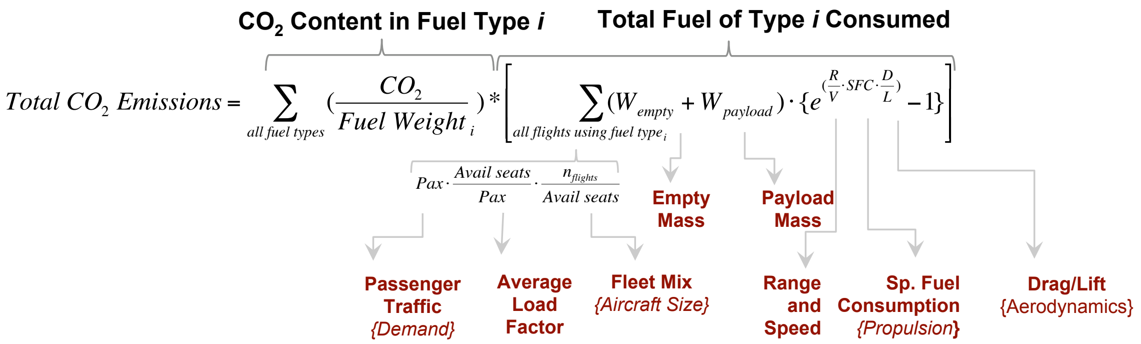
4.0 Improving Fleet Fuel Efficiency Through Technology Innovation

In the short- and medium-term, increases in effective fuel costs are expected to result in higher direct operating costs and airfares, as well as reductions in air service to markets no longer economical to serve. In the long-term, fleet fuel efficiency can be improved by replacing old aircraft with fuel-efficient aircraft, reducing the negative social and economic impacts of increased effective fuel costs. Fuel efficiency improvements counteract increasing fuel costs and reduce the environmental impact of aviation. But innovation takes time and aircraft are long-lived assets, resulting in a slow diffusion of new technologies into the fleet. Further, before a new technology is implemented in an aircraft, manufacturers must have the economic incentives to innovate.

In this chapter, historical and projected future aircraft fuel intensity improvements are reviewed and the dynamics of fleet turnover are discussed. The structure of the single aisle aircraft market is outlined and the competitive game between manufacturers is introduced. Two key elements are required to perform the game theory analysis of aircraft manufacturer competition in Chapter 6: (1) an understanding of the structure of the game, and (2) an estimation of strategy payoffs. This chapter describes the structure of the game while Chapter 5 introduces an aircraft program valuation model used to estimate the payoffs to manufacturers.

4.1 Historical Aircraft Fuel Intensity Improvements

The Breguet range equation can be adapted to demonstrate the levers available to reduce aircraft fuel burn and CO_2 emissions, as shown in Equation 1 (Kar, 2010; adapted from Lee et. al., 2001):



$$Total\ CO_2\ Emissions = \overbrace{\sum_{all\ fuel\ types} \left(\frac{CO_2}{Fuel\ Weight}\right)_i}^{CO_2\ Content\ in\ Fuel\ Type\ i} * \overbrace{\left[\sum_{all\ flights\ using\ fuel\ type_i} (W_{empty} + W_{payload}) \cdot \{e^{(\frac{R}{V} \cdot SFC \cdot \frac{D}{L})} - 1\}\right]}^{Total\ Fuel\ of\ Type\ i\ Consumed}$$

$$Pax \cdot \frac{Avail\ seats}{Pax} \cdot \frac{n_{flights}}{Avail\ seats}$$

Equation 1

Kerosene based jet fuel is currently the only safety certified fuel available in sufficient quantities. It has a CO_2 content of 3.15 kg CO_2/kg fuel. The use of alternative jet fuels with lower fossil carbon contents may result in CO_2 emission reductions, but to reduce the amount of fuel burned, the available levers are (Kar, 2010):

- ***Weight*** - reduce the aircraft's empty weight and the payload mass.
- ***Engine Efficiency*** – reduce the specific fuel consumption by improving the engine efficiency, such as through higher bypass ratios.
- ***Aerodynamics*** - increase the lift to drag ratio.
- ***Average Load Factor*** – fill flights with more passengers and cargo.
- ***Fleet Mix*** - use larger aircraft that take advantage of scale economies to be more efficient on a seat-mile or ton-mile basis.
- ***Flight Distance*** – modify network topology to reduce connections and improve air traffic control procedures to reduce flight distances.
- ***Cruise Speed*** – operate at cruise speeds that minimize fuel burn.

The IPCC (1999) used Figure 22 to demonstrate that jet aircraft fuel efficiency has improved over time, with current aircraft burning 70% less fuel per seat mile than early jets. About 40% of the improvement has come from engine efficiency improvements and 30% from airframe efficiency improvements.

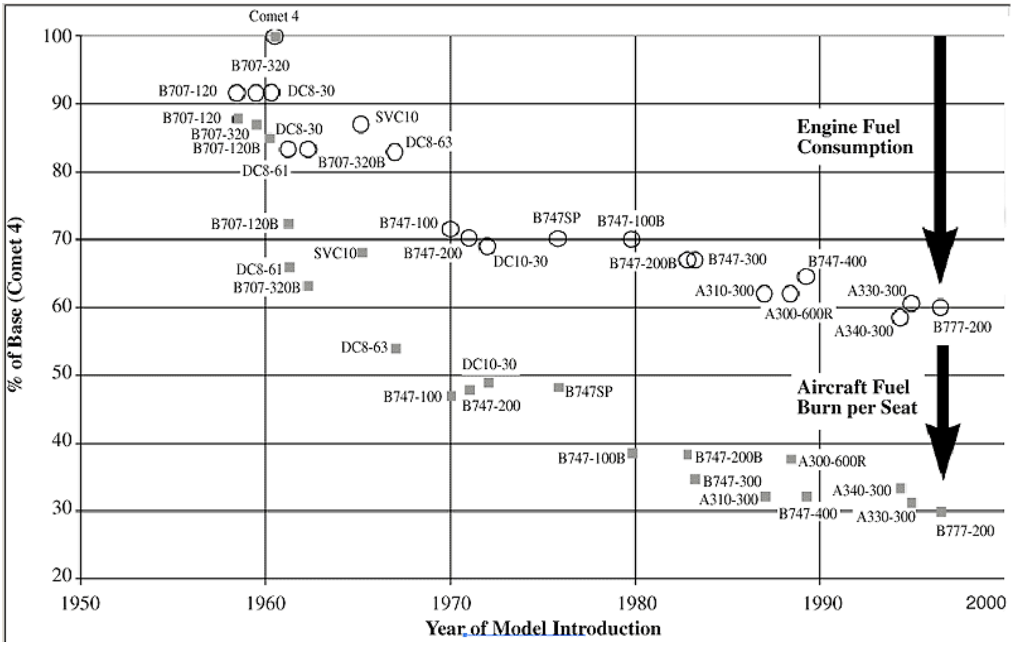


Figure 22. Trend in Transport Aircraft Fuel Efficiency. de Havilland Comet 4 Base Aircraft. Source: IPCC, 1999.

Successive generations of engine technologies have led to reductions in specific fuel consumption, as shown in Figure 23.

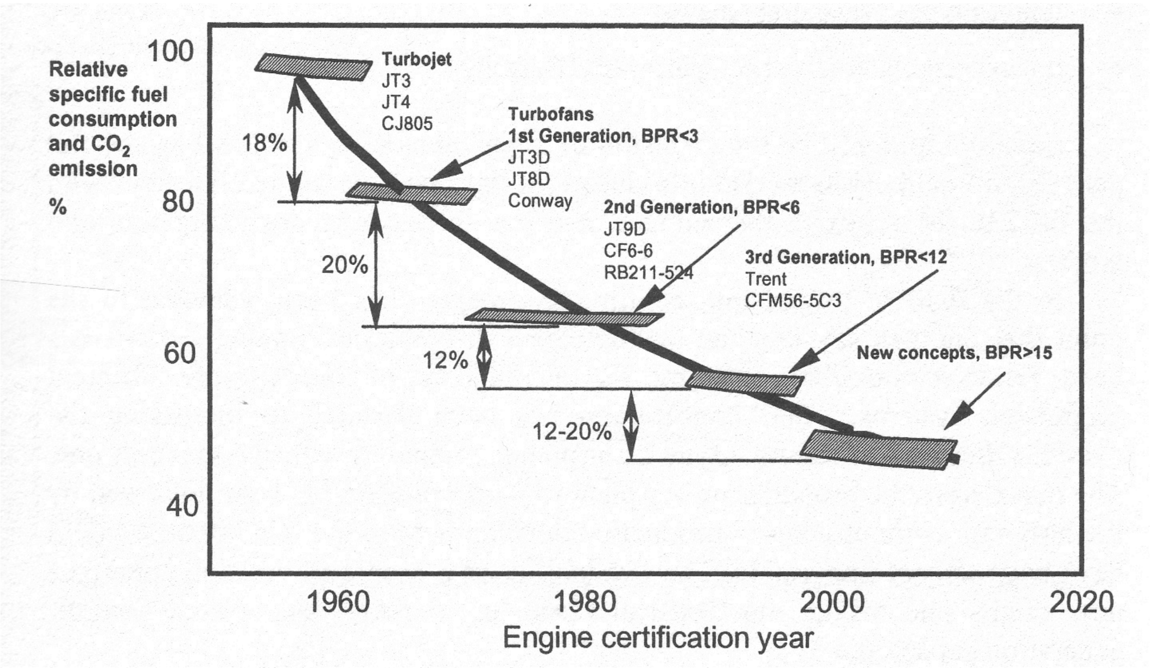


Figure 23. Reduction in Fuel Consumption and CO_2 Emissions by Engine Technology. Source: Ferreri, 2003.

Lee et. al. (2001) used BTS operational data to compare historic trends in the energy intensity of aircraft per available seat kilometre (ASK). Extrapolating the historic trends, they project energy intensity to decline at an expected rate of 1.2%-2.2% per year, as shown in Figure 24:

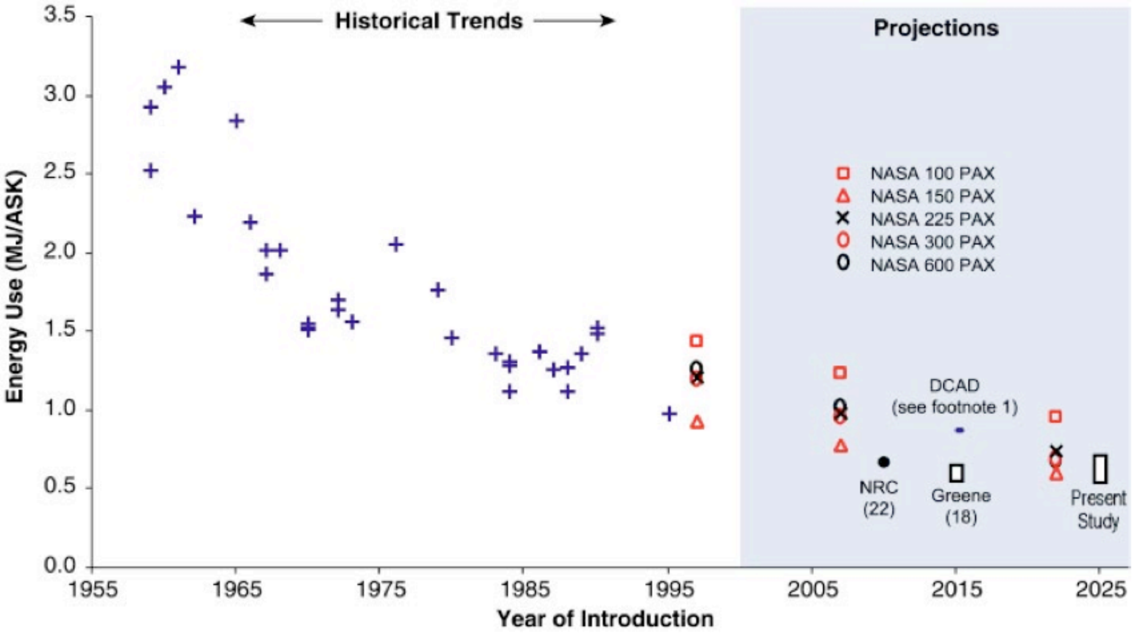


Figure 24. Future Aircraft Energy Usage. Source: Lee et. al., 2001.

Using operational data, Babikian et. al. (2002) demonstrated that regional aircraft are 40-60% less fuel efficient than narrow- and wide-body aircraft, and that regional jets are 10-60% less fuel efficient than turboprops, as shown in Figure 25. The disparities in fuel efficiency were largely explained by differences in operations as opposed to technology levels. Regional aircraft operate with lower load factors and perform fewer miles over which to spread the fixed costs of taxiing, takeoff and climb. To improve fleet fuel efficiency, it is not enough to improve technology in only the largest wide body aircraft. Operations and technology levels in narrow body and regional jets must also improve.

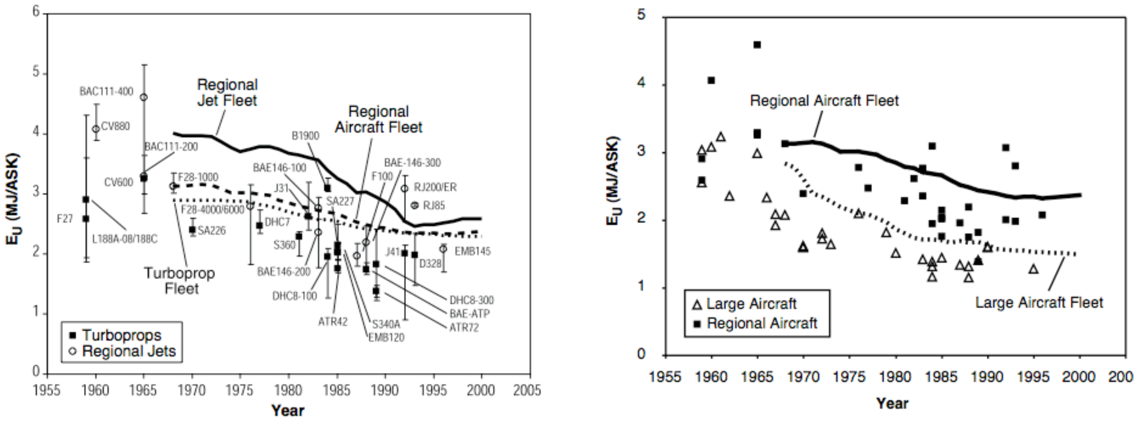


Figure 25. Energy Intensity of Regional Aircraft Compared to Fleet Averages and Large Aircraft
Source: Babikian et. al., 2002.

Peeters and Hoolhorst (2005) showed that the last piston-powered aircraft were as fuel efficient as the current average jet. They noted that defining future cuts in energy consumption in terms of a constant annual percentage reduction ignores the fact that energy consumption will never reach zero. The annual rate of reduction in fuel intensity is slowing, making studies that project historical fuel intensity improvements into the future optimistic. Historically, fuel efficiency has not been the primary objective of commercial aircraft designers. Jets replaced piston airliners. The A380 was designed with an 11% increase in fuel burn over optimal to conform to the airport handling constraint of an 80m wingspan. Peeters and Hoolhorst claimed that a power curve is a more faithful fit to historic data than an annual percent reduction. As shown in Figure 26, they used the power curve model in equation 2 to fit historical improvements in aircraft energy intensity, E_i,:

$$E_i = e^{a+b\ln(n)}$$ **Equation 2**

where *a* and *b* are constants while *n* is the number of years from the base year.

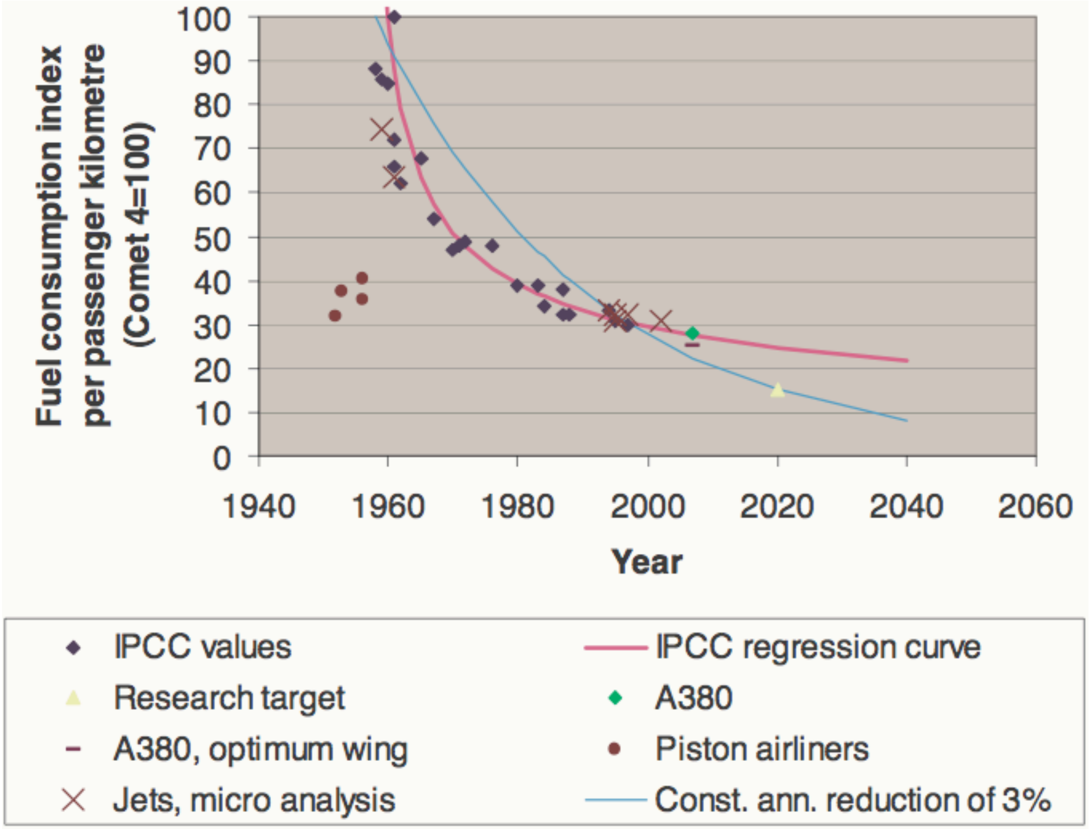


Figure 26. Aircraft Fuel Efficiency Trends and Projections. Source: Peeters and Hoolhurst, 2005.

Using sales-weighted average aircraft fuel burn, Rutherford and Zeinali (2009) demonstrated that the average aircraft fuel efficiency has improved by only ~50% since the first jets, while efficiency gains have slowed to 0.0% since 2000, as shown in Figure 27. The reduction in annual efficiency gains is correlated with low fuel prices from 1987 to 2004 and a tripling in the average age of aircraft and engine manufacturer production lines since 1989. Rutherford and Zeinali conclude that fuel costs have not been sufficient to stimulate increased aircraft efficiency, suggesting that a CO_2 standard applying to newly built aircraft is more likely to reduce emissions. But the 1980s marked a period of fierce competition between manufacturers and rapid fleet fuel efficiency improvements. Therefore, We hypothesize that competition between aircraft and engine manufacturers is a key driver of innovation resulting in fuel efficiency improvements.

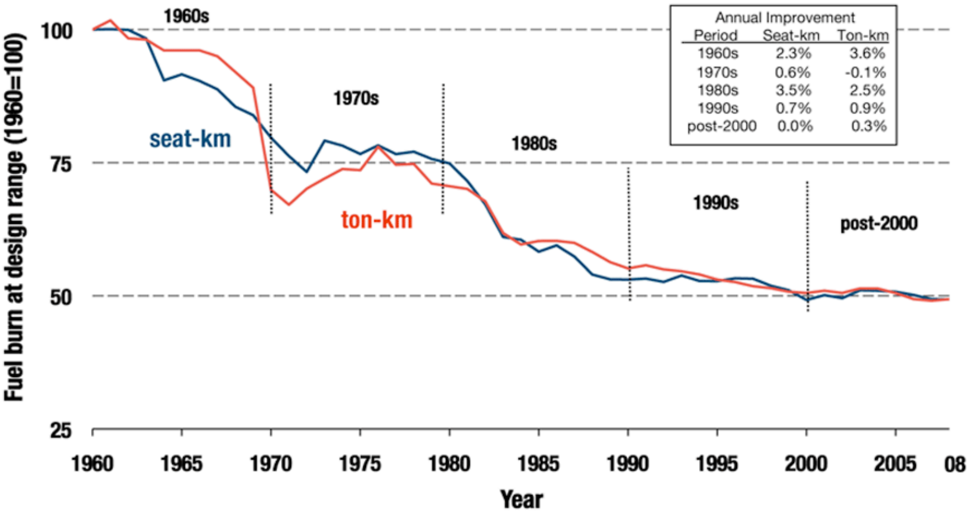


Figure 27. Sales-Weighted Average Jet Aircraft Fuel Burn, 1960-2008.
Source: Rutherford and Zeinali, 2009.

4.2 Future Potential Fuel Intensity Improvements

Tube and wing designs have dominated commercial aircraft since the 1950s, while engine technology innovations have led to three product cycles during the jet era, as shown in Figure 28.

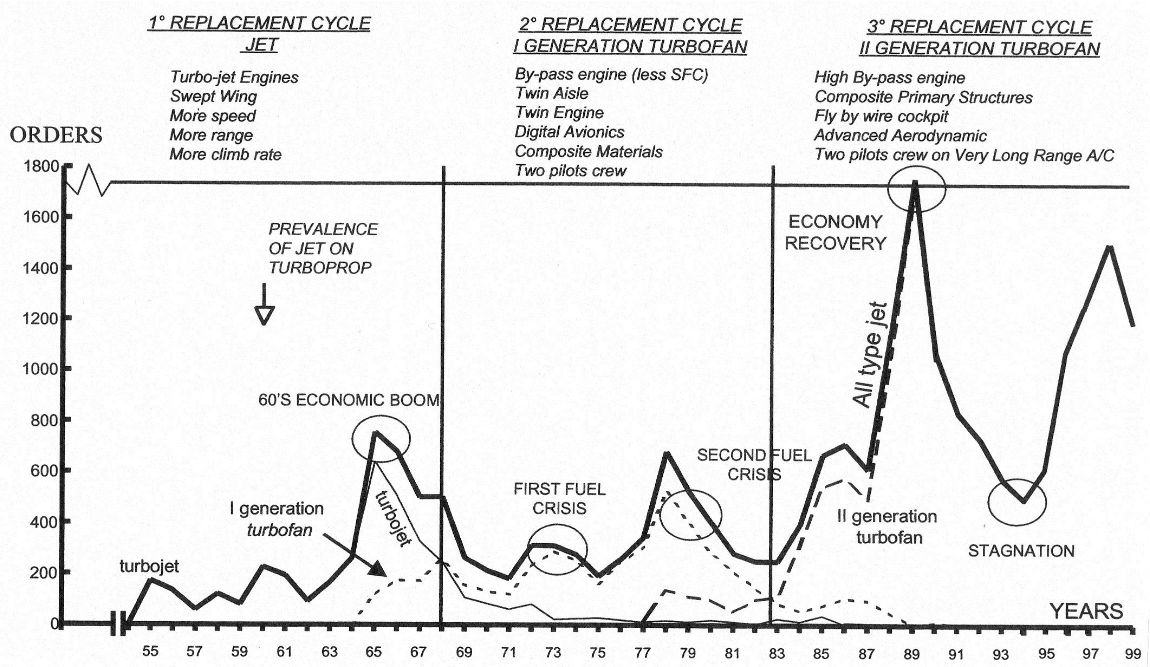


Figure 28. Life Cycles and Replacement of Jet Aircraft Class Product. Source: Ferreri, 2003.

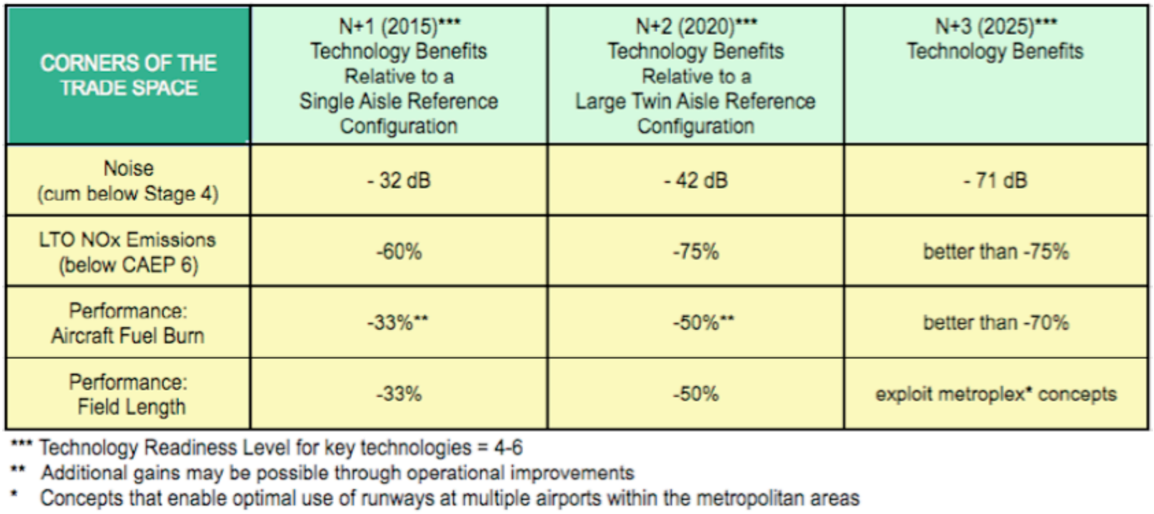
Dominant designs emerge from a process of experimentation and competition within a product class. As a synthesis of a number of proven concepts, the dominant design becomes locked-in to future designs and consumer expectations. Tushman and Anderson (1986) wrote:

> …technology evolves through periods of incremental change punctuated by technological breakthroughs that either enhance or destroy the competence of firms in an industry. These breakthroughs, or technological discontinuities, significantly increase both environmental uncertainty and munificence….while competence-destroying discontinuities are initiated by new firms and are associated with increased environmental turbulence, competence-enhancing discontinuities are initiated by existing firms and are associated with decreased environmental turbulence. These effects decrease over successive discontinuities. Those firms that initiate major technological changes grow more rapidly than other firms.

In the next jet aircraft product cycle, incumbent manufacturers have an opportunity to innovate. By building on their past successes and implementing technology innovations in new designs, incumbents can raise entrance barriers and prevent increased competition. If they choose not to innovate, incumbent manufacturers may lose their technological superiority and significant market share to new entrants. Although fuel efficiency is not the sole aircraft design criteria, with the expectation of increasing fuel costs and pressure to reduce aviation's environmental impacts it is likely that fuel efficiency will increasingly be the critically important design criterion. While safety will always be aviation's primary concern, it is probable that the next discontinuous aircraft design change will be a step improvement in fuel efficiency.

NASA's Environmentally Responsible Aviation (ERA) project aims to assess vehicle concepts and enabling technologies that have the potential to mitigate aviation's impact on the environment. Table 6 outlines the project's goals for subsonic vehicles.

Table 6. NASA's Environmentally Responsible Aviation (ERA) Project Goals for Subsonic Vehicles
"N" - the current generation of commercial aircraft. "N+1" - the next generation, and so forth.



CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

In the first stage of the NASA ERA project, MIT, Boeing, GE Aviation, and Northrop Grumman developed conceptual designs for N+3 vehicles. MIT developed two designs that met the NASA goals: (1) a double-bubble, and (2) a hybrid wing body. The D8 Series double-bubble was a 180-seat advanced tube and wing design that could fulfill the current role of Boeing's 737-800. It incorporated a lifting nose, embedded aft engines, and a reduced operational Mach number allowing for nearly unswept wings. The H3 Series was a more radical 350-seat design with a payload and range comparable to Boeing's 777-200LR. As a triangular-shaped hybrid wing body aircraft, the H3 blended a wider fuselage with the wings for improved aerodynamics. The center body created lift, eliminating the need for a tail to balance the aircraft (Greitzer et. al., 2010). Non-traditional aircraft designs would be a risky and costly project for a private firm to undertake. New technologies need to be developed, manufactured, tested, and safety certified. This creates significant financial and technical barriers to implementation of such discontinuous technologies.

Kar (2010) demonstrated that there are a number of technologies at various stages of technology readiness that have the potential to reduce fuel burn. In the near-term, new engine technologies, aerodynamic improvements, and weight reduction opportunities exist that could result in substantial fuel burn improvements in retrofitted or new aircraft. In the long-term, fuel burn reduction potential is even greater. Table 7 outlines a selection of the technologies identified.

Table 7. Selection of Technologies to Improve Fuel Efficiency.
Source: Kar, 2010.

	Near-Term <5 years	**Long-Term** >5 years
Propulsion	High bypass ratio engines Geared turbofan engines	Open rotor engines
Aerodynamics	Winglets Riblets Laminar nacelles	Hybrid laminar flow High aspect ratio wings
Weight	Composites Reduced OEW	

Figure 29 shows a temporal representation of the 41 CO_2 mitigating measures identified by Kar (2010). The amount of time required to reach market saturation is called the diffusion time while the start time represents the estimate of the measure's year of entry into service. The area of each bubble represents the percent potential CO_2 emissions reduction.

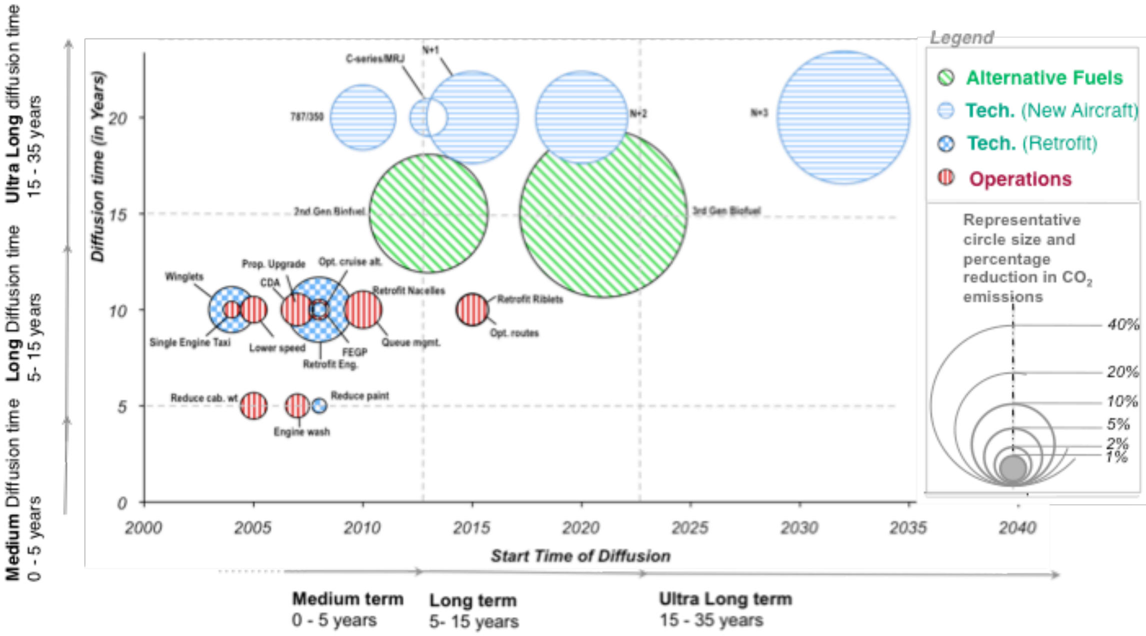


Figure 29. Distribution of Mitigating Measures' Start and Diffusion Times. Source: Kar, 2010.

While it is likely that technologies either do, or will, exist to substantially reduce aircraft fuel burn, they will only be implemented if they are economically feasible. Retrofitting in-service aircraft with non-safety required equipment has generally not proven economical. Updating technologies on current in-production aircraft leads to incremental fuel efficiency improvements, but engineers are constrained by previous design choices that limit the achievable improvements. Clean sheet design aircraft offer the most flexibility in implementing fuel burn reducing technologies, but the long time constants associated with aviation result in decades between new designs for a market segment. These factors reduce the effectiveness of innovation at improving fleet fuel efficiency.

4.3 Economics and Dynamics of Implementation of Mitigating Measures

Before a fuel efficiency measure is implemented, it must be economically feasible. Morris et. al. (2009) developed a framework to estimate the marginal abatement costs (MAC) for CO_2 and other emissions from the aviation sector, as shown in Figure 30. Measures with a negative abatement cost are financially beneficial to implement while those with a positive abatement cost are only cost effective if fuel prices rise above expectations or a carbon price is imposed. The horizontal axis shows the estimated magnitude of European fleet CO_2 reductions in 2012 for each measure.

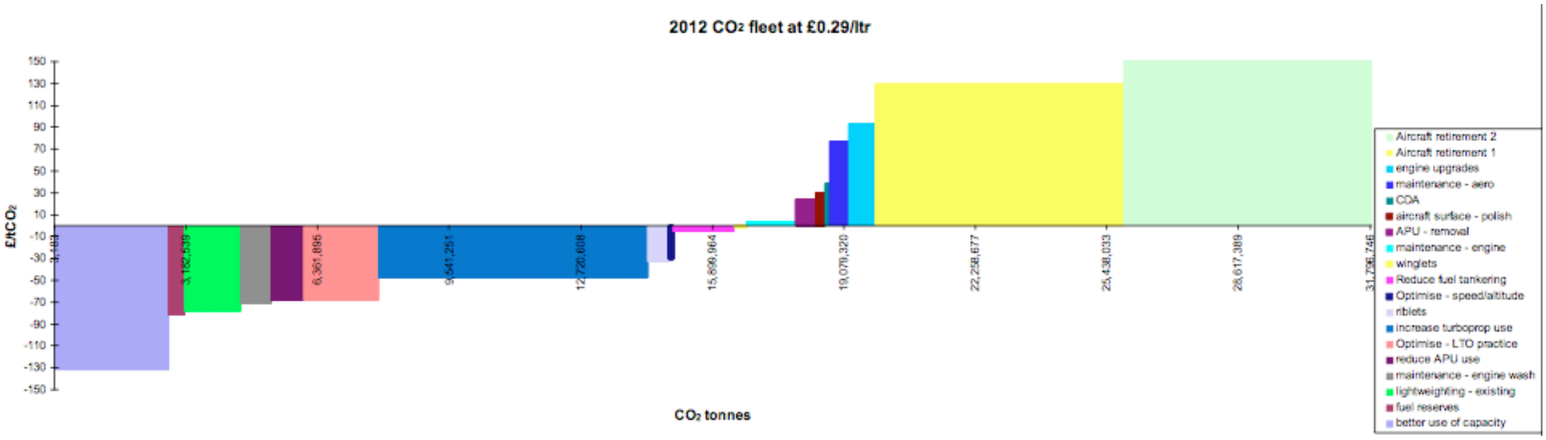


Figure 30. CO_2 Marginal Abatement Cost Curve for the 2012 European Fleet, Base Case Fuel Prices. Source: Morris et. al., 2009.

Better use of capacity, reducing fuel reserves, and light-weighting aircraft were estimated to be the most cost effective mitigating measures, while early aircraft retirements and engine upgrades are expected to have the highest abatement costs. It is economically efficient to implement those measures with the lowest abatement costs first, progressing up the MAC curve until the marginal abatement cost is positive.

Although early retirement of aircraft may not be an economically efficient means of reducing fuel burn, the natural process of fleet turnover is. As older aircraft in the fleet are retired and replaced by current in-production aircraft, the fleet fuel efficiency improves. But, if in-production aircraft technology levels remain constant, operating fleet fuel efficiency improvements slow as all aircraft in the fleet approach the same technology level. Kar (2010) found that the early adoption of available technology, as opposed to waiting and delaying entry for more fuel-efficient technologies, has a greater potential to improve fleet fuel efficiency by 2050. With operating lifetimes of 20-25 years, significant changes to the average fleet fuel efficiency require a combination of step improvements in the fuel burn of new models and an acceleration of adoption of new models.

Morrell and Dray (2009) analyzed fleet turnover and the incorporation of new technologies. They found that airline purchase decisions have historically not been affected by fuel prices when the selection of aircraft types available remains constant. However, the mean fuel burn of new aircraft orders is strongly affected by the introduction of new aircraft models with significantly lower fuel burn. This finding suggests that influencing the rate of technology development may be an effective policy lever for reducing emissions via fleet turnover. Single aisle aircraft currently make up 61% of the world’s jet fleet and 68% of 2010-29 forecasted deliveries (Boeing, 2010a). As the largest lever, the single aisle market was investigated to determine what factors and policies might lead to the introduction of new aircraft models with step improvements in fuel efficiency.

4.4 Single Aisle Aircraft Market Structure

As an industry with economies of scale that requires large capital investments, high technical capabilities, and a worldwide service network, large commercial aircraft manufacturing is naturally concentrated to a small number of competitors (Busch, 2001). The 100+ seat commercial market has historically been split between the American manufacturers (Boeing, McDonnell-Douglas, and Lockheed) and the European Airbus consortium, as shown in Figure 31.

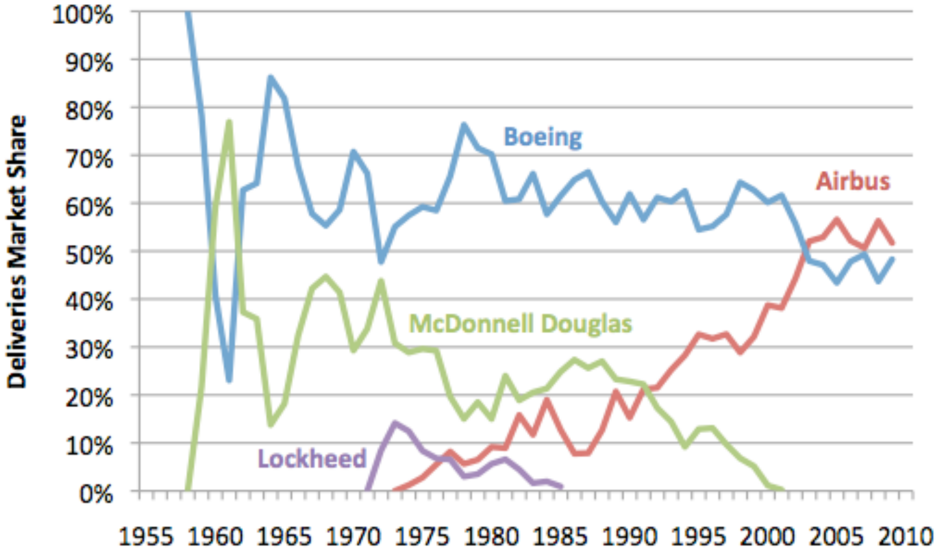


Figure 31. Large Commercial Aircraft Manufacturer Market Shares by 100+ Seat Jetliner Deliveries, 1960-2009. Date Source: Airbus, 2010b; Boeing, 2010b.

Since Boeing's purchase of McDonnell-Douglas in 1997, Airbus and Boeing have competed in a global duopoly. Large barriers to entry exist which protect the incumbents from new competition. The cost of developing a new aircraft ranges from estimates of $3 to $14 billion (depending on the aircraft size and technology level) and requires expertise only developed over long periods of time. Production learning effects result in unit costs dropping on the order of 20% every time the quantity produced doubles, creating significant unit cost advantages for aircraft with long production runs (Benkard, 2000). Further, airlines purchasing new aircraft demand low operating costs and competitive pricing. Fleet commonality reduces operating and maintenance costs, as well as spare part inventories, providing incentives for airlines to lock-in to one aircraft family. In order to maintain market share in a segment, manufacturers are forced to develop aircraft with essentially equivalent performance. To gain market share, significant performance improvements are required to overcome the switching costs of airlines locked-in to one product family.

Boeing and Airbus compete in market segments defined by the aircraft's range and seating capacity, which vary from 2000 to 8000+ miles and 100 to 500+ seats. Narrow body aircraft serve short- and medium-haul routes while wide body aircraft generally serve cross- and inter-continental routes. Both companies recently updated their large wide bodies with the introduction of Airbus's A380 in 2007 and the expected first delivery of Boeing's 747-8 in 2011. In the medium wide body market segment, the manufacturers are entering a battle between Boeing's 787 Dreamliner and Airbus's larger A350 XWB, with first deliveries expected in 2011 and 2013, respectively. Manufacturers generally respond to each other's moves to prevent an inferior aircraft in a market segment from losing market share and profit potential. As both manufacturers have a complete product line and have performed significant updates to their wide body aircraft families, the next area of competition is likely the narrow body, single aisle segment - Boeing's 737 and Airbus's A320 families.

Boeing's 737 first entered service in 1968. A variety of derivative aircraft based on the initial design, with different ranges and seating capacities, have been produced over the years. Members of the Next Generation 737 family were launched in the late 1990s and early 2000s with updated engines, cabin interiors, and flight deck avionics as well as winglets and changes to the airframe. Airbus entered its A320 family into service in 1988. The aircraft's fuselage has been stretched and shrunken to fill different market niches with the introduction of the A321, A319, and A318. A variety of engines have been used on the Airbus airplanes allowing for incremental improvements in fuel efficiency. Figure 32 shows a timeline of upgrades performed to both manufacturers' single aisle product lines over the past 30 years.

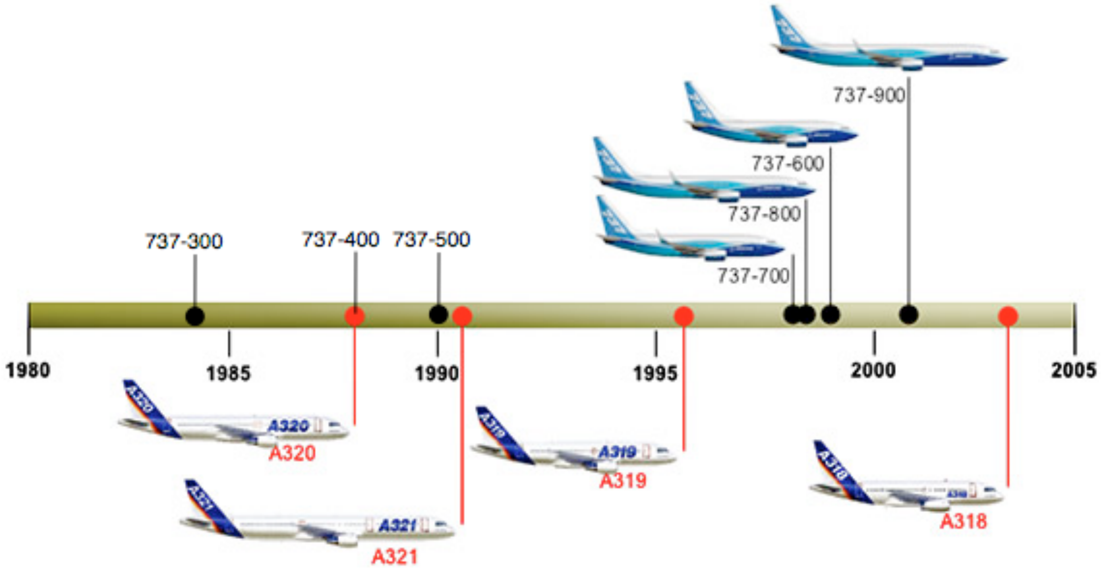


Figure 32. Narrow Body Single-Aisle Jet Aircraft, 1980-2010. Source: Boeing, 2010c.

If one manufacturer develops a superior aircraft, its competitors risk losing market share, as shown in Figure 33. In the 150-185 seat single aisle short- to medium-range market segment, Boeing's 727-200 enjoyed a monopoly until the MD-80 entered service in 1980 with an estimated 37% fuel burn improvement at the R1 range[7] (not shown in the figure). Boeing's 737-400 and Airbus's A320 entered service in 1988, offering significant performance improvements over the MD-80. McDonnell Douglas exited the market in 1997 leaving the two remaining manufacturers to split the market. Since the late 1990s when Boeing introduced the 737-800 and 737-900, the manufacturers have performed incremental improvements on their existing product lines.

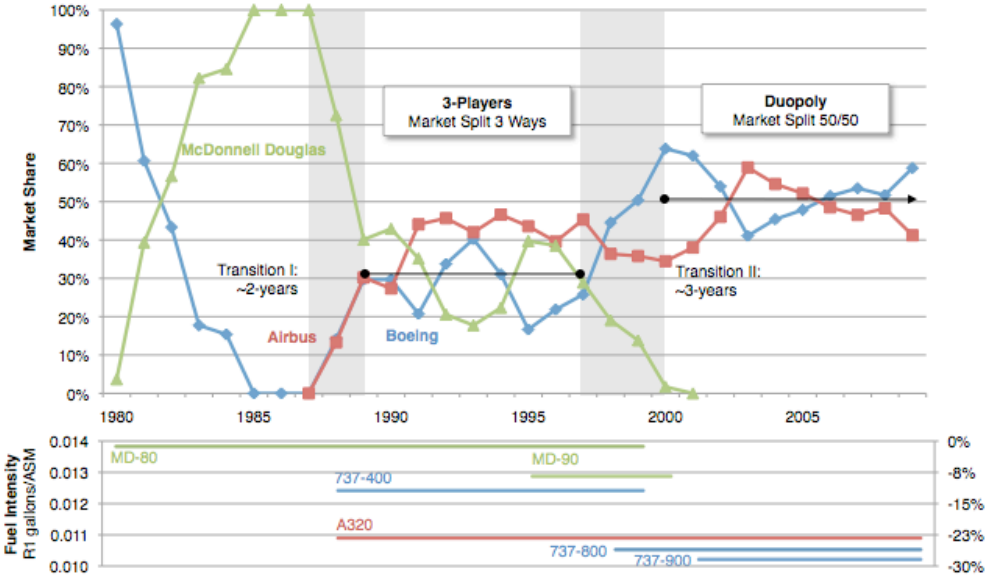


Figure 33. Single Aisle, 150-185 Seat Market Shares and Fuel burn Performance, 1980-2009. Data Source: Airbus, 2010b; Boeing, 2010b; Piano-X.

New competition in the single aisle markets may be on the horizon. Figure 34 demonstrates that while only a few firms enjoy the technical competency, financial resources, and market control that allow them to carry on the development of an aircraft program in all phases, the number of competitors expands moving down the productive pyramid (Ferreri, 2003). As regional aircraft manufacturers and major structure sharing suppliers develop design and production capabilities, they may decide to compete with the incumbents in the large commercial aircraft market segments (Bediér et. al., 2008). Embraer's E195 encroaches on the 100+ seat market while Bombardier's CSeries is due

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[7] R1 range is the maximum aircraft range after which payload must be sacrificed to gain additional range.

to enter service in 2013 with 100-145 seat variants. Commercial Aircraft Corporation of China (Comac) is planning to introduce its 168-190 seat C919 in 2016 while Russia's Irkut is developing the 150-210 seat MC-21 family for entry into service in 2015-16. While the performance of these new aircraft is uncertain, if new entrants are able to gain market share, Airbus and Boeing may decide to update their single aisle fleet - creating opportunities to reduce the environmental impacts of aviation.

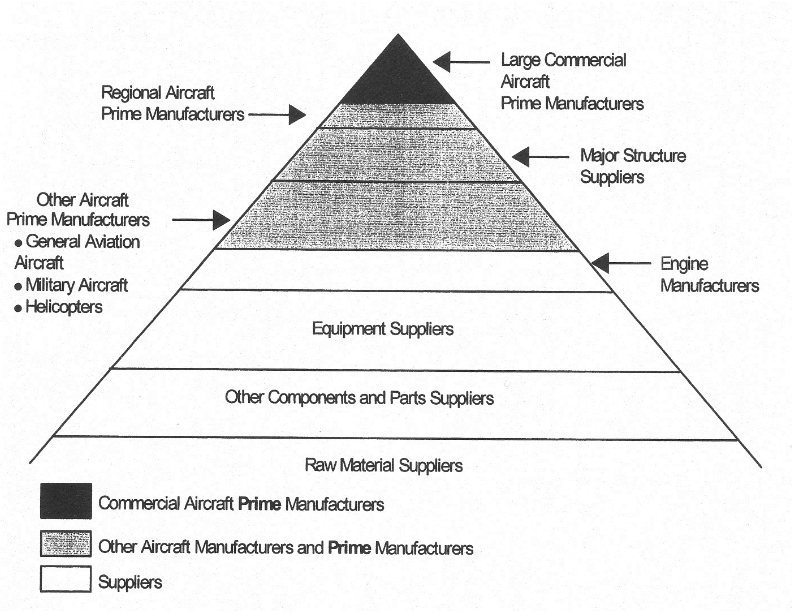


Figure 34. The Productive Pyramid in the Civil Aeronautic Industry. Source: Ferreri, 2003.

A potential strategy for incumbent manufacturers is to re-engine their existing airframes, taking advantage of recent breakthroughs in propulsion technologies to improve aircraft performance. Due to past design decisions, Boeing's 737-800 sits lower to the ground than the A320. Fully loaded, the engine ground clearance on the 737-800 is only 19" (Boeing, 2005). The 737's current CFM56-7 engines have an inlet diameter of 61" while next generation high bypass ratio and geared turbofan (GTF) engines will have larger diameters (e.g. 81" for Pratt & Whitney's PW1100G) and will be heavier. Therefore, Boeing's 737 requires additional engineering work to re-engine than Airbus's A320. This provides a re-engining advantage to Airbus as a smaller investment and less technical risk is required.

4.5 Structure of the Competitive Game

Game theory frameworks have been used in the past to analyze competition between aircraft manufacturers. Brander and Spencer (1985) showed how government subsidies could be used to change the initial conditions of games between non-cooperative international rivals. Krugman (1987) used hypothetical payoff matrices to show how government subsidies could enable domestic firms to increase profits in excess of the subsidy amounts by deterring foreign entry and allowing domestic firms to capture excess returns, increasing social welfare. A game theory analysis enables the discovery of the Nash equilibrium of multiple, competing players' who all act in their own best interests. Understanding how competition impacts the decision to invest in new aircraft designs can assist policy makers in developing plans of action to improve aviation's fuel efficiency.

As both Boeing and Airbus have existing in-production single aisle aircraft, the game has been altered since the economists analyzed it in the 1980s. Incumbent manufacturers have four generic strategies: (1) *maintain* their existing product lines, with incremental improvements over time, (2) *re-engine* their existing airframes, providing superior performance improvement, (3) develop *new*, clean sheet design aircraft that offer the greatest fuel burn improvements, or (4) *exit* the market. Based on historical data, incremental improvements to an aircraft generally amount to ~1%/annual fuel intensity reductions. Re-engining Airbus's A320 or Boeing 737-800 is expected to offer up to 15% fuel savings (Airbus, 2010a). A new aircraft with a clean sheet design would offer a fuel efficiency improvement on the order of 25% (ACARE, 2008; Morrell and Dray, 2009).

As technologies mature, clean sheet design aircraft in the future will offer greater efficiency, with expected improvements on the order of 70% by 2040 (Kar, 2010). NASA's ERA goals include developing technologies that will enable 70% or better fuel burn performance on clean sheet design aircraft by 2025. Therefore, in the long term, there is a performance advantage to delay the design of a new aircraft. Due to payback periods on the order of 10-15 years for large commercial aircraft programs, when a manufacturer commits to a new aircraft, they lock-in to the technology level for the duration of the program, enabling only incremental improvements. Figure 35 shows that if Manufacturer A decides to re-engine in 2010, the aircraft is expected to enter service around 2015, providing a performance advantage over Manufacturer B's product. But, if Manufacturer B decides to develop a new aircraft around 2015, they would gain the performance advantage when it enters service around 2020. Locking into a technology may leave a competitor vulnerable to their aircraft being obsolete five or ten years later - around the same time manufacturers hope for their programs to become profitable and benefit from reduced production unit costs through learning effects. Aircraft that have superior performance gain market share and yield higher sale prices. Although manufacturers can always purchase market share by dropping sale price, this strategy reduces profit margins.

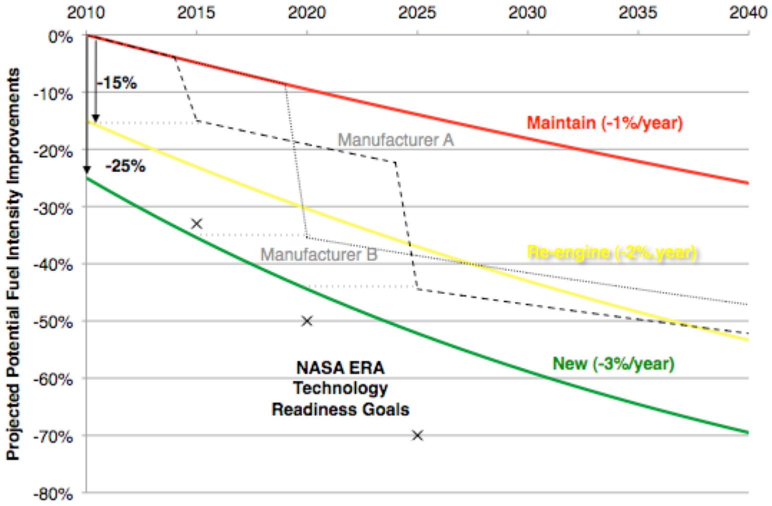


Figure 35. Potential Fuel Burn Improvements of Future Technologies.

Uncertainties in future demand and fuel prices impact the expected value of an aircraft program. The demand for new aircraft is dependent on the profitability of airlines and is therefore volatile, impacted by GDP growth, macroeconomic cycles, and passenger preferences (Sgouridis, 2007). Manufacturers must build production facilities and supply chains with the flexibility to meet expected demand. Optimistic forecasts expose the manufacturer to downside risks that may result in severe financial consequences while overly pessimistic forecasts limit the potential upside of the program. Operating cost savings is a major selling point of new aircraft programs, but the magnitude of operating cost savings is partially dependent on future fuel prices. Fuel prices are volatile, resulting in uncertainty in the value of efficiency improvements and prices manufacturers can obtain for increased aircraft technology levels.

In Chapter 6, two types of games are analyzed: (1) static games in which the manufacturer's decision space is limited to *maintaining* their product lines, *re-engining* their current aircraft, or developing a *new* aircraft, and (2) dynamic games in which manufacturers update their decisions at 5-year increments, based on the evolution of fuel prices and demand for single aisle aircraft. Figure 36 outlines the decision space in both types of games. It is assumed that there is a 5-year delay from when a decision is made to when the aircraft enters service. Therefore, a decision to develop a new aircraft includes the production and sale of the existing aircraft for 5-years until the new aircraft enters service. In the dynamic game, it is assumed that a manufacturer would produce a re-engined aircraft for 10-years to receive a sufficient payback on their investment. In each case, it is assumed that a player's moves in the game terminate when they decide to develop a new aircraft. A 20-year period is used for the static games to correspond to the manufacturer demand forecasts and oil price forecasts while a 30-year period is used for the dynamic games to enable a sufficient payback period for new aircraft introduced in later stages.

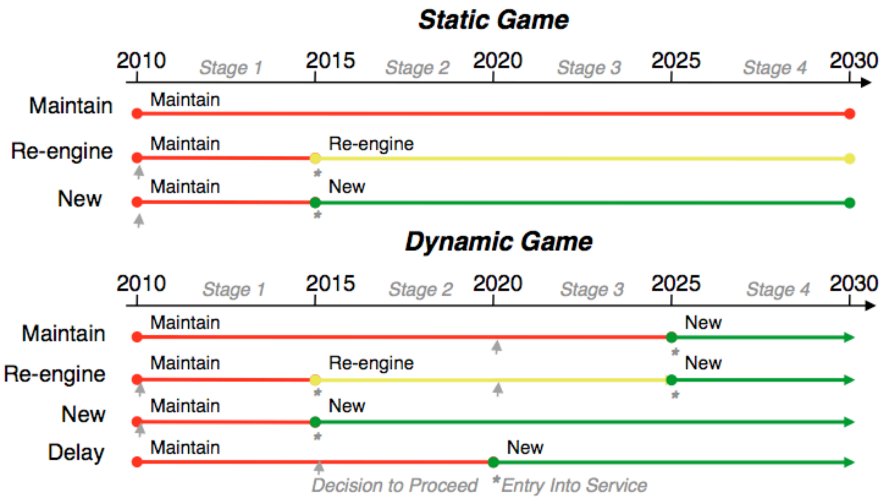


Figure 36. Structure of the Static and Dynamic Games Analyzed.

4.6 Summary

Chapter 4 reviewed historical improvements in aircraft fuel efficiency. Fleet wide fuel efficiency improvements will only be obtained by the introduction of new single aisle aircraft with step performance improvements. New technologies have the potential to create a discontinuity in the product cycle that offers opportunities for new entrants to compete or incumbents to solidify their hold on the market. Aviation's marginal abatement cost (MAC) curve was introduced, demonstrating that although the natural process of fleet turnover has a long time constant, it is an economically efficient approach to improving fleet fuel efficiency. Before new aircraft offering step fuel efficiency improvements are produced, manufacturers must have the incentives to innovate. The history of competition in the single aisle market segment was reviewed to understand the structure of the game that manufacturers are faced with in their current decisions to *maintain*, *re-engine*, or develop a *new* single aisle aircraft. Before proceeding with the static and dynamic game analyses, an aircraft program valuation model is introduced in Chapter 5 that will be used to estimate the manufacturers' payoffs for the game theory analysis in Chapter 6.

CHAPTER 5

5.0 Methodology for Aircraft Program Valuation

A game theory analysis is rooted in determining: (1) the structure of the game, and (2) the payoffs to each player. The structure of the game was outlined in Chapter 4 using a historical analysis of aircraft fuel efficiency improvements and manufacturer competition in the single aisle aircraft market. This chapter develops an aircraft program valuation model to estimate the payoffs for the manufacturers' strategies under varying market conditions. Following the principle of Occam's razor, a simple model is constructed to avoid unnecessary complexity, improving our ability to understand its behaviour. Aircraft manufacturers keep much of their production and sales financial data proprietary to protect competitive interests. Therefore, there is uncertainty in the model's input parameters. The purpose of this aircraft program valuation model is to determine the correct rank ordering of manufacturers' generic strategy payoffs in expected value terms under the different scenarios investigated in Chapter 6. We make no assertions concerning the validity of the absolute value of payoffs estimated, but only their rank ordering. An organization with access to more complete financial data could develop an improved valuation model and use the framework of analysis developed in Chapters 4 and 6 to yield more accurate cardinal estimates of the manufacturer payoffs.

How manufacturers make the business case for new aircraft programs is discussed in Section 5.1. The aircraft program valuation model is developed in Section 5.2. A sensitivity analysis is conducted in Section 5.3 to determine whether the aircraft program valuation model is robust and how altering the model's input parameters impact the rank ordering of payoffs. The chapter is summarized in Section 5.4.

5.1 Making the Case for New Aircraft Programs

Successful aircraft programs require longevity to achieve efficient production volumes in the face of constantly changing market conditions, competitive actions, and technological alternatives. Steiner (1982) listed the key drivers for program decisions as: market needs and timing, government actions and priorities, competitor actions, technology readiness, and fiscal considerations. Often decisions made become irreversible due to program cost penalties. Therefore, it is critical to make decisions that will yield the highest payoff, given all technical, political, and economic variables in the problem, as well as their associated uncertainty.

Previous works highlight the need to consider more than just the technical aspects of an aircraft program when making product line decisions. Mavris and Birney (2002) outlined the need to link the engineering and business sides of a program to provide decision-makers with a clearer understanding of payoffs and risk. Markish (2002) developed an aircraft program valuation model that combined a performance model, a development and manufacturing cost model, and a revenue model with a dynamic programming algorithm to account for uncertainty in future market conditions, demonstrating the usefulness of design based on maximum value to the aircraft manufacturer. Peoples (2004) used a multidisciplinary design optimization (MDO) approach to assess aircraft performance, finances, and business risk in aircraft program design. Justin et. al. (2010) are working towards a game-theoretic and real-options based method that will optimize research and development strategies and properly value large development projects. The aircraft program valuation model developed in this report estimates the financial payoffs of aircraft programs to incorporate strategic factors into aircraft program decisions using game theory. Further work is needed to integrate technical requirements with the financial and strategic aspects of the problem.

Before deciding to pursue an aircraft program, manufacturers must close the business case. The right aircraft must target the broadest market segment and rely on a level of technology that makes production costs reasonable while offering performance improvements that competitors will have difficulty exceeding. An aircraft design that includes technologies not yet at an appropriate readiness level will lead to excessive program delays and cost overruns while a program not ambitious enough will open opportunities for competitors to capture market share by producing a superior product.

A number of figures of merit are commonly used to value and compare investment options. These include the payback period, internal rate of return (IRR), cost-benefit ratio, and net present value (NPV). Each metric has drawbacks and benefits. Net present value enables cash flows over multiple years to be compared while recognizing the time value of money through the selection of a discount rate. Expected net present value, E(NPV), incorporates the uncertainty of NPV calculations by taking the probability weighted mean of NPV under a range of future scenarios. It is likely that manufacturers make aircraft program decisions in expected terms using NPV calculations. Therefore, this metric was selected as the manufacturers' objective functions used to calculate payoffs for the game theory analysis in Chapter 6.

5.2 Aircraft Program Valuation Model

As in Irwin and Pavcnik (2004), the objective function of manufacturers is assumed to be the net present value of expected profits:

$$\pi_{ft} = E_t \left[\sum_{t=s}^{n} \partial^t \left(q_t(p) \left(p_t - c_t \right) \right) + I_t \right] \qquad \textbf{Equation 3}$$

where E_t is the expectation operator conditional on information at time t, n is the number of periods included in the analysis, δ is the discount factor, q_t is the quantity of aircraft sold (which is a product of the firm's market share and total market size), p_t is the sale price of the aircraft, c_t is the variable cost of production, and I is the nonrecurring investment required. This objective function is expected for nongovernmental firms operating in market economies. Firms operating in different home country market structures may choose different objective functions, but this complexity is not examined. A symmetric duopoly is assumed in which firm's are risk neutral and identical, except for the investment required to re-engine (as discussed in Section 4.4). The static analysis was limited to a 20-year period as manufacturers release 20-year demand forecasts and discounting reduces the present value of future cash flows, while the dynamic game was extended to a 30-year period to enable manufacturers to book revenues from aircraft that enter into service at later stages in the game. The periods of analysis were broken into five-year stages to reduce the number of future states considered, making the problem tractable. Forecasted demand and fuel prices represent average values over the course of a business cycle. In the following subsections, the objective function in equation 3 is expanded and assumptions are outlined. The model input parameters are summarized in Table 14.

Nonrecurring Investments

Aircraft program nonrecurring investments consist of the research, development, testing and evaluation (RDT&E) of the aircraft. This includes the design, prototypes, flight testing, production facility construction, and tooling that is required to produce the first plane that enters commercial service. While this analysis assumes symmetric firms, due to past design decisions, Boeing's 737 requires additional engineering work to re-engine. Therefore, it was assumed that Player B requires a \$3 billion investment to re-engine its aircraft, while Player A only requires a \$1.5 billion investment. New aircraft development programs are much more costly, likely in the range of \$10 billion for the single aisle market (Rothman, 2010). It was assumed that nonrecurring costs are distributed over one five-year stage in the model. Although designing and testing a new aircraft is a more complex task than re-engining an existing airframe, the model is broken into 5-year periods to reduce the number of feasible states explored. Estimates of the investment required were taken from industry press, based on historical programs.

Recurring Production Costs

Recurring costs of manufacturing aircraft are subject to a learning curve that incentivizes manufacturers early in a program to produce more, reducing unit production costs for the remainder of the program. Raymer (2006) uses the learning curve model:

$$c_{q_i} = c_1 q_i^{\ln\beta/\ln 2} \qquad \textbf{Equation 4}$$

where c_{qi} is the unit production cost of the ith unit produced, c_1 is the theoretical first unit cost (TFUC), q_i is the number of units produced, and β is the learning curve slope.

The learning curve slope has been estimated to be between 75% and 95%, with 80% generally accepted based on empirical analysis and expert opinion (Benkard, 2004; Irwin and Pavcnik, 2004). The theoretical first unit cost was estimated using the DAPCA

IV model, developed by the RAND Corporation using a statistical analysis of past commercial and military aircraft programs (Raymer, 2006). The estimated unit cost of the 100th aircraft produced was used to estimate the theoretical unit cost of the first based on the learning curve slope assumption, in the same manner as Markish (2002).

The initial quantity of units produced for the *maintain* strategy was estimated from historical deliveries. To the end of 2009, Boeing had delivered 1806 737-800s while Airbus had delivered 2257 A320s. For the re-engine strategy, it was assumed that the manufacturer would benefit from significant learning effects due to a long history of producing the air frame, but the learning curve would be reset to some lower number of units produced due to the design and production changes required. The initial quantity of units produced for the re-engine strategy was set at a level where the estimated unit production cost approximated sale price.

Demand Forecast

Narrow body aircraft deliveries are cyclical, with high volatility, as shown in Figure 37:

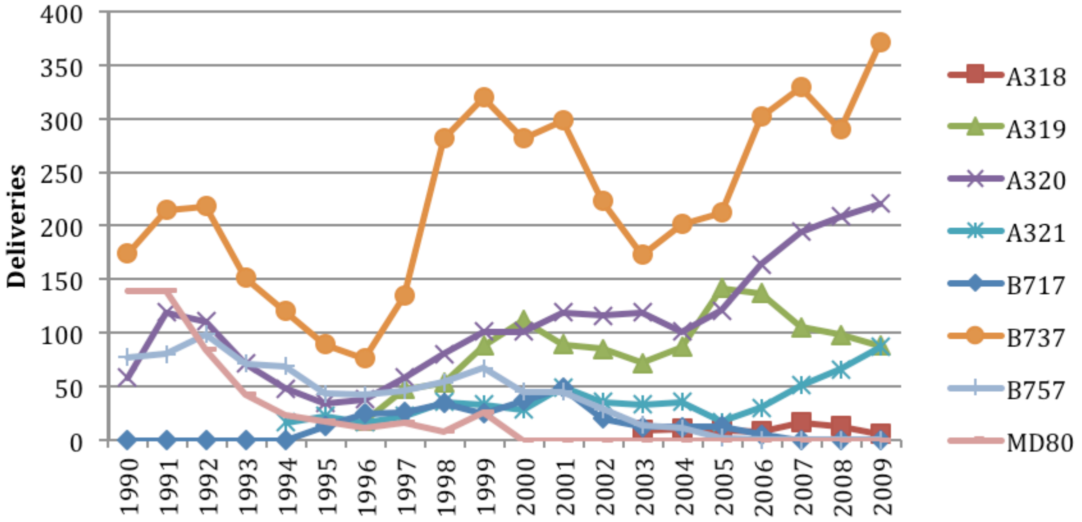


Figure 37. Narrow Body Deliveries, 1990-2009. Data Source: Airbus, 2010b; Boeing, 2010b.

Figure 38 shows that the percentage change in annual deliveries has been volatile over the past 20 years, around the mean annual growth rates of 10% for A320s and 5.5% for 737s. The business cycles in the 1990s led to much more dramatic changes in yearly deliveries than in the 2000s, suggesting that manufacturers have taken steps to reduce the classic supply chain bullwhip effect that was present in earlier decades (Sgouridis, 2007, p. 322).

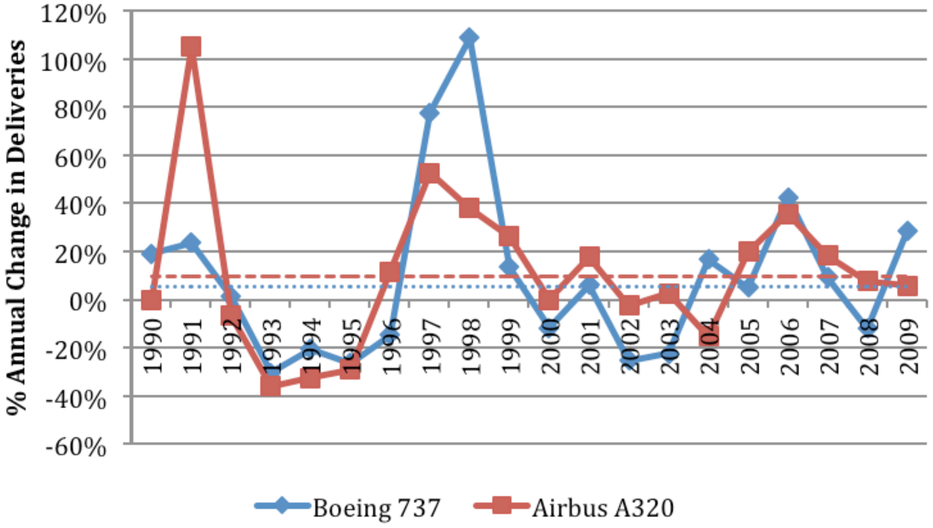
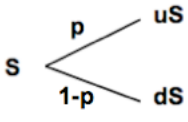


Figure 38. Annual Percent Change in 737 and A320 Deliveries, 1990-2009.
Data Source: Airbus, 2010b; Boeing, 2010b.

The global demand for single aisle aircraft was forecasted as average yearly deliveries, for each five-year stage, using a recombinant binomial lattice model, as shown in Table 8. For each stage of the lattice model, the average demand over the next five-year stage (i.e. the state, *S*) was assumed to either increase by amount *u* or decrease by amount *d*, with probability *p* or 1-*p*, respectively. Repeating these calculations for each state, in each stage, yielded a cone of possible demand states and the forecasted probability of each demand state occurring. The values for *u*, *d*, and *p* were estimated from historical delivery data using the formulas (Chance, 2007):



$$u = e^{\sigma\sqrt{\Delta t}} \qquad d = e^{-\sigma\sqrt{\Delta t}} \qquad p = \frac{e^{v\Delta t} - d}{u - d}$$

Equation 5

where σ is the delivery variance, v is the expected mean growth rate of deliveries, and Δt is the number of periods. The expected deliveries per year for each stage in the lattice model was the probability weighted average of the stage's demand states. This method limited the number of states to explore in the model, but recognized the uncertainty inherent in forecasting demand over 20 years.

The variance was calculated from the 2000-09 deliveries of MD-80/90, Boeing 737-800/900 and Airbus A320. High and low estimates were calculated using the periods 1990-2009 and 2005-09. The mean growth rate was calculated so that the expected deliveries over the next 20 years equaled the average of the Airbus and Boeing 2010-2029 single aisle market forecasts. The high and low estimates of the mean growth rate were calculated using the two manufacturer's independent forecasts. Each state of the lattice model in Table 8 represents the average expected deliveries over each five-year stage in the years indicated. The initial state represents the average deliveries in the 2005-09 period.

Table 8. Base Case Aircraft Demand Binomial Lattice Model

	Stage 0 2005-09	Stage 1 2010-14	Stage 2 2015-19	Stage 3 2020-24	Stage 4 2025-29
Aircraft Deliveries/Year	391	738	1393	2630	4965
		207	391	738	1393
			110	207	391
				58	110
					31
Probability	100%	47%	22%	10%	5%
		53%	50%	35%	22%
			28%	40%	37%
				15%	28%
					8%
Expected Deliveries/Year	**391**	**455**	**530**	**617**	**718**
Total Deliveries, 2010-2029	11,599				

Jet Fuel Price Forecast

The expected price of jet fuel influences airlines willingness to invest in fuel burn reducing technologies. It was assumed that if fuel prices are expected to escalate, airlines will be more willing to invest in new aircraft that reduce fuel burn, as discussed in Section 3.3. Therefore, the expected price of fuel influences the prices airlines are willing to pay for new aircraft and the amount of risk manufacturers are willing to take to implement fuel efficiency technologies in new aircraft. Jet fuel prices were modeled in the same manner as the demand for aircraft using a binomial lattice model. The mean growth rate was taken from the Energy Information Administration's (EIA) 2010 Annual

Energy Outlook while the variance was determined from historical jet fuel prices (ATA, 2010a). High and low estimates were taken from the EIA oil price scenarios.

Table 9. Base Case Jet Fuel Price Binomial Lattice Model

	Stage 0 2005-09	Stage 1 2010-14	Stage 2 2015-19	Stage 3 2020-24	Stage 4 2025-29
Jet Fuel Price/Gallon	$2.24	$4.58	$9.35	$19.12	$39.07
		$1.10	$2.24	$4.58	$9.35
			$0.54	$1.10	$2.24
				$0.26	$0.54
					$0.13
Probability	100%	42%	18%	7%	3%
		58%	49%	31%	17%
			34%	42%	36%
				20%	33%
					11%
Expected Fuel Price	**$2.24**	**$2.56**	**$2.92**	**$3.33**	**$3.80**

Aircraft Lifecycle Cost Analysis

New aircraft often fetch a higher sale price to compensate manufacturers for the risk of increased technology levels. From an airline perspective, the benefits of advanced technology come from reductions in fuel and maintenance costs over the course of the aircraft's operating life, as shown in Figure 39.

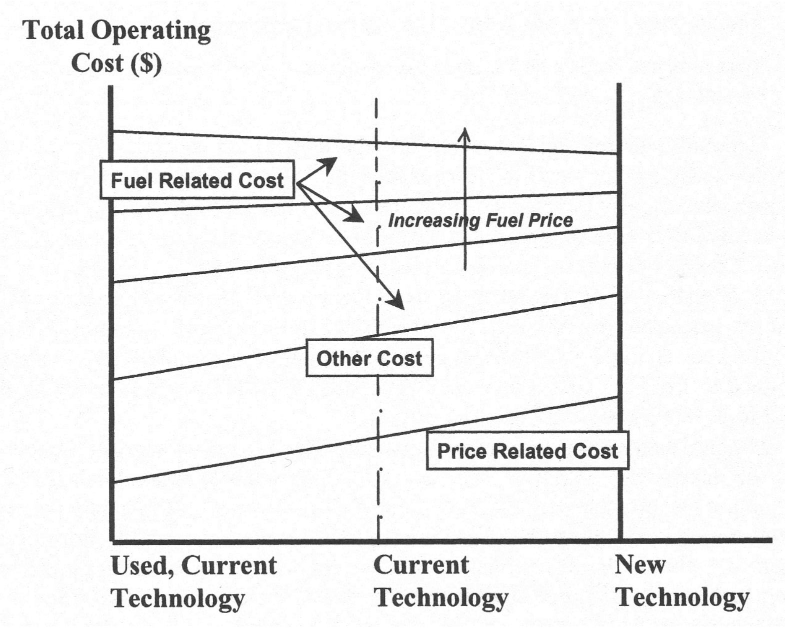


Figure 39. The Benefits of Advanced Technology – Fuel Related Cost Savings. Source: Ferreri, 2003.

Airline purchase decisions are modeled using an aircraft life cycle cost model. The model was developed using assumptions based on Morrell and Dray (2009), updated with average BTS (2010) operations and cost data for A320s and 737-800s operated by US carriers in the year 2009, as shown in Table 10. The discount rate was selected based on an IATA analysis of the weighted average cost of capital (WACC) for the airline industry (Pearce, 2009). The estimated sale price of the aircraft represents 20% of the present value of the life cycle costs, as shown in Figure 40. Fuel can account for 33% of total aircraft related operating costs (TAROC) using an 8% discount rate, the base fuel price scenario, and a 20-year operating lifetime. Although these calculations are approximate, they demonstrate that sale price is one component of an airline's decision to purchase an aircraft while lifecycle operating cost is likely a larger share. A manufacturer that can reduce operating costs will be able to increase sale price within a range that keeps TAROC constant, or reduces it.

Table 10. Aircraft Lifecycle Fuel Cost Model Input Parameters

Variable		Source
Block Hours	3658 block hour/year	BTS, 2009
Fuel Burn	792 gallon/block hour	
Fuel Intensity Degradation	Year 1-5: 0%	Morrell and Dray, 2009
	Year 6-10: 0%	
	Year 11-15: 0%	
	Year 16-20: 0.5%	
Discount Rate	8%	Pearce, 2009

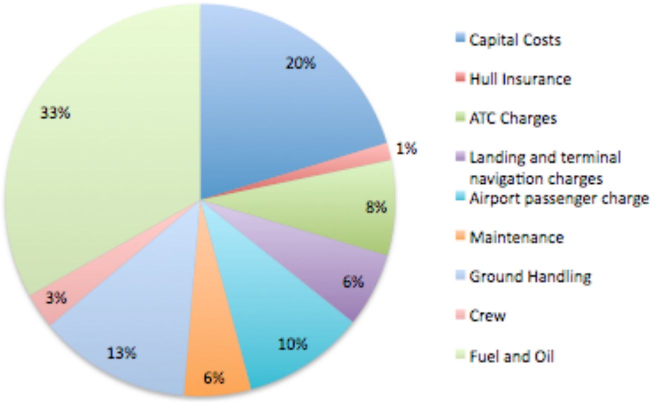


Figure 40. A320/737-800 Lifecycle Cost Estimates
Data Source: BTS, 2010; Morrell and Dray, 2009.

Aircraft Pricing

There are strong anecdotal reports of significant discounting in large commercial aircraft pricing (Newhouse, 2007; Gittel and O'Reilly, 2001). An analysis of Boeing and Airbus Annual Reports (2000-2009) demonstrated that revenues from commercial aircraft sales have never matched the list prices of the aircraft delivered in any one year. Figure 41 shows Boeing and Airbus's average list price discounts, as calculated by the difference between the manufacturers' commercial aircraft revenues and the 2008 aircraft list prices times the number of deliveries of each aircraft type, in each year. The Airline Monitor (2004) reported average A320 and 737-800 sale prices of $53.3 and $49.4 million (2008 US$), respectively. A 35% discount from list prices was assumed, yielding an estimated base sale price of $50 million.

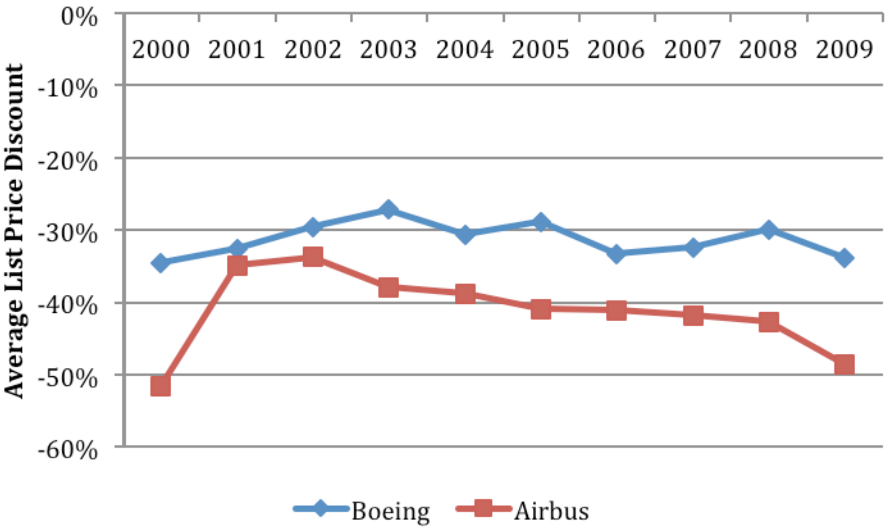


Figure 41. Estimated Average Aircraft List Price Discounts for All Deliveries.
Data Source: Boeing and EADS Annual Reports, 2000-09.

Markish (2002) demonstrated that there is no correlation between aircraft deliveries and sale price. Therefore, it was assumed that market demand evolves independently of sale prices, while the relative differences in competitor's sale price combined with lifecycle operating costs (i.e. TAROC) impacts market shares. A market-based pricing model was assumed in which the aircraft price balances the other aircraft related operating costs. Forecasting prices forward, it was assumed that current aircraft prices remain constant in real terms, but manufacturers are able to negotiate price increases proportional to reductions in lifecycle cost on the introduction of new aircraft, as shown in Figure 42. Assuming a basic bargaining game in which both parties have equal power, lifecycle operating cost reductions would be split evenly between the buyer and seller. Therefore, if a new aircraft with 25% fuel burn improvement yields an expected present value of $20.8 million in lifecycle cost savings (given the fuel price binomial lattice model in Table 9), it is assumed manufacturers would be able to increase sale price by $10.4 million.

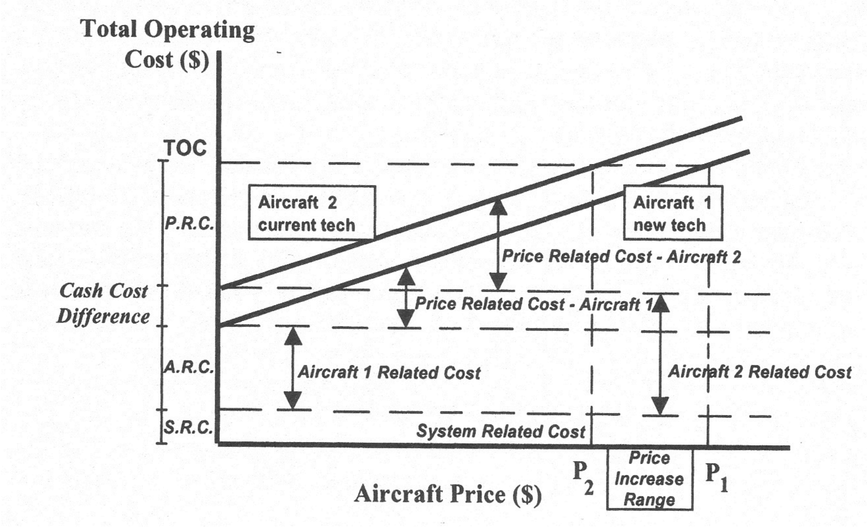


Figure 42. Cost Analysis Approach to Price Setting. Source: Ferreri, 2003.

Market Share Model

Airlines select the aircraft that gives them the highest utility. It was assumed that each manufacturer produces essentially equivalent aircraft, with fuel burn the only differentiating factor. But, due to past fleet decisions, airlines have generally committed to one manufacturer's product line. Airlines prefer a fleet composed of aircraft from the same family to reduce training and maintenance costs, as well as the cost of spare part inventories. As of November 2010, 62 airlines worldwide had unfilled orders for the 737 family while 82 airlines had unfilled orders for the A320 family. Only 6 airlines had unfilled orders for both. In the future it is expected that airlines will select the aircraft with the lowest TAROC, as long as the reduction of TAROC of the aircraft is greater than the switching cost the airline may incur.

Although Boeing has an advantage in the number of single aisle aircraft in the world's fleet, Airbus holds 52% of unfilled orders (Airbus, 2010b; Boeing, 2010b). It is expected that incremental improvements in the fuel efficiency of one manufacturer's aircraft are not enough to convince airlines operating the competitor's aircraft to switch. A substantial operating cost improvement is required relative to the competitor's to gain market share. It was assumed that some airlines will never choose to switch manufacturers, leaving some minimum market share that a manufacturer will maintain as long as they choose to produce their aircraft.

A historical analysis was conducted to understand how aircraft performance impacts market share. Figure 33 shows the evolution of market shares in the single aisle, 150-185 seat market segment, while Figure 43 and Figure 44 show historical market shares for twin aisle, medium sized jets in the medium and long range markets. In each figure, an estimation of the aircraft type fuel intensity at its R1 range and maximum payload is given for comparison. There are a number of confounding factors that prevent the determination of a statistical relationship between fuel intensity and market share. For example, jets with longer ranges must carry additional fuel, increasing fuel intensity. Also, although Boeing's 767 and Airbus' A330 compete in the same market segment, the A330 has a larger payload and range. Other operating costs were not compared in this analysis. Despite these shortcomings, several heuristics can be devised that were used to estimate the market shares of competing aircraft.

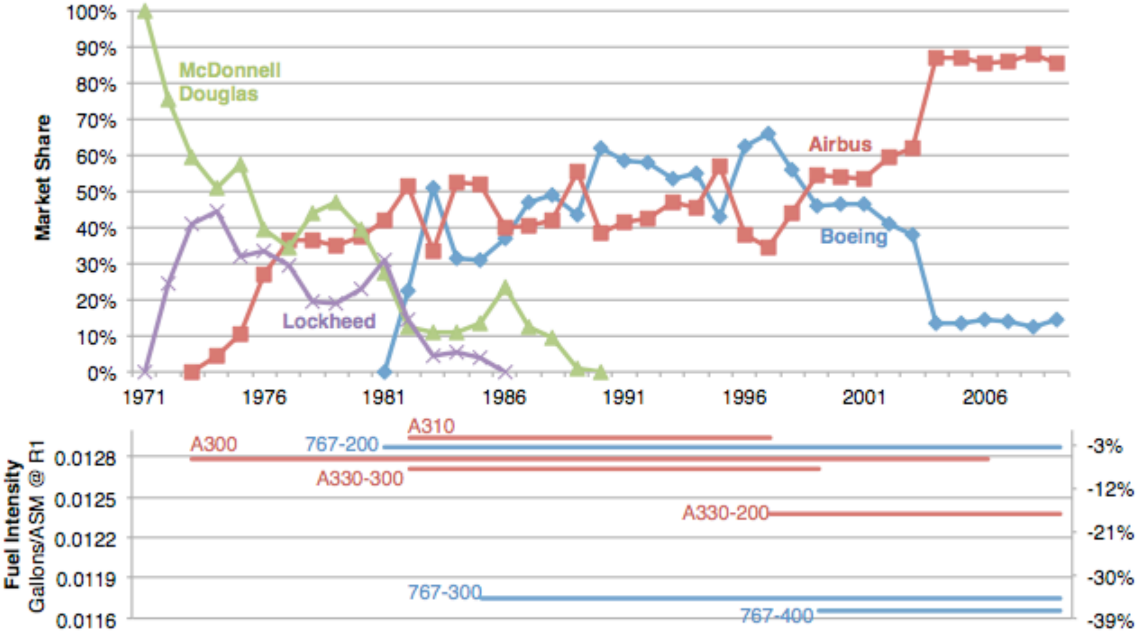


Figure 43. Wide Body, Medium Range Market Share Analysis
Data Source: Airbus, 2010b; Boeing, 2010b.

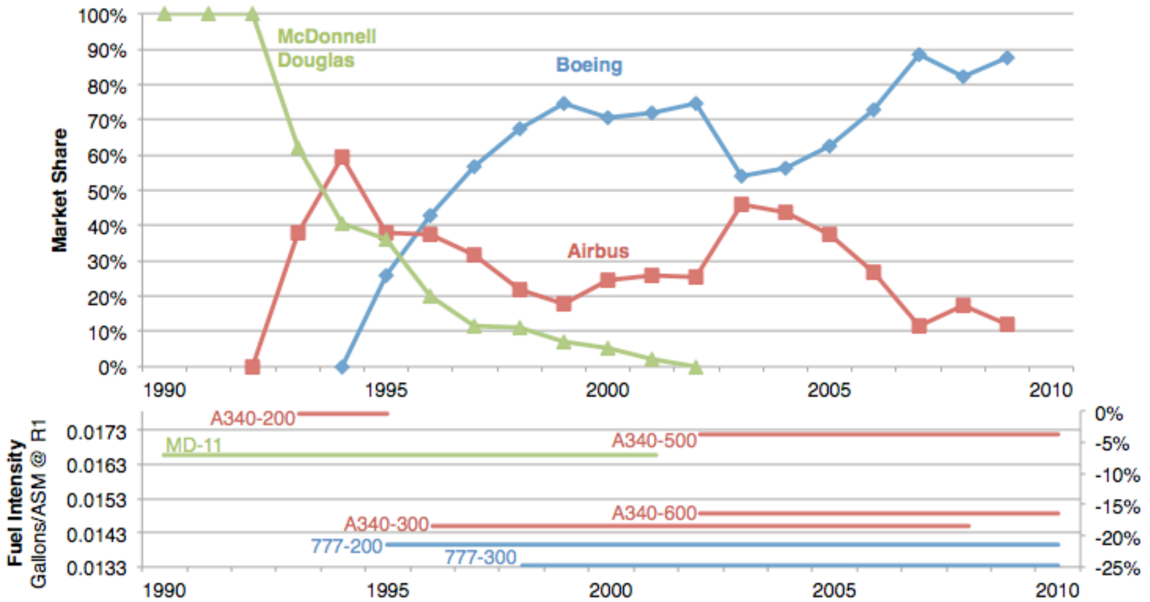


Figure 44. Wide Body, Long Range Market Share Analysis. Data Source: Airbus, 2010b; Boeing, 2010b

The market share heuristics derived from the historical analysis were:

- *15% Minimum Market Share:* The minimum market share for an aircraft that a manufacturer still finds profitable to produce was assumed to be 15%, based on the wide body market segment historical analysis. Boeing's 777 controls ~85% of the market vs. Airbus's A340, while Airbus's A330 takes ~85% of the market vs. Boeing's 767.
- *50%/50% Split for Equivalent Aircraft:* Aircraft with equivalent performance are assumed to split the market, as the 737-800 and A320 do currently.
- *Switching Costs:* Switching costs prevent airlines from receiving a higher utility from aircraft that have a marginally (e.g. <5%) performance advantage. Therefore, incremental improvements generally do not result in market share increases as competitors generally match each other's incremental improvements, with some time lag.

These heuristics were used to estimate long-run market shares for aircraft in different competitive situations. Table 11 shows the market share assumptions for the two-player incumbent manufacturer games, while Table 12 and Table 13 show the assumptions for the three-player games that include a new entrant. It was assumed that if the new entrant produces an aircraft of superior performance to the incumbent's current product, the new entrant would take market share. The amount of market share would be dependent on the level of performance of the new entrant's aircraft. An aircraft with equivalent performance to the incumbents' new aircraft was assumed to leave stagnant incumbents' products with the minimum market share. But, if the new entrant's aircraft has the performance of the incumbents' re-engined aircraft, it would only capture 50% of the market from two unmoving incumbents. Such logical games were used to estimate the remaining market shares in each cell representing the intersection of the players' strategies in the tables below.

Table 11. Two-Player Game Market Share Rules

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	50%, 50%	35%, 65%	15%, 85%
	Re-engine	65%, 35%	50%, 50%	35%, 65%
	New	85%, 15%	65%, 35%	50%, 50%

Table 12. Three-Player Game Market Share Rules
New Entrant Performance = Incumbent New

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	15%, 15%, 70%	15%, 25%, 60%	15%, 43%, 43%
	Re-engine	25%, 15% 60%	25%, 25%, 50%	25%, 38%, 38%
	New	43%, 15%, 43%	38%, 25%, 38%	33%, 33%, 33%

Table 13. Three Player Game Market Share Rules
New Entrant Performance = Incumbent Re-engined

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	25%, 25%, 50%	20%, 40%, 40%	15%, 55%, 30%
	Re-engine	40%, 20% 40%	33%, 33%, 33%	25%, 50%, 25%
	New	55%, 15%, 30%	50%, 25%, 25%	40%, 40%, 20%

Without operating cost improvements, manufacturers could reduce TAROC by reducing the sale price, purchasing market share. This possibility is neglected in the model as it is assumed that manufacturers prefer to maintain a certain level of profitability on existing models. For new aircraft models, there is an incentive to reduce sale price to gain market share, increase production numbers, and work down the learning curve. This option is not considered in this model, but is addressed in Benkard (2004).

As the purpose of this aircraft program valuation model is to estimate the rank order of manufacturer payoffs, these market share assumptions are sufficient. The impacts of these assumptions are tested in the sensitivity analysis of Section 5.3. The range of market share assumptions for which the outcome of the game is unchanged is determined.

Production Capacity Constraints and Fixed Costs

Increasing demand or market share would require a manufacturer to expand their production facilities. Production capacity in the aircraft program valuation model is expanded at the beginning of each stage if the expected deliveries in the demand state exceed capacity. A one-time investment is made to expand capacity, but it was assumed that capacity is never lost. Therefore, if demand drops in the next stage, production capacity remains steady. It was assumed that manufacturers have fixed costs proportional to their production capacity. Therefore, if capacity is larger than demand at any stage, the manufacturer will be required to pay for excess capacity that is not utilized. Estimates of the expansion costs and fixed costs of unit production capacity (i.e. the ability to produce one aircraft per year) were derived from Boeing and Airbus annual reports.

Expected Net Present Value Calculation

Table 14 summarizes the model input parameters, as well as the low and high values used in the sensitivity analysis performed in Section 5.3:

Table 14. Aircraft Program Valuation Model Assumptions

Variable	Low	Base	High	Source/Units
Investment, I – Maintain	$0	$0	$0	Rothman (2010)
Re-engine	$1.0 ($1.0)	$1.5 ($3.0)	$3.0 ($6.0)	Billion, <Airbus> (<Boeing>)
New	$5	$10	$15	
Learning Curve Slope, β	75%	80%	85%	Benkard (2004)
Theoretical First Unit Cost, c_1	$260	$380	$500	million, Raymer (2006)
Year 0 Quantity, q_0 – Maintain		2000		
Re-engine		300		
New		0		
Sale price, p – Maintain	$40	$50	$60	million
Re-engine	$50	$56.6	$63.2	million
New	$50	$60.4	$70.8	million
Expansion Costs	$0	$20	$30	million/unit capacity
Fixed Costs of Capacity	$0	$4	$6	Million/unit capacity
Discount Rate	6%	8%	10%	
Single Aisle Market Demand, μ	2.36%	3.04%	3.66%	Boeing (2010b)
ν	10.2%	28.4%	45.0%	Airbus (2010b)
Jet Fuel Price, μ	-0.23%	2.64%	4.59%	EIA (2010)
ν	22.0%	32.0%	42.8%	ATA (2010a)

To calculate the E(NPV) of a manufacturer's strategy, the NPV and probability of each possible path through the demand lattice model was calculated. E(NPV) was the probability of each path times its calculated NPV. This approach was necessary as the path through the lattice model impacted the unit production cost (as the cost of any unit produced was dependent on how many previous units had been produced) and the fixed costs (as the production capacity was assumed to not contract). Figure 45 shows the cumulative distribution functions (CDFs) for each symmetric strategy (i.e. where both players choose the same strategy, splitting the market) for the low fuel price scenario where fuel burn reduction technologies do not receive a higher sale price. The CDF curves for each strategy show the probability that the NPV of the aircraft program will be less than or equal to the NPV on the horizontal axis. The distribution of NPVs is a result of the uncertainty in future demand, as modeled using the binomial lattice model in Table 8. The vertical dashed lines represent the E(NPV) for each strategy.

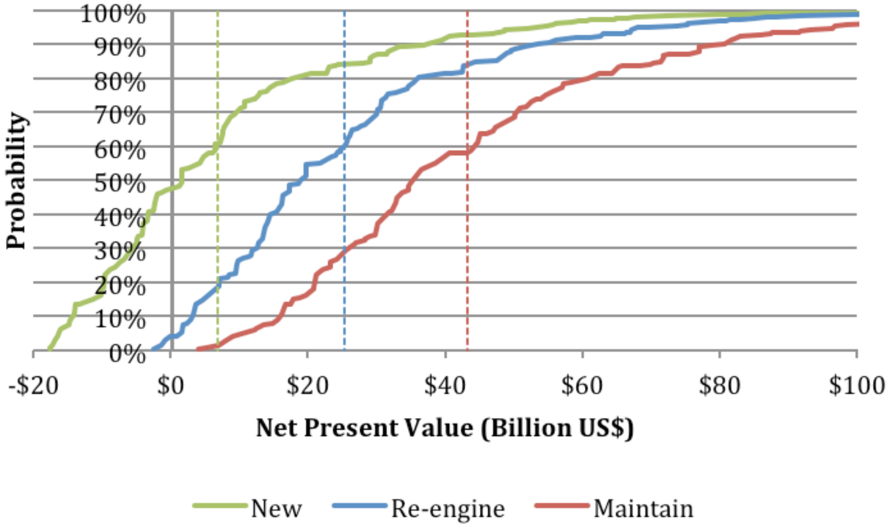


Figure 45. Aircraft Program Valuation Cumulative Distribution Functions for Symmetric Strategies

Although the E(NPV) is used as the payoff in the game theory analysis in Chapter 6, each value represents a distribution of possible payoffs due to the uncertainty in demand and fuel prices discussed in Section 5.2. Table 15 displays statistics summarizing the distribution of payoffs for each strategy shown in Figure 45. The *maintain* strategy has the highest upside (represented by the 95% value) while the *new* strategy has the most downside (represented by the 5% value). There is significant variance in the valuation of each strategy, demonstrated by the standard deviation (Std).

Table 15. Valuation Model Symmetric Strategy Statistics (billions US$)

	New	Re-engine	Maintain
E(NPV)	$6.8	$25	$43
Std	$35	$36	$41
95%	$92	$111	$140
5%	$-16	$1.5	$12

The assumption that players are risk neutral results in the competing firms ignoring each strategy's distribution of NPVs. Utility functions that account for the different levels of risk inherent in each strategy could be used to relax this assumption, but this complexity was not considered.

5.3 Sensitivity Analysis

A sensitivity analysis was performed to determine whether the aircraft program valuation model is robust, within the high and low range of input parameters listed in Table 14. Figure 46 shows that the aircraft program valuation model is most sensitive to the learning curve slope and theoretical first unit cost (TFUC) assumptions. In comparison, the development cost and discount rate assumptions have little impact on the E(NPV) of the new aircraft program.

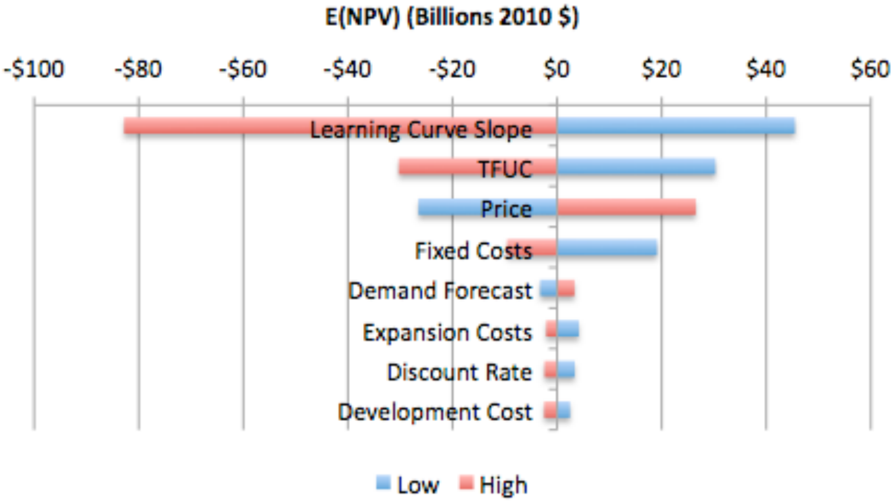


Figure 46. Sensitivity of New Aircraft Program E(NPV) to Changes in Input Assumptions

The rank ordering of the three strategies (i.e. *maintain*, *re-engine*, and *new*), under each market share assumption in Table 11 was tested to determine if changes in the model inputs resulted in a change in the rank ordering of the decisions. Although the estimated value of the aircraft programs changed, the rank ordering of the payoffs did not, assuming a 50% market share.

Next, each high and low input value was tested individually to determine if it would change the outcome of the game, given the market share assumption in Table 11. The only parameters to change the outcome of the game were the low inputs for the learning curve slope and the theoretical first unit cost. By decreasing these values, the new aircraft option had a higher E(NPV), resulting in both players choosing to develop a new aircraft. No other parameters within the range investigated changed the outcome of the two-player game. A learning curve slope of 75% is generally thought to be optimistic, so the sensitivity of the model to this parameter was considered to be acceptable.

The market share assumptions in Table 11 were tested to determine what magnitudes of changes were required to alter the outcome of the game. Each assumption was varied between 50% and 100%, with the reciprocal underperforming aircraft market share assumption varied between 50% and 0%. The outcome of the game was only sensitive to the *re-engine* vs. *maintain* market share assumption. Using the base case input parameters, the outcome of the game remained the same for the range 50% to 77%. It is unlikely that a re-engined aircraft would capture more than 77% of the market when competing against an in-production aircraft.

In general, the model was robust within the range of input parameters examined for the two-player game. The outcome of the game was only significantly changed by extreme input parameters. Therefore, it can be concluded that the aircraft valuation program models the competitive dynamics of the single aisle aircraft duopoly market robustly within the range of parameters indicated.

5.4 Summary

Chapter 5 developed the aircraft program valuation model that is used in Chapter 6 to estimate the rank ordering of payoffs under different market conditions to perform the game theory analysis. The model contains the primary features of an aircraft program (i.e. a research, development, testing, and evaluation investment; a production learning curve; fixed costs of production; production expansion investments; sales price assumptions; market share assumptions) as well as uncertainty of future demand for single aisle aircraft and fuel prices. Base case input parameters were derived from publicly available data sources. High and low estimates of the input parameters were used to test the sensitivity of the model to the input parameters and to demonstrate the range of input assumptions that resulted in the same outcome of the competitive game. The results of the two-player game were robust, providing confidence in the rank ordering of estimated payoffs. An organization with access to more detailed aircraft manufacturer financial data could develop a more detailed aircraft program valuation model and use the game theory analysis methodology in Chapter 6.

CHAPTER 6

6.0 Game Theory Analysis of the Incentives to Innovate

This chapter introduces a game theory framework of analysis to evaluate which factors may incentivize single aisle aircraft manufacturers to innovate. Manufacturers and policy-makers can apply the methodology developed here to improve the objective analysis of product line decisions and emission reduction policies. The aircraft program valuation model developed in Chapter 5 is used to estimate the payoffs for several static and dynamic games under different market scenarios. The static games demonstrate how various factors are likely to affect the outcome of the competitive game while the dynamic games give insight into the timing of the development of a new aircraft. The market scenarios tested were: (i) expectation of low fuel prices, (ii) technology forcing regulations, (iii) manufacturer subsidies, (iv) expectation of high fuel prices, and (v) new market entrants. First, a brief introduction to game theory is provided.

6.1 Game Theory

Von Neumann and Morgenstern founded the field of game theory in their seminal 1944 book *Theory of Games and Economic Behavior*. They were in search of a more effective way of solving certain kinds of economic problems to account for the presence of others who are making decisions in accordance with their own best wishes (Davis, 1997). In a competitive environment, game theory provides a framework to analyze the impacts of competition on players' decisions. Lindstädt and Müller (2009) describe their use of game theory as a technique to support managerial decisions by developing a range of outcomes based on decisions by reasonable actors. In a complex world, there must be a balance between simplifying a problem to make it manageable and retaining enough complexity to make it relevant. Managers must be aware of the assumptions that were used to find a solution, as the final outcome is sensitive to the initial conditions.

A game has two or more players, each of whom are assumed to be rationally self-interested, seeking the highest possible benefit. The key requirements of a game theory analysis are determining: (1) the structure of the game, and (2) the payoffs. The structure of the game is the set of strategies available to each player. A strategy is a player's complete plan of action at each decision point to the end of the game. The payoffs available to each player for each strategy, given the other players' strategies, represent the benefit the player achieves at the completion of the game. Payoffs can be monetary or non-monetary. Time, utility, and happiness may be equally or more important than money. The payoff to use in the game theory analysis is dependent on the assumed objective function of the players. The structure of the single aisle aircraft manufacturer's games analyzed in this chapter was introduced in Chapter 4 while the aircraft program valuation model developed in Chapter 5 is used to estimate the payoffs.

This analysis uses normal form games to determine the outcomes. A normal form game displays the strategies for each player, and the payoffs for each combination of the players' strategies, in a matrix where the first number in each cell represents the payoff for Player A given Player B's strategy, and the second number in each cell represents the payoff for Player B, given Player A's strategy. The maximum number of players in the games analyzed in this chapter are three, but the constraints of a two dimensional page do not limit the possible number of players in a game theory analysis.

The outcome of the game is determined by finding the Nash equilibrium. A Nash equilibrium is the predicted strategy for each player that is the best response to the predicted strategy of all other players (Gibbons, 1992). A dominant strategy has a higher payoff than all other strategies for a player, no matter what strategy the other player selects. In each normal form game presented, the <u>underlined</u> payoffs represent the best strategy for each player, assuming the other players' strategy selection. For example, in Table 17: assuming Player B selects the *maintain* strategy, the set of possible payoffs for Player A is [43, 34, 29]. As 43 is the highest payoff, it is underlined to indicate that if Player B chooses to *maintain*, the best strategy for Player A is to *maintain*. To determine the Nash equilibrium, this logic is repeated for each strategy, for each player. The cell with payoffs for both players underlined represents the Nash equilibrium as neither player can choose a better strategy, given the actions of the other player.

Mixed strategy Nash equilibriums occur when a probability is assigned to each of the competitors' strategies. Mixed strategies can be used to determine unique Nash equilibriums when multiple pure strategy equilibriums exist. Mixed strategies are not incorporated into this analysis, although they provide an interesting extension of complexity that could be incorporated into future work.

The normal form games examined are solved simultaneously. Players are assumed to make their decisions within the same time frame. Although one player may announce their decision before the other, this action could simply indicate a signaling game in which one player attempts to impact the other player's decision. The decision to proceed with an aircraft program is only truly made when significant disincentives to reversing the decision exist (such as a substantial order backlog for the new aircraft, or significant sunk costs in design and engineering work exist).

It is assumed that all players have perfect information enabling competitors to determine each other's payoffs for each strategy set. This assumption may not be entirely true in reality, but the aircraft program valuation sensitivity analysis performed in Chapter 5 demonstrates that the outcome of the two-player game is primarily sensitive to the learning curve assumptions. Therefore, as long as competing players' learning curves are similar in nature, it is reasonable to assume that they are able to estimate competitors' payoffs within the margin of error required to maintain the same outcome of the game.

This is a conceptual analysis in which players are assumed to be symmetric, except for the difference in re-engining investment required by Player A and Player B (as discussed in Chapters 4 and 5). Labeled A, B, and C, the players in the games presented are not meant to reflect real world manufacturers. It is assumed that Players A and B are incumbent manufacturers that have existing single aisle aircraft product lines, while Player C is a new competitor with the strategy set [*Enter*, *Don't Enter*].

Nine games are examined, as summarized in Table 16:

Table 16. Overview of Games Played

Expectation(Fuel Price) indicates the low fuel price (-) or increasing fuel price (+) scenarios.

Games	Players		Type		E(Fuel Price)	
	2	3	Static	Dynamic	-	+
1) Expectation of Low Fuel Prices	x		x		x	
2) Technology Forcing Regulations	x		x		x	
3) Manufacturer Subsidies	x		x		x	
4) Expectation of High Fuel Prices	x		x			x
5) New Entrant, -25% Fuel Intensity		x	x			x
6) New Entrant, -15% Fuel Intensity		x	x			x
7) Two-Player Dynamic Game	x			x		x
8) New Entrant Dynamic Game, -25%		x		x		x
9) New Entrant Dynamic Game, -15%		x		x		x

Game 1 is the base case against which the other games are compared to understand how the scenario examined impacts the outcome of the game. Complexity is built up with each game, providing an understanding of how different factors change the expected outcome of the game. Two- and three-player games were analyzed to understand the impact of new competition on the current duopoly market. Static and dynamic games were used to show how long-term product line strategies might impact decisions made in the present. The expectation of future fuel prices had important impacts on the outcome of the games investigated. The first three games were played under the expectation of low fuel prices, while the remaining games assumed increasing fuel prices.

6.2 Two-Player Static Games

Game 1: Expectation of Low Fuel Prices

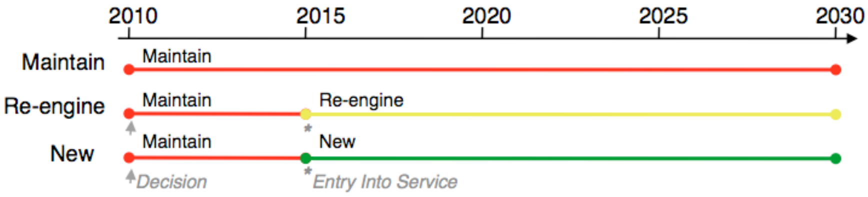


Figure 47. Game 1 Expectation of Low Fuel Prices Decision Timeline

Under the expectation of low fuel prices, incumbent manufacturers are not able to increase the sale price of a new aircraft as fuel cost savings are negligible over the course of the aircraft's life. The incentive to develop a new aircraft is to gain market share from a competitor or to raise entrance barriers to protect against new entrants. Table 17 shows that the status quo is the competitive equilibrium. Both incumbents maintain their current aircraft, reaping large profits while splitting the market. The development of a new aircraft is strictly dominated for both players. This scenario provides a baseline against which scenarios explored in the next sections can be compared to understand their impacts.

Table 17. Game 1 Low Fuel Prices
E(NPV) billions 2010 US$. (Player <A>, <B>)

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	**43, 43**	32, 33	18, 29
	Re-engine	34, 32	25, 24	17, 16
	New	29, 17	16, 15	7, 7

Game 2: Technology Forcing Regulations

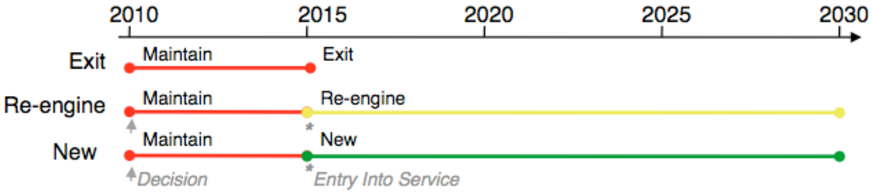


Figure 48. Game 2 Technology Forcing Regulations Decision Timeline

If low fuel prices are expected, a technology forcing regulation could be implemented to obsolete existing aircraft product lines, forcing manufacturers to re-engine or develop a new aircraft. Rutherford and Zeinali (2009) point out that if the standard applied to new aircraft types, grandfathering in existing production lines, the introduction of new aircraft designs may be delayed to avoid triggering the standard. It is assumed here that the regulation would force manufacturers to either *exit* the market, *re-engine*, or develop a *new* aircraft within a five-year time frame (i.e. one stage in the valuation model). Exiting the market would be preceded by a phase-in period in which incumbent manufacturers sell their current product lines while replacements are developed, resulting in a positive exit payoff, as shown in Table 18. The predicted equilibrium is for manufacturers to harvest their existing product lines while making the minimum investment to meet the regulation by re-engining. Incumbent manufacturers would not have an incentive to make the larger investment required to develop a new aircraft in the near-term.

Table 18. Game 2 Technology Forcing Regulations

		Player B		
		Exit	Re-engine	New
Player A	Exit	11, 11	11, 57	11, 39
	Re-engine	59, 11	25, 24	17, 16
	New	39, 11	16, 15	7, 7

In this scenario, the manufacturers' payoffs are reduced by 40% from the low fuel price scenario. This suggests that manufacturers have a significant incentive to lobby against technology forcing regulations that would obsolete their existing product lines unless the regulations yield additional benefits for the incumbents. Games 5 and 6 introduce a new entrant to the market. Increased competition may further erode manufacturer payoffs as the market is split between three competitors instead of two. Although technology-forcing regulations may force incumbents to move, they have the additional effect of raising market entrance barriers by requiring higher technology levels that favor entrenched incumbent manufacturers. Therefore, under the threat of a new market entrant, incumbent manufacturers may use their political power to seek regulations that raise entrance barriers, creating a situation of regulatory capture in which government action protects incumbents at the expense of new competition (Stigler, 1971).

Game 3: Manufacturer Subsidies

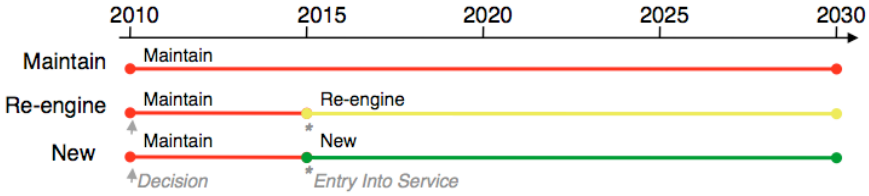


Figure 49. Game 3 Manufacturer Subsidies Decision Timeline

Aircraft manufacturers have traditionally received substantial direct and indirect subsidies. The rationale by governments has been to support their national champion to gain a larger global market share and induce spillover effects in related domestic industries whose value exceed the amount of the subsidy (Krugman, 1987; Busch, 2001). If so inclined, governments would likely provide matching subsidies, preventing their national champion from losing their competitive advantage in the global market.

To incentivize the development of a new aircraft, the payoff for a *new-maintain* strategy must be greater than the payoff for a *maintain-maintain* strategy. Based on our model's assumptions and the expectation of low fuel prices, governments would need to provide new aircraft subsidies on the order of $15 billion to increase the *new-maintain* payoff to shift the competitive equilibrium, as shown by comparison of Table 19 and Table 17.

Table 19. Game 3 Manufacturer Subsidies

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	43, 43	32, 33	18, 44
	Re-engine	34, 32	25, 24	17, 31
	New	44, 17	31, 15	22, 22

Krugman (1987) argues that free trade is the best rule of thumb. Gains from intervention are limited by uncertainty over the correct policies (as the exact payoffs in the real world are uncertain) and by general equilibrium effects (as promoting one sector diverts resources from others). Further, past subsidies have threatened trade wars between the United States and the European Union. Adverse political consequences could outweigh potential gains. Therefore, while subsidies may result in the production of an aircraft with improved fuel efficiency, subsidies could prove to be a potentially dangerous policy option that negatively impacts other sectors of each country's economy through increased trade barriers.

Game 4: Expectation of Increasing Fuel Prices

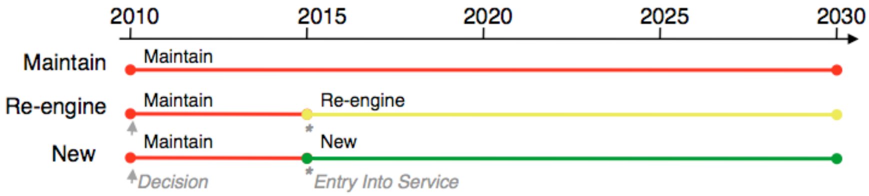


Figure 50. Game 4 Expectation of Increasing Fuel Prices Decision Timeline

Under the expectation of increasing effective fuel prices (due to market forces and/or carbon pricing policies), it is assumed that manufacturers are able to increase the sale price of new aircraft that reduce fuel burn. The expected lifecycle fuel cost savings is split between the airline and manufacturer, as described in Chapter 5. Therefore, a new aircraft program yields increased revenue for the manufacturer, but requires a large capital investment and significant demand to reduce unit costs by working down the production learning curve. If demand does not develop as expected, this can be a risky endeavour. Table 20 demonstrates that the increased revenue from a higher sale price provides the incentive required to shift the equilibrium to a new aircraft for both players.

Table 20. Game 4 Increasing Fuel Prices

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	43, 43	32, 48	17, 60
	Re-engine	50, 32	37, 35	24, 39
	New	60, 17	39, 23	**25, 25**

This game is a Prisoner's Dilemma - each player would be better off maintaining their current aircraft, but each has an incentive to deviate, resulting in reduced payoffs for both. Implicit or explicit collusion between the incumbents could result in both manufacturers maintaining their current aircraft, receiving the highest combined payoffs, but testing airlines' and governments' willingness to accept competitive distortions. Collusion would result in technology levels stagnating, providing an opportunity for new entrants to develop a competitive aircraft that could take market share away from the incumbents, as discussed in the next section. In fact, the manufacturer subsidies examined in Game 3 resulted in a Prisoner's Dilemma as well, but the dilemma was induced by government intervention. Competitive forces induce the dilemma in Game 4.

This scenario assumes a ~20% increase in new aircraft sale prices, resulting in a significant transfer of capital from airlines and leasing companies to manufacturers. Increased capital requirements would be offset by reduced airline operating costs over time, but it is uncertain whether additional capital is available for the airlines. The airline industry is highly competitive and has historically had limited profits. Undercapitalization of airlines could stall the introduction of new aircraft models by manufacturers.

For the remainder of the games examined in this paper, the expectation of increasing fuel costs using the base case values shown in Table 14 were used to calculate the expected aircraft sale price increase over the base price.

6.3 Three-Player Static Games

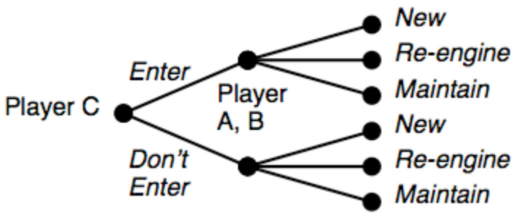


Figure 51. New Entrant Extended Form Game

With a new entrant, the game changes from a single move to two moves, as shown in Figure 51. In the first move, Player C decides whether or not to enter the market. In the second move, the incumbent manufacturers simultaneously choose their best response to the new entrant's strategy. To deter Player C from entering the market, the incumbents could send credible threats of developing a new aircraft that is superior to the new entrant's. Further, the new entrant could send a threat forcing the incumbents to decide their optimal strategy given their perceived probability of a new competitor entering the market. For this analysis, it is assumed that Player A and B decide their optimal strategy given Player C's decision to enter the market. Given this outcome, Player C would decide whether or not to enter. Therefore, if Player C expected a negative E(NPV) given Player A and B's expected response to the new entrant, Player C would decide to not enter the market, returning the game to the two-player games discussed in

Games 1 to 4. Games 5 and 6 demonstrate that the performance of the new entrant's aircraft impacts the outcome of the game. An aircraft with superior performance would capture a greater market share, reducing the incumbents' payoffs further.

Game 5: New Entrant, -25% Fuel Intensity

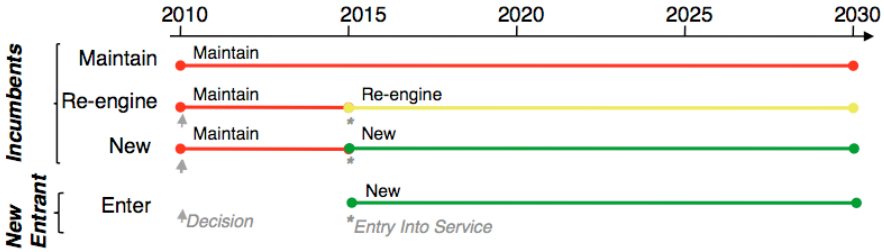


Figure 52. Game 5 New Entrant, -25% Fuel Intensity Decision Timeline

If the new entrant's aircraft has superior performance to the incumbents', the incumbents would expect to lose a significant number of sales, providing them with an incentive to develop a new aircraft. Assuming that sale prices are increased to reflect lifecycle fuel cost savings under the increasing effective fuel price scenario (as in Game 4) and that the new entrant produces a new aircraft that meets the performance of the incumbent's new aircraft option (i.e. a 25% fuel burn improvement), Table 21 shows that an equilibrium may exist in which one incumbent chooses to *maintain* while the other decides to *re-engine*. Although this equilibrium is sensitive to the input parameters in the aircraft program valuation model, the greater investment required by Player B to re-engine results in an off-symmetric equilibrium. The superior performance of the new entrant's aircraft captures a significant market share while Player A attempts to maintain market share by re-engining. Player B's optimal strategy is to avoid the investment and maintain its current aircraft. Once the competitors' new and re-engined aircraft enter service in stage 2, Player B suffers from a greatly reduced market share, but continues to make small profits due to its unit production cost advantage while harvesting its existing product line. The new entrant has a positive expected net present value in each possible outcome, except if both of the incumbents develop a new aircraft. This result suggests that there may be rents available in the single aisle market, providing an incentive for increased competition if new entrants are able to overcome the significant entrance barriers to develop an aircraft that can compete with the incumbents' new aircraft option.

Table 21. Game 5 New Entrant, -25% Fuel Intensity
E(NPV) billions 2010 US$. (Player <A>, <B>, <C>)

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	17.1, 17.1, 29	17.1, 16, 20	17.1, 17.3, 5
	Re-engine	**17.5, 17.1, 20**	17.5, 16, 11	17.5, 13, 1
	New	17.3, 17.1, 5	13, 16, 1	9.5, 9.5, -2.4

Game 6: New Entrant, -15% Fuel Intensity

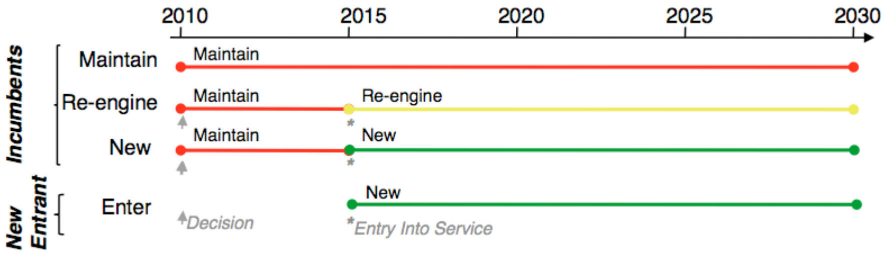


Figure 53. Game 6 New Entrant, -15% Fuel Intensity Decision Timeline

Due to limited design and production experience, a new entrant may not be able to match the incumbents' new aircraft option performance. In Game 6, it is assumed that the new entrant is only able to develop an aircraft that matches the performance of the incumbents' re-engined aircraft (i.e. a 15% fuel burn improvement). A different off-symmetric equilibrium is shown in Table 22. Player B develops a new aircraft to maintain a 50% market share while Players A and C split the remaining market by offering an aircraft with an inferior performance to Player B's.

Table 22. Game 6 New Entrant, -15% Fuel Intensity

		Player B		
		Maintain	Re-engine	New
Player A	Maintain	24.6, 24.6, 11	20.8, 27.4, 3	17.1, 28.8, -5
	Re-engine	29, 20.8, 3	23.7, 22.2, -2	**17.5, 24.2, -8**
	New	28.8, 17.1, -5	24.2, 16.0, -8	15.1, 15.1, -11

The new entrant only receives a positive payoff if neither incumbent develops a new aircraft. This result suggests that a profit-maximizing firm would decide to not enter the market. Therefore, incumbent manufacturers may not be concerned with new entrants unless there is a threat that they could match or exceed the performance of the incumbents' new aircraft option. But, if a new entrant has government support, it may be profitable to enter the market. Further, if the new entrant has a different objective function than the incumbents', other factors may make it beneficial to enter the market, such as spillover effects to other sectors of the economy, national pride, and military capabilities. Therefore, when determining the probability of a new competitor entering the market, additional factors must be taken into account.

The three-player static games have shown how differences in the investment required by incumbent players may result in off-symmetric game equilibriums as well as how new competition in addition to increased expected fuel prices may shift the competitive equilibrium from the duopoly equilibrium in Game 1.

6.4 Two-Player Dynamic Game

If manufacturers consider how their decisions in the present impact future product line decisions, the game can be modeled dynamically where the evolution of demand and fuel prices impacts the equilibrium strategy set. Committing to a *re-engined* or *new* aircraft locks into a technology level for 10 or more years, requires an investment, and can be risky. Delaying the decision provides more flexibility for future actions, but gives competitors an opportunity to develop a superior aircraft. If it is assumed that both incumbent manufacturers will decide to proceed with a new aircraft by the third stage (i.e. 2020-24), a dynamic game (as depicted in Figure 54) can be evaluated to understand the timing of the decision, given the competitive scenarios developed in this section.

Game 7: Two-Player Dynamic Game

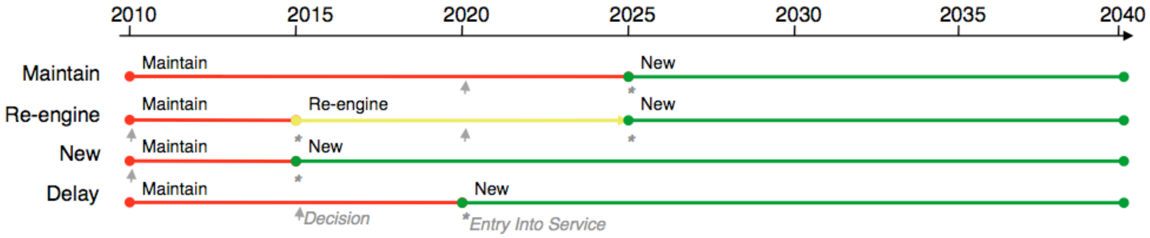


Figure 54. Game 7 Two-Player Dynamic Game Decision Timeline

The dynamic game examined has four stages: 2010-14, 2015-19, 2020-24, and 2025-2039. Incumbent manufacturers are able to select the *maintain, re-engine*, or *new* strategies at each of the first two stages, but are forced to choose *new* in the third. It is assumed that the *re-engine* strategy is a stopgap until a new aircraft enters into service ten years after the re-engined aircraft. This creates a fourth strategy for the incumbents named *delay*. For the delay strategy, the decision to develop a new aircraft is delayed five years to the second stage, for entry into service in the third stage (2020-2024).

The payoff for the *new* strategy was determined for the fourth stage, based on the expected demand and fuel prices. Increased fuel costs enabled manufacturers to increase the sale price of the *new* or *re-engined* aircraft while the existing aircraft sale price was assumed to hold constant in real dollar terms. Technology levels were assumed to improve at the rates shown in Figure 35. Therefore, delaying the decision enabled a superior aircraft to be developed that yielded a higher sale price, assuming the expectation of future fuel prices increased or remained constant. Backwards induction down each possible decision path, with each possible fuel and demand scenario, was used to determine the expected payoffs in present value terms in the normal form game shown in Table 23. The dynamic game demonstrates that delaying the development of a new aircraft to take advantage of improved technology levels and increased sale prices may be the incumbents' optimal strategy.

Table 23. Game 7 Two-Player Dynamic Game

		Player B			
		Maintain	Re-engine	New	Delay
Player A	Maintain	38, 38	30, 39	35, 34	29, 48
	Re-engine	40, 30	31, 30	28, 34	31, 37
	New	34, 35	34, 26	27, 27	33, 31
	Delay	48, 29	37, 30	31, 33	**35, 35**

The two-player dynamic game was repeated for each combination of the high/low fuel price and demand scenarios in Table 14. Higher fuel prices raise the value of fuel burn reduction technologies, enabling manufacturers to increase the sale price of new and re-engined aircraft, while high demand enables manufacturers to work down the production learning curve more rapidly and spread the fixed costs of development across more aircraft. The low states have the opposite effects. It was found that varying demand did not alter the outcomes of the dynamic game, whereas the low fuel price scenarios resulted in both players selecting the maintain strategy. Therefore, as in the static game, the expectation of higher fuel costs drives manufacturers to develop a new aircraft. This is a result of the aircraft program valuation model's greater sensitivity to price than demand, as shown in Figure 46. All dynamic game results displayed were found using the expectation of increasing fuel costs.

6.5 Three-Player Dynamic Games

Game 8: New Entrant Dynamic Game, -25% Fuel Intensity

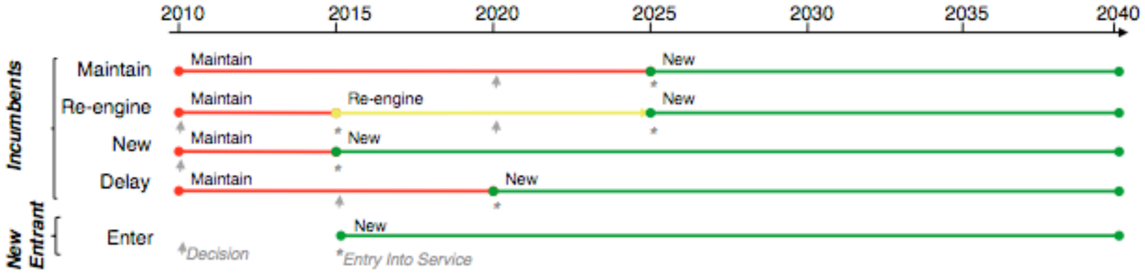


Figure 55. Game 8 New Entrant Dynamic Game, -25% Fuel Intensity Decision Timeline

The dynamic game was played with a new market entrant in the 2015-19 time frame. This analysis enabled the understanding of how new competition – or the credible threat of new competition – may change the game. As in Games 5 and 6, the level of performance of the new entrant's aircraft impacted the outcome of the game. A new entrant's aircraft with the same performance as the incumbents' new option would take significant market share unless the incumbents' decide to move. A new entrant's aircraft that has the same performance as the incumbents' re-engined aircraft would capture less market share.

Table 24 shows that there are two potential pure strategy equilibriums. While the incumbents may find it most profitable to harvest their existing product lines, there is an incentive for one incumbent to develop a new aircraft, but not both. The incumbents play a waiting game, with the first one to move taking the risk of developing a new aircraft along with a higher expected payoff, while the other stands pat with the less risky *maintain* strategy. To determine which manufacturer is likely to move first would require information regarding the incumbent manufacturer's assessment of the probability of a new entrant and the new entrant’s aircraft performance. The manufacturer that believes it is more likely that a new competitor will enter the market with a competitive aircraft will be the first to move, resulting in the late mover delaying the introduction of their new aircraft until the fourth stage (2025-29). The payoffs for the first mover to select the *new* or *delay* strategy are very close, with payoffs that are sensitive to the assumptions of the aircraft program valuation model. Therefore, the timing of the first incumbent’s new aircraft entry into service may be either the second (2015-19) or third stage (2020-24).

Table 24. Game 8 New Entrant 2015 Dynamic Game, -25% Fuel Intensity

		Player B			
		Maintain	Re-engine	New	Delay
Player A	Maintain	16.7, 16.7, 20.6	16.7, 13.7, 13.9	16.7, 19.7, 2.6	**16.7, 19.9, 11.5**
	Re-engine	15.2, 16.7, 13.9	15.2, 13.7, 7.5	15.2, 16.4, -0.4	15.2, 18.3, 6.8
	New	19.7, 16.7, 2.7	16.4, 13.7, -0.4	11.9, 11.9, 0.7	14.8, 15.0, 3.6
	Delay	**19.9, 16.7, 11.5**	18.3, 13.7, 6.8	15.0, 14.8, 3.6	15.0, 15.0, 10.3

Game 9: New Entrant Dynamic Game, -15% Fuel Intensity

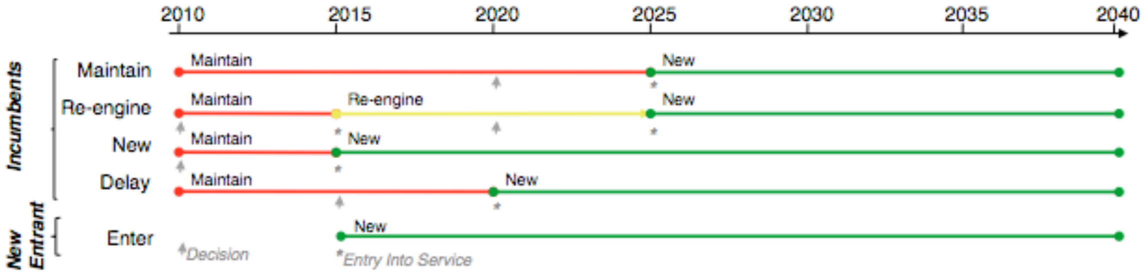


Figure 56. Game 9 New Entrant Dynamic Game, -15% Fuel Intensity Decision Timeline

If a new entrant is expected to develop an aircraft that has the same performance as the incumbents’ re-engined aircraft, the incumbents have an incentive to develop a new aircraft, as shown in Table 25. The Nash equilibrium is predicted to be the case were either Player A or B enters a new aircraft into service in 2015-19 while the other delays until 2020-24. Player C gains less market share than required to have a positive E(NPV), suggesting an early move by one of the incumbents could prevent the new competitor from entering the market. The incumbent that delays entry into service of a new aircraft temporarily loses market share while it produces an aircraft inferior to the new entrant and the other incumbent, regaining market share in the third stage (2020-24) when it introduces a new, superior aircraft. If both incumbents delay the entry into service of a new aircraft, the new entrant is able to capture significant market share in the short term, increasing its payoff, and the likelihood of entry.

Table 25. Game 9 New Entrant 2015 Dynamic Game, -15% Fuel Intensity

		Player B			
		Maintain	Re-engine	New	Delay
Player A	Maintain	22.8, 22.8, 6.1	20.1, 21.9, -0.2	17.5, 28.9, -6.0	20.4, 27.9, 0.2
	Re-engine	23.4, 20.1, -0.2	20.0, 18.5, -4.2	16.0, 25.6, -8.6	19.7, 24.7, -4.5
	New	28.9, 17.5, -6.0	25.6, 14.5, -8.6	19.7, 19.7, -12.3	**24.7, 20.7, -10.1**
	Delay	27.8, 20.4, 0.2	24.7, 18.2, -4.5	**20.7, 24.7, -10.1**	23.6, 23.7, -4.4

The three-player dynamic games are sensitive to the aircraft program valuation model and market share assumptions, but are used here to demonstrate how the credible threat of new competition may lead incumbent manufacturers to select different strategies depending on their own risk tolerance and assessment of the threat of new competition.

6.6 Summary

The static Games 1 to 6 demonstrated the impact of different scenarios on the single-aisle aircraft manufacturer's competitive game. Dynamic decision-based analysis was introduced to combine multiple factors in Games 7 to 9, demonstrating how a game theory analysis of the single aisle aircraft market segment may be used to determine the optimal timing of manufacturer's strategies. Table 26 summarizes the games discussed, showing that while subsidies or expected increasing fuel prices may incentivize the development of new aircraft, consideration of longer-term strategies in the dynamic game may provide incentives for manufacturers to delay the entry of a new aircraft. This may result in superior performing aircraft that enter into service in the next decade, at the cost of increased carbon emissions in the near-term. Kar (2010) showed that early entry into service of available technology (as opposed to delaying entry for more advanced technologies) has greater potential to improve fleet fuel-burn performance due to the dynamics of fleet turnover. Therefore, public policies may be required to incentivize the development of new aircraft.

Table 26. Summary of Game Equilibriums

		Player B			
		Maintain	Re-engine	New	Delay
Player A	Maintain	(1) Low Fuel prices			(8) Dynamic Game (New Entrant, -25%)
	Re-engine	(5) New Entrant, -25% Performance	(2) Technology Forcing Regulations	(6) New Entrant, -15% Performance	
	New			(3) Subsidies (4) High Fuel Prices	(9) Dynamic Game (New Entrant, -15%)
	Delay	(8) Dynamic Game (New Entrant, -25%)		(9) Dynamic Game (New Entrant, -15%)	(7) Dynamic Game (2-player)

Different assumptions in the model may lead to different outcomes. For example, Games 5 and 6 (the static, three-player games) were sensitive to the reduced investment required by Player A to re-engine. Further, the dynamic games were sensitive to the expectation that fuel prices will increase. If fuel prices were to drop, the sale price of a new aircraft with large fuel burn improvements is assumed to decrease, reducing the incentives to develop a new aircraft. This analysis assumed that all players are rational, risk-neutral, profit-maximizing firms. Payoffs for firms with different risk tolerances would be altered, potentially leading to different off-symmetric equilibriums not explored in this analysis. New entrants to the market from China and Russia may have alternative objective functions. Other manufacturers may attempt to maximize market share, minimize costs, or maximize revenues. Softer factors, such as national pride or technical curiosity, may lead players to make seemingly irrational decisions when evaluated in profit maximizing terms. Therefore, although this analysis has demonstrated how a variety of factors and policies may impact the competitive game, it is important for managers and policy makers to understand the assumptions and the limitations of the game theory analysis.

CHAPTER 7

7.0 Conclusions

Effective fuel cost increases due to crude oil market prices and environmental charges may result in air service reductions that have negative economic and social impacts. The 2004-08 fuel price surge was used as a historical case study to further understanding of the short- and medium-term impacts of effective fuel cost increase on the US air transportation system. It was found that non-hub airports serving small communities lost 12% of connections, compared to a system-wide average loss of 2.8%. Increased effective fuel costs will provide incentives for airlines to improve fleet fuel efficiency, reducing the environmental impacts of aviation, but may cause an uneven distribution of social and economic impacts if small communities suffer greater loss of mobility. Government action may be required to determine acceptable levels of access as the system transitions to higher fuel costs.

One long-term hedge against increasing effective fuel costs is efficiency improvements. Aircraft fuel intensity has historically decreased at a rate of 1.2%-2.2% per year, but fleet fuel intensity improvements have stalled during the past decade. To improve aviation's fuel efficiency new single aisle aircraft with higher technology levels will be required. Competition is an important factor to consider when designing policies to reduce aviation's environmental impacts.

This report outlined a framework of analysis for competition in the single-aisle aircraft market segment. Using an aircraft program valuation model and a game theoretic approach, the impacts of market changes on manufacturers' decisions to *maintain*, *re-engine*, or develop *new* aircraft was investigated. It was found that subsidies and higher fuel prices should provide sufficient incentives for incumbent manufacturers to develop new aircraft, but may lead to Prisoner's dilemmas in which manufacturers would be better off not moving from the status quo. New competition in the market segment is likely to trigger innovation as incumbent manufacturers attempt to produce more efficient aircraft that maintain sales in a market with increased competition. Interestingly, it was found that a new entrant's aircraft that offers a fuel efficiency improvement on the order of 15% may incentivize the incumbent manufacturers to develop a new aircraft while a new entrant with a 25% fuel burn improvement may cause incumbents to select a less risky strategy. Dynamic games demonstrated that the incumbents' optimal strategies might be to delay the entry of new single aisle aircraft until 2020-24. As political pressure mounts to take action on climate change and airlines search for ways to reduce operating costs in the face of rising effective fuel costs, delaying may not be acceptable. This situation could result in government intervention to incentivize the development of new aircraft.

A number of further complexities could be explored using the framework developed in this report. It was assumed that competitors act with perfect information. Imperfect information would cast doubt on the technical capabilities of competitors' aircraft(s) as well as financial payoffs. Incumbent manufacturers could collude either implicitly or explicitly to select the strategy that yields the highest total payoff with least risk. The riskiness of new aircraft programs was not incorporated into this analysis. Risk-averse or risk-seeking players may change the outcome of the games or result in unique Nash equilibriums in the three-player dynamic games examined. Further, it was assumed that all manufacturers have the same objective function – to maximize expected net present value of a program. But aircraft manufacturing has spill over effects that impact other sectors of a nation's economy, providing incentives for governments to subsidize new aircraft programs that may otherwise not be profit maximizing.

This work is an initial step in using game theory to understand the impacts of competition, market conditions, and technological progress on large commercial aircraft manufacturer decisions. A number of simplifying assumptions have been made in the models presented to facilitate the analysis of a problem that quickly scales in complexity. To tackle this problem in a more holistic manner, a multidisciplinary approach should be implemented in which the technical and financial implications of strategic options are integrated into the decision making process. The question of what level of performance to design into the next generation aircraft has a continuous solution set, not the three-pronged strategy set used in this work. The technical risk of increasing performance of a new aircraft impacts the financial risk of the program, while external market conditions outside of the control of managers will ultimately determine the success of a new program. Therefore, manufacturers and policy makers will require more complex and integrated tools to understand the implications of their decisions and to tackle aviation's environmental challenges.

The application of game theory to management problems is still a nascent field. Game theory provides a simple, yet powerful tool to insert objective, competitive analysis into the decision making process. The decision analysis methodology developed in this report could be generalized to other applications and fields, such as: semiconductor fabrication plant investment decisions, automobile product line decisions, and airline fleet planning decisions. Investment decisions made by agents in a competitive environment could benefit from a game theory analysis to determine their best strategy, given their competitors' likely response.

While aircraft efficiency improvements will reduce airline operating costs, it is uncertain whether reductions in air service would be mitigated. Further, to meet environmental goals, efficiency may not be enough. Herring (2006) challenges the idea that improving the efficiency of energy use will lead to a reduction in energy consumption. Energy efficiency lowers the implicit price of energy, potentially leading to greater use. As a greater share of the world's population gains access to affordable air transportation in developing countries, aviation's environmental externalities will continue to grow. To face the world's climate change challenge without limiting the economic enabling effects of air transportation by suppressing demand, aircraft technology will need to be improved. The incentives for manufacturers to stand still will need to be overcome.

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APPENDIX

9.0 Airline Classification

Although it is expected that carriers within the same classification vary significantly in their businesses, markets, and operations, airlines were classified to simplify the presentation of data. The following categories were used to group airlines with similar business models, based on common practices found in the literature and the author's discretion. The top two US airlines in each category, by July 2007 available seat miles (ASM), are listed:

- ***Network Legacy Carrier (NLC)*** – airlines that flew interstate routes prior to deregulation in 1978, have international operations, and are certified under Part 121 of Title 14 of the Code of Federal Regulations, including American Airlines and United Air Lines.
- ***Low Cost Carrier (LCC)*** – airlines that have a stated low fare business model, and are certified under Part 121 of Title 14 of the Code of Federal Regulations, including Southwest Airlines and JetBlue Airways.
- ***Regional*** – feeder, charter, and commuter airlines that fly aircraft less than 100 seats, and are certified under Part 121 of Title 14 of the Code of Federal Regulations, including Skywest Airlines and Expressjet Airlines.
- ***Commuter*** – commuter and on demand airlines that are certified under Part 135 of Title 14 of the Code of Federal Regulations, including Hageland Aviation Service and Boston-Maine Airways.