Dynamics of Implementation of Mitigating Measures to Reduce CO_2 Emissions from Commercial Aviation

by

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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
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June 2010

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ABSTRACT

Increasing demand for air transportation and growing environmental concerns motivate the need to implement measures to reduce CO_2 emissions from aviation. Case studies of historical changes in the aviation industry have shown that the implementation of changes generally followed S-curves with relatively long time–constants. This research analyzed the diffusion characteristics of a portfolio of CO_2 emission mitigating measures and their relative contribution to cumulative system wide improvements. A literature review identified 41 unique measures, including (1) technological improvements, (2) operational improvements, and (3) the use of alternative fuels. It was found that several operational changes can be implemented in the short term but are unlikely to significantly reduce CO_2 emissions. Technology retrofits and some operational changes can be implemented in the medium term. 2nd and 3rd generation biofuels can significantly reduce carbon emissions but are likely to have long diffusion times and may not be available in sufficient quantities to the aviation industry. Technology measures in the form of next generation aircraft have the highest CO_2 reduction potential, but only in the long term due to slow fleet turnover.

An Aircraft Diffusion Dynamic Model (ADDM) was developed using System Dynamics modeling techniques to understand how the fleet efficiency will be influenced by the entry of various generations of aircraft with different levels of emissions performance. The model was used to evaluate effects of several future potential scenarios on the US narrow body jet fleet as well as their sensitivity to S-curve parameters.

Results from the model showed that strategies that emphasize the early entry into service of available technology, as opposed to waiting and delaying entry for more fuel-efficient technology, have greater potential to improve fleet fuel-burn performance. Also, strategies that incentivize early retirement of older aircraft have marginal potential for reducing fuel burn.

Future demand scenarios showed that the infusion of fuel-efficient aircraft alone is unlikely to reduce emissions below 2006 levels. Instead, a portfolio of measures that also include demand reduction mechanisms, operational improvements, and adoption of alternative fuels will be required in order to limit the growth of CO_2 emissions from aviation.

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ACKNOWLEDGEMENTS

I would like to thank Professor Hansman for giving me the opportunity to work on this research and for his valuable directions. Philippe Bonnefoy has been outstanding in guiding this effort and I am grateful for his insight and suggestions. Professor Sgouridis at the Masdar Institute was very helpful with his advice and encouragement. Jim Hileman and Tom Reynolds at the PARTNER-ICAT laboratory were tremendous resources for me to tap into and they were always very accommodating. A shout out to my peers at the laboratory – specially, Jim Morrison for going through my thesis and suggesting edits. Special thanks to all my wonderful friends at the Technology and Policy Program – particularly Sydney Miller who is simply the most fabulous person I have ever met. Thank you so much for your support.

Coming to MIT would not have been possible without the unfailing encouragement and love of my parents. This thesis is dedicated to their sacrifices. Shilpa has been amazingly patient with me while this thesis took shape. Special thanks to her for putting up with me over the past few months.

I would like to acknowledge Simon Pickup, Director, Business Operations, Airbus Americas, for providing Airbus aircraft orders and deliveries data that was used to calibrate the Aircraft Diffusion Dynamic Model.

This work was supported by the MIT/Masdar Institute of Science and Technology under grant number Mubadala Development Co. Agreement 12/1/06.

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ACRONYMS & ABBREVIATIONS

Acronyms		Description
ACI	:	Airport Council International
ADDM	:	Aircraft Diffusion Dynamic Model
ASK	:	Available Seat Kilometer
ASM	:	Available Seat Mile
ATA	:	Air Transport Association
ATC	:	Air Traffic Control
ATM	:	Air Traffic Management
BTS	:	Bureau of Transportation Statistics (United States)
BCA	:	Boeing Commercial Aircraft
CDA	:	Continuous Descent Approach
DOT	:	Department of Transportation (United States)
ESD	:	Engineering Systems Division (MIT)
EIS	:	Entry Into Service
EU ETS	:	European Union Emissions Trading Scheme
ETOPS	:	Extended-range Twin-engine Operational Performance Standards
FAA	:	Federal Aviation Administration
FT	:	Fischer Tropsch process
GAO	:	Government Accountability Office (United States)
GDP	:	Gross Domestic Product
GHG	:	Green House Gas (es)
GIACC	:	Group on International Aviation and Climate Change
GTF	:	Geared Turbo Fan
HLFC	:	Hybrid Laminar Flow Control
HBPR	:	High By Pass Ratio Engines
HRJ	:	Hydrogenated Renewable Jet
IATA	:	International Air Transport Association
ICAO	:	International Civil Aviation Organization
JPDO	:	Joint Planning and Development Office
NAS	:	National Airspace System
NASA	:	National Aeronautics and Space Administration
NB	:	Narrow Body (Jet)
NextGen	:	Next Generation Air Transportation System (U.S. Initiative)
OEP	:	Operational Evolution Plan
PW	:	Pratt and Whitney
RJ	:	Regional Jet
RPK	:	Revenue Passenger Kilometer
RVSM	:	Reduced Vertical Separation Minimum
SD	:	System Dynamics

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Challenge of Reducing Emissions while Meeting Growing Demand for Air Transportation

Air transportation has been, and remains, a key enabler to economic growth and development by providing fast and reliable access to people and markets. Worldwide increase in economic activity during the last few decades has resulted in significant rise of demand for commercial aviation. As shown in Figure 1, the two largest markets in terms of passenger traffic, North America and Europe have grown at an average annual rate of 5.7% and 5.0% respectively over the last 20 years. Asia-Pacific has also exhibited significant growth at 8.8% average annual growth rate. This market is now reaching passenger traffic levels comparable to the European market. More recently, impressive growth of traffic has been observed in the Middle East that exhibited an average annual growth rate of 13% per year, between 2000 to 2007.

Disregarding the recent economic downturn in 2008 and 2009, the global aviation industry has grown between 4.5% and 5% annually since 1990[1]. Numerous forecasts estimate that similar rates of growth are likely to prevail in the next decades (BCA 2008).

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[1]Data source: International Civil Aviation Organization (ICAO), Civil Aviation Statistics of the World, ICAO Statistical Yearbook, ICAO, Table 1-16 (1986 to1987), Table 1-13 (1998 to 1999), Annual Review of Civil Aviation 2001, 2002, 2003, ICAO Journal, vol. 57 No.6 2002, vol. 58, No. 6 2003, vol. 59, No. 6 2004, vol. 60, No. 6 2005, vol. 61 No. 6 2006 and International Air Transport Association (IATA) data for years 2005 to 2007.

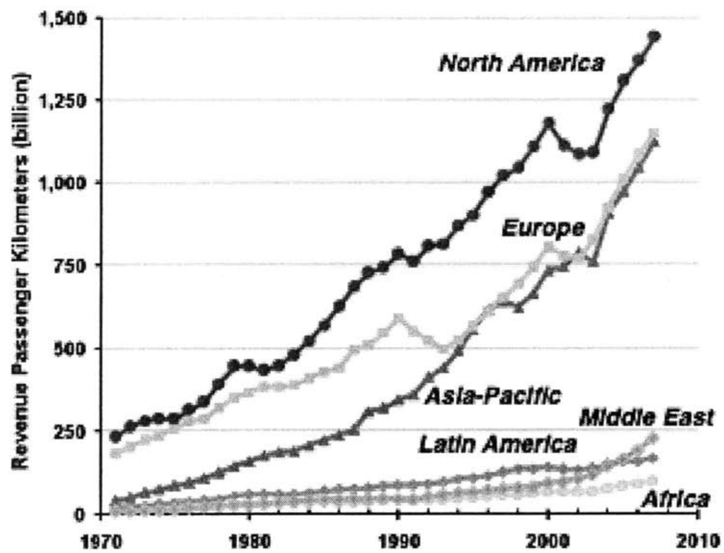

Figure 1: Passenger traffic growth (RPK) worldwide from 1971 to 2007
(Data sources: ICAO (1970-2000), IATA (2001, 2007), Courtesy of Bonnefoy P.)

While demand was growing at a rate of approximately 4-5% every year, fuel efficiency improvements ranged from 1.2 to 2.2% annually (BTS 2008). This rate of improvement was not sufficient to compensate for demand growth and resulted in a net increase in fuel burn (Figure 2).

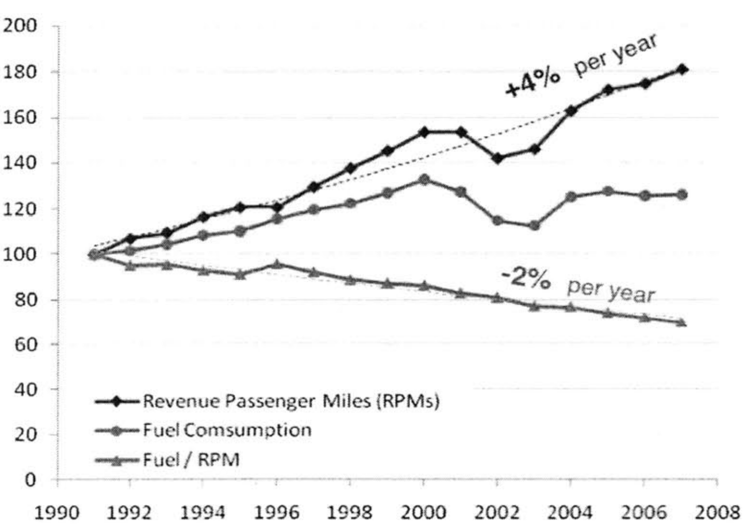

Figure 2: Historical evolution of fuel consumption in the United States
(Data sources: DOT BTS T2 U.S. Air Carrier Traffic and Capacity Statistics by Aircraft Type, Courtesy of Bonnefoy P.)

It is therefore expected that with growing demand and marginal improvements in fuel efficiency, aviation's contribution to anthropogenic greenhouse gas emissions will increase in the future. The International Civil Aviation Organization (ICAO) recently forecast that global CO_2 emissions from aviation would increase an additional 150% above 2006 levels by 2036 (ICAO 2009). At this rate, emissions would quadruple by 2050.

Future increases in net emissions are likely to reinforce public and political pressure on the aviation sector to reduce its greenhouse gas emissions (IATA 2009a)(DECC 2009).

Emissions Reduction Goals & Challenges

In order to reduce the adverse effects on climate change from aviation induced emissions, governments and international agencies have set goals for future emissions reduction. Figure 3 shows long-term emission trends, forecasts and targets for the aviation industry. It should be noted that these targets are aspirational and non-binding.

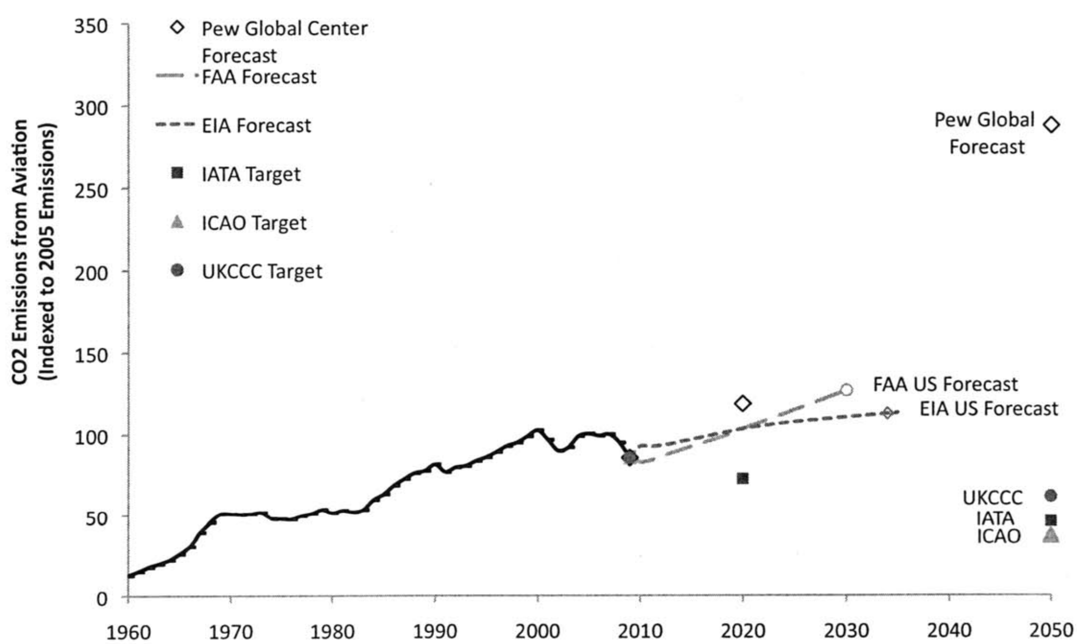

Figure 3: Long term targets for CO_2 emissions from Aviation.
Data sources: (IATA 2009b), (Flint 2009), (UKCCC 2009), (McCollum D. 2009) (FAA 2009)(ATA 2010)

Targets for the Industry:

Targets for 2020:

1. The International Airline Industry Association (IATA) aims at achieving carbon neutral growth of aviation in the medium term. It has set the following broad aspirational goals (endorsed by the ATA) for the aviation sector (IATA 2009b):

- A cap on aviation CO_2 emissions from 2020 (carbon-neutral growth)
- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020

2. The International Civil Aviation Organization (ICAO) has adopted a target of a "global annual average fuel efficiency improvement of 2%" for the airline industry through 2020.

Targets for 2050:

1. IATA has a set a target reduction in CO_2 emissions of 50% by 2050, relative to 2005 levels.

2. The ICAO has set "an aspirational global fuel efficiency improvement rate of 2% per annum in the long term from 2021 to 2050, calculated on the basis of volume of fuel used per RTK performed (Flint 2009).

3. A report by the UK Committee on Climate Change (UKCCC 2009) estimates fuel efficiency improvements of 0.8% under current technology trends and a subsequent reduction of carbon intensity of 30% by 2050.

Targets for Aviation Alternative Fuels:

Targets for 2020:

1. The IATA has set separate goals for alternative fuels – 10% usage by 2017 and assumes a 6% mix of second-generation biofuels (80% lower life cycle carbon intensity) by 2020.

Targets for 2050:

1. The UKCCC research claims that biofuels will only account for at most 10% of global aviation fuel consumption by 2050 because of land availability and sustainability issues.

Industry Forecasts:

Figure 3 shows these goals along with the emissions forecasts based on current trends and potential improvements. The contrast between the goals and the forecast (e.g. Pew Center for Global Climate Change estimates emissions increase by 300% by 2050) compared to ICAO goals of 60% reduction) highlights the challenges of meeting these goals.

The 'wedge' between projected and aspirational emissions will most likely require the use of aggressive solutions to reduce aviation's emissions.

Levers for Reducing Emissions

From first principles, carbon dioxide (CO_2) emissions are proportional to aircraft fuel burn. For every kilogram of jet fuel burnt, 3.15 kg of CO_2 are emitted. As shown in the modified and expanded Breguet range equation (adapted from (Lee, et al. 2001), the fuel consumption of an aircraft is a function of its weight, engine efficiency (i.e. specific fuel consumption) and aerodynamic efficiency (i.e. lift-to-drag ratio) for a specified range and speed.

$$Total\ CO_2\ Emissions = \overbrace{\sum_{all\ fuel\ types} \left(\frac{CO_2}{Fuel\ Weight}\right)_i}^{\textbf{CO}_2\ \textbf{Content in Fuel Type } i} * \overbrace{\left[\sum_{all\ flights\ using\ fuel\ type_i} (\underbrace{W_{empty}}_{\text{Empty Mass}} + \underbrace{W_{payload}}_{\text{Payload Mass}}) \cdot \{ e^{(\frac{R}{V} \cdot SFC \cdot \frac{D}{L})} - 1 \} \right]}^{\textbf{Total Fuel of Type } i \textbf{ Consumed}}$$

$$\underbrace{Pax}_{\substack{\text{Passenger Traffic} \\ \text{\{Demand\}}}} \cdot \underbrace{\frac{Avail\ seats}{Pax}}_{\substack{\text{Average Load} \\ \text{Factor}}} \cdot \underbrace{\frac{n_{flights}}{Avail\ seats}}_{\substack{\text{Fleet Mix} \\ \text{\{Aircraft Size\}}}}$$

$$\underbrace{\frac{R}{V}}_{\substack{\text{Range and} \\ \text{Speed}}} \quad \underbrace{SFC}_{\substack{\text{Sp. Fuel Consumption} \\ \text{\{Propulsion\}}}} \quad \underbrace{\frac{D}{L}}_{\substack{\text{Drag/Lift} \\ \text{\{Aerodynamics\}}}}$$

Equation 1

Equation 1 illustrates that there are several levers to reduce CO_2 emissions assuming constant demand[1] by:

- reducing *CO_2 content of fuel* by adopting alternative fuels with lower life-cycle carbon content per unit of fuel,

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[1] This research excludes the discussion of mitigation of emissions through demand since to first order emissions scale with demand. In addition, some airline business practices were not included because they do not follow S-curve dynamics. This includes for example increasing aircraft load factor which also has limited potential for mitigation -at least in the United States. Load factors have been approaching high levels (i.e. 80%) in recent years.

- reducing *Aircraft weight*, through a reduction in empty weight and payload,
- improving *Engine efficiency* by reducing the specific fuel consumption,
- improving *Aerodynamics* by increasing the lift to drag ratio,
- increasing *Average Load Factor*,
- changing *Fleet mix* by using larger more fuel efficient aircraft
- changing *Flight distance* by modifying network topology,
- changing *Cruise speed* by flying at speeds that minimize fuel burn (e.g. 'Maximum Range Cruise' speed).

These levers can be grouped into 3 general areas of improvements, which will be used as reference for the remainder of this study:

(1) Technology (i.e. *Aircraft weight, Engine efficiency, Aerodynamics)*

(2) Operations (i.e. *Aircraft weight, load factor, fleet mix, flight distance, speed)*

(3) The use of Alternative fuels (i.e. *CO_2 content of fuel)*

Challenges with the Implementation of Changes in the Air Transportation System

The previous sections motivated the need for the aviation industry to make significant improvements in fleet wide fuel burn efficiency and reductions in net emissions. While mitigation measures may be available for reducing emissions, it is expected that actual benefits from these measures will not be instantaneous due to the long diffusion time into the system.

Figure 4 illustrates the diffusion of the first generation jet aircraft into the aviation industry in the 1960s and early 1970s. Even though the technology was disruptive in terms of its performance and capabilities compared to previous generations of products (i.e. piston powered aircraft), it took 15 years for jet aircraft to account for 80% of the total aircraft fleet in the United States.

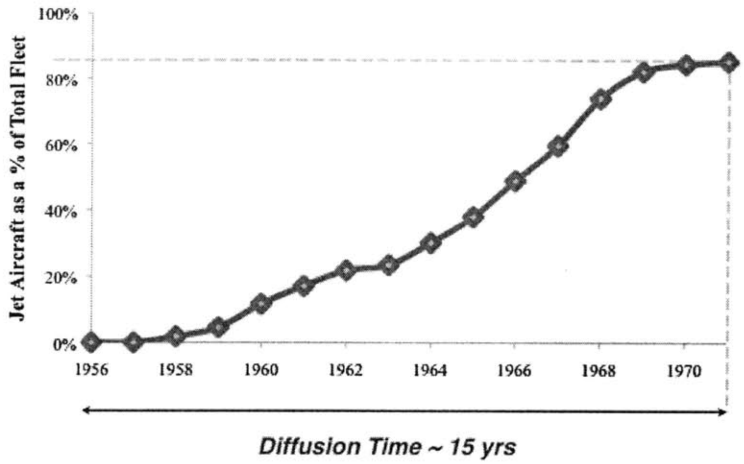

Figure 4: Diffusion of early jets into the airline fleet took 15 years
(Data source: ATA Annual Reports 1958-1980)

It is expected that mitigating measures to reduce emissions from aviation (e.g. technologies, operational improvements and alternative fuels) are also expected to follow S-curve type diffusion dynamics and that changes are not going to be instantaneous. Chapter 3 provides additional and more detailed cases supporting these expectations.

Summary

This chapter showed that rising demand for air transportation in the future and the slower rates of improvement in fuel efficiency would result in net increase in emissions and eventually pressure on the industry to reduce its carbon footprint. It is necessary to implement mitigating measures to meet the emissions reduction goals. The modified Breguet range equation has established three key areas of improvement - technology, operations and alternative fuels that can reduce carbon emissions. The adoption of mitigating measures within these three categories will most likely follow S-curve type adoption dynamics with benefits that will accrue over a long time period.

CHAPTER 2

RESEARCH APPROACH

2.1 Hypothesis and Research Questions

Changes and the diffusion of technology, procedures, and practices in the airline industry have generally followed S-curve type dynamics. This type of dynamic is characterized by, first, a slow growth rate, followed by a period of rapid diffusion and, finally, declining growth once a system saturation point is reached. It is expected that future mitigating measures that have the potential to reduce emissions from aviation are likely to exhibit similar dynamics and that the full benefits will only be realized over a long time horizon. Among the broad set of options to reduce CO_2 emission, some may provide significant benefits but require a very long time to diffuse. Others may provide short-term solutions but with very negligible impacts on the system.

This thesis aims at answering the following questions:

(1) What are the mitigating measures available to the aviation industry to reduce CO_2 emissions?

(2) What are the measures that will have the highest impact toward reducing the carbon footprint of aviation in the short, medium and long term?

(3) What are the adoption dynamics of these mitigating measures?

(4) What are the tradeoffs between a) time of entry of mitigating measures, b) time of diffusion and c) potential for CO_2 emission reduction?

2.2 Research Approach

This research follows a five-step process to identify and categorize mitigating measures and to investigate the dynamics that govern their implementation and diffusion (see Figure 5).

The research first reviews examples of past changes in the aviation industry to understand historical patterns of diffusion. Cases of technology adoption (e.g. introduction of early jet engines), operational changes (e.g. implementation of reduced vertical separation minimum) and uptake of alternative fuels in the automobile industry (as a proxy for dynamics that may be encountered in the airline industry) are analyzed.

Second, a framework to characterize the mitigating measures is developed. This framework includes a) the modified Breguet range equation to identify the measures and b) the *Bass Diffusion* model to capture the key parameters that characterize the impacts of individual mitigating measures on emissions reduction; namely the development time (or start date of diffusion), the diffusion time constant and the CO_2 reduction potential after full adoption.

Third, a literature review is conducted using the framework to develop a broad portfolio in the three key areas of mitigating measures that the aviation industry can consider to reduce its carbon footprint.

Fourth, a bottom-up model is constructed based on the portfolio of measures to estimate the CO_2 reduction from each of the three key areas of improvement – technology, operations and alternative fuels.

Finally, a system dynamic model of aircraft fleet turnover is developed to study the diffusion of next generation of fuel-efficient aircraft into the industry. The model is used to conduct scenario analyses and trade-off studies that investigate the effects of future S-curve dynamics in terms of: (1) time of entry into service, (2) potential fuel efficiency improvements and (3) diffusion time on the fleet wide fuel burn performance.

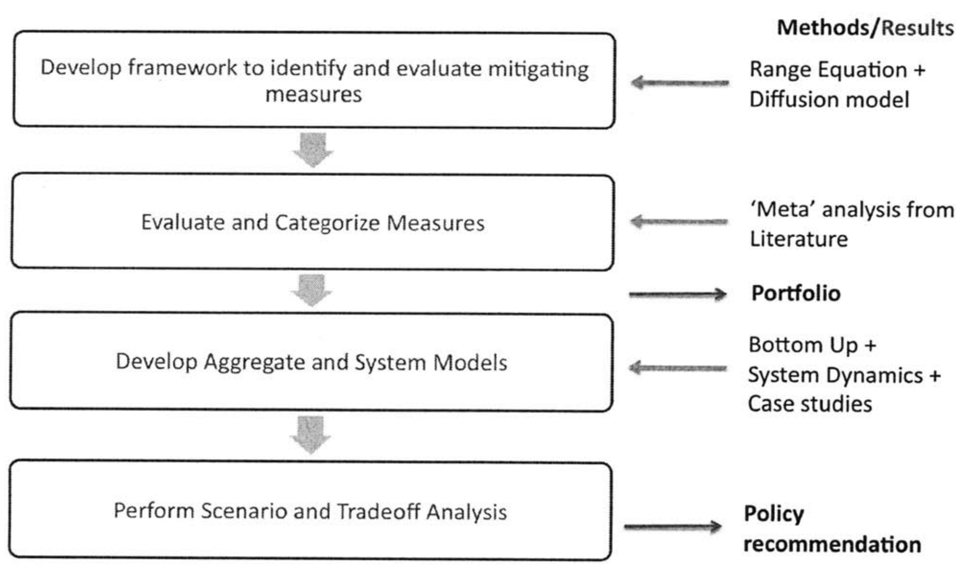

Figure 5: Schematic of the Research Approach

CHAPTER 3

BACKGROUND

3.1 Aviation Emissions and the Environment

Aircraft emit a wide variety of chemical species including greenhouse gases (Figure 6). Majority of these emissions occur in the upper troposphere and the lower stratosphere. (5 miles and upward). The effect of the specimens on radiative forcing (i.e. difference in incoming and outgoing energy in a given climate system) are expected to negatively affect the climate and the effect is approximately double (J. Lee 2005) that due to burning the same fuels at ground level.

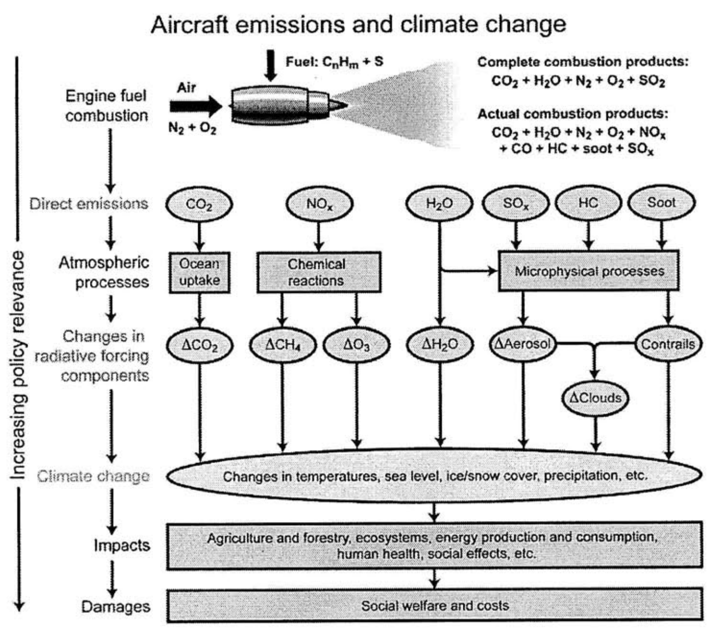

Figure 6: Schematic showing aviation's impact on the environment
(Source: Lee et al, 2009)

According to the Intergovernmental Panel on Climate Change (IPCC) Working Group Three (WGIII), aviation's contribution to total anthropogenic radiative forcing (RF) was 3% in 2005. Figure 7 puts this in perspective with emissions from other anthropogenic activities – power generation industry, road transportation, residential and commercial buildings that use fuel and power etc. The Environmental Protection Agency

(EPA 2009a) reported that all U.S. aviation (international and domestic commercial fuel, general and military aviation) was responsible for 3.4%[1] of total U.S. CO_2 emissions.

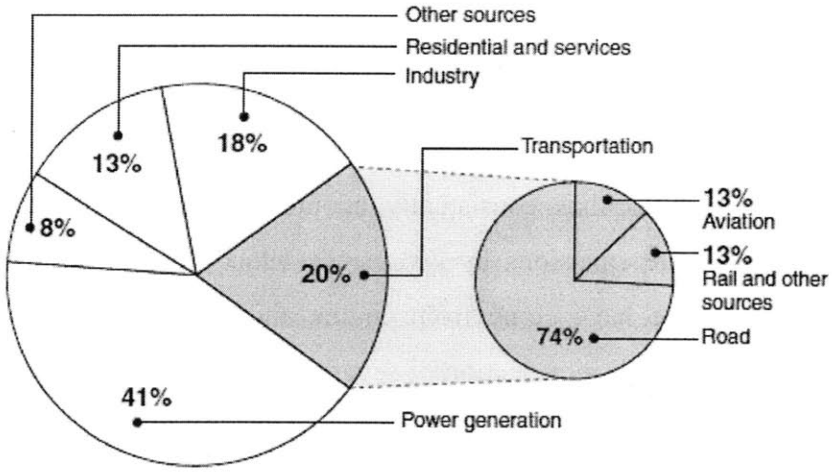

Figure 7: Global Transportation's and Global Aviation's Contributions to Carbon Dioxide Emissions
Source: (GAO 2009)

In December 2009, the EPA declared that increase in greenhouse gases (GHGs[2]) in the atmosphere was the primary driver of climate change (EPA 2009b). i.e. "threaten the public health and welfare of current and future generations". The evidence of anthropogenic climate change is not limited to increase in average surface temperatures but *"includes melting ice in the Arctic, melting glaciers around the world, increasing ocean temperatures, rising sea levels, acidification of the oceans due to excess carbon dioxide, changing precipitation patterns, and changing patterns of ecosystems and wildlife"*(EPA 2009b).

Aviation's contribution to the net climate change problem is not fully understood. For example, there are large uncertainties involved regarding the effects of contrails and aviation induced cloud formation (AIC) that can multiply the contribution of aviation to climate change (David S. Lee 2009). Sulfate aerosols on the other hand may have a cooling effect by reacting with methane and reducing the global warming potential of

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[1] As per the UNFCCC's reporting guidelines, international bunker fuels are reported seperately and not included in the domestic greenhouse gas inventory

[2] The EPA identifies carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) as GHGs. Source: EPA, *Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act*, December 7, 2009, (URL: www.epa.gov, accessed March 24, 2010).

CH_4. Never the less, the aviation industry is under political and public pressure to reduce its emissions footprint.

3.2 Literature Review on Reducing Emissions from Aviation

Historical Trends

The aviation sector has consistently adopted fuel efficiency measures that have lowered system wide emissions by 70% since 1960 (Penner, et al. 1999). The trends reported in literature have come from engine and/or airframe improvements and the period has witnessed the introduction of several disruptive technologies – introduction of jet engines to replace piston engines, introduction of high by pass ratio turbofan jet engines, the introduction of large aircraft such as the Boeing 747 and the introduction of twin engine long range aircraft after ETOPS[1]. Lee (Lee, et al. 2001) and Peeters (Peeters P.M. 2005) have reported efficiency improvements of 64% and 55% over the same time period (1965-2000).

Future Trends

Table 1 summarizes the goals and forecasts for potential emissions reduction in the future. Literature sources consistently report maximum benefits (-20% to -50%) from technological improvements – new airframe and engines, in the long term. Operational improvements till 2020 are reported between -5 to -15% in the medium term.

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[1] ETOPS = Extended-range Twin-engine Operational Performance Standards

Table 1: Summary of goals and forecasts from literature review

Area of Improvement	Reference	Goals	Forecasts	Time Period	Description
Technology - New aircraft	(IPCC 1999)	-20%		by 2015	aircraft
		-40 to -50%		by 2050	
Technology - New aircraft	(J. Lee 2005)		-1.2 to -2%/yr	by 2025	
Technology - New aircraft	(Farries and Eyers 2008)		-20 to -25%	2025 onwards	
Technology - New engines	(Farries and Eyers 2008)		-10 to -15%	2025 onwards	
Technology - New aircraft	(IATA 2009c)		-25 to -35%	by 2020	
Technology - New aircraft	(IATA 2009c)		-25 to -50%	2020 onwards	
Operations- ATM	(IPCC 1999)		-8-18%	by 2020	
Operations	(Farries and Eyers 2008)		-10 to -15%	by 2025	Upto -25% with radical changes
Operations - CNS/ATM	(Schäfer, et al. 2009)		-5 to -10%	Medium term	
Alternative Fuel	(IATA 2009c)	-80%			
Retirement	(IATA 2009c)		-21%	by 2020	

While IATA claims a 80% reduction from the adoption of alternative fuels, a report by The Pew Center (McCollum D. 2009) is circumspect about the impacts of alternative fuels in the short or medium term and finds that the only feasible options for "drop-in" replacements to petroleum-based jet fuels are hydroprocessed renewable jet fuel (HRJ) and Fischer-Tropsch (FT) fuels. While most literature sources comment on the possibility of increased aviation activity because of increased capacity from ATM improvements, no scientific study has been conducted to quantify such second-order feedbacks.

CHAPTER 4

HISTORICAL EXAMPLES OF PAST CHANGES IN THE AVIATION INDUSTRY

Historically, most transitions in the commercial aviation industry have exhibited S-curve dynamics with long time constants of diffusion. The implementation of mitigating measures to reduce the carbon footprint of aviation is also expected to show similar diffusion trends.

This chapter studies past diffusion trends of technological and operational changes within the aviation industry. In addition, it presents the case of diffusion of ethanol in the United States and Brazil. Large-scale transition to alternative fuels has been absent in the aviation industry and the study of adoption of an alternative fuel by the automobile industry can provide valuable insights into some of the dynamics that the aviation industry could experience.

Table 2 shows the list of cases that were studied to understand the patterns of diffusion in the industry.

Table 2: List of case studies of past changes in the aviation industry

Case Number	Case Name	Case Type	System Impact
Tech Case I	Jet Aircraft in the 1960s	Technology Diffusion	New aircraft fleet
Tech Case II	Regional Jets	Technology Diffusion	New aircraft fleet
Tech Case III	Blended Winglets	Technology Diffusion	Aircraft retrofit
Ops Case I	E-tickets	Operational Diffusion	Airlines
Ops Case II	Reduced Vertical Seperation Minimum	Operational Diffusion	Air traffic management
Alt. Fuels Case I&II	Ethanol in the US and Brazil	Alt. Fuels Diffusion	Fuels

Methodology for Selecting Cases

Cases were chosen within each of the three categories of improvements i.e. technology (new aircraft types and retrofit solutions), operations and alternative fuels.

Within the set of technology cases, the adoption of jet aircraft in the 1960s was chosen to represent a paradigm shift in aircraft technology in the industry. The case of regional jets was used to investigate the dynamics of diffusion of a more recent (1990s) aircraft type. The adoption of blended winglets illustrates the case of a component technology that can diffuse with new aircraft and as a retrofit option.

Within the set of operational examples, the implementation of RVSM is illustrative of a system wide change. The implementation of e-tickets represents as a solution that improves the operational efficiency by reducing cost.

The case of adoption of ethanol in Brazil and in the US presents a comparison of two markets where diffusion of an alternative fuel followed different rates of uptake because of government policies.

For each case study, time series data of a representative metric was collected. For example, for early jet aircraft, the fraction of aircraft that were powered by jet engines as compared to the overall fleet was estimated from fleet data available from airline industry reports. Key enablers and barriers that influenced the rate of adoption of each measure were also evaluated for this study.

4.1 Patterns of Aircraft Technology Diffusion

Tech Case I: Diffusion of First Generation of Jet Aircraft in the 1960s and 1970s

The adoption of the first generation of jet aircraft demonstrated S-curve growth and despite their advantages took a long time to diffuse into the fleet. Figure 8 shows that it took 15 years to achieve approximately 80% fleet penetration by jet powered aircraft.

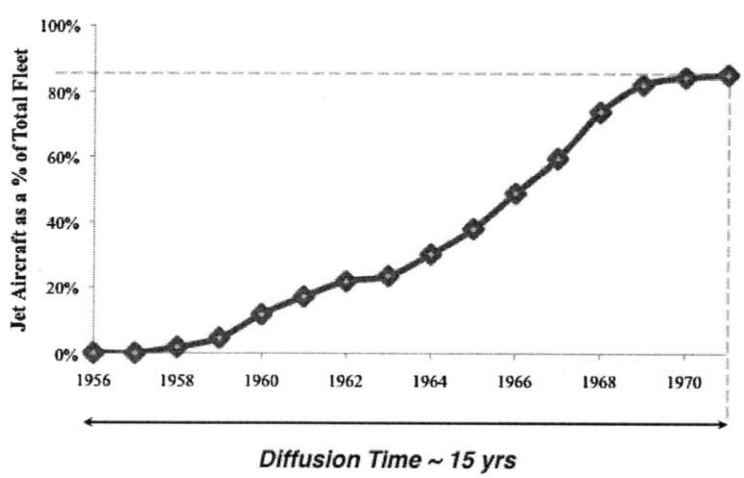

Figure 8: Diffusion of Jet Aircraft into the U.S. Fleet
(Data: ATA Annual Reports 1957 to 1972)

The entry and adoption of jet aircraft in the late 1950s and early 1960s revolutionized air travel worldwide by making travel faster and safer (Smithsonian National Air and Space Museum 2010). Early stage development of jet engines was started to replace piston engine turboprops that were noisy and limited in speed (tip speed of the propellers reaching mach velocity)[1]. The capability of higher climb rates, and faster and high altitude cruising were attractive to the military, and jet engines were developed primarily to meet the requirements of the U.S. Air Force. The Pratt & Whitney JT3C turbojet engine that powered the first U.S. commercial airplane – the Boeing 707, was actually developed as the J57 to power the experimental B52 bomber for the U.S. Air Force[2]. The spillover benefits of jet engine development for military applications resulted in the technology becoming quickly available for commercial applications.

The early adoption of jet aircraft by airlines was slow because of large capital investments required to purchase new aircraft in a period of economic downturn (ATA 1960). Jet aircraft also consumed more fuel and had higher operating costs. Pan Am was the first adopter of jet aircraft in the U.S. and launched the Boeing 707-120 on a New York-London route in 1958. Pan Am exploited the first mover advantage to full potential by dominating the trans-Atlantic routes using the Boeing 707 fleet, subsequently influencing Boeing to build the longer range 707-320 in 1958 for non-stop flights[3]. Passenger preferences for faster travel combined with the possibility of long-haul flight made 11 airlines adopt the 707-320 within a year. Several key drivers influenced the adoption dynamic from this point onwards. In 1958, the U.S. Congress passed the Federal Aviation Act, which among other things reduced taxes on air transportation and aided in making jet travel popular amongst travelers. American Airlines introduced the 707 to operate between New York and Los Angeles in 1959 and started competition amongst domestic airlines in the transcontinental market. TWA and United Airlines quickly joined in the race by purchasing/leasing jet aircraft. Decline in airline ticket prices also contributed to increasing passenger preference for air travel (ATA 1965,1966). The

[1] http://www.centennialofflight.gov (accessed - Feb 18, 2010)
[2] http://www.globalsecurity.org/military/systems/aircraft/systems/j57.htm (accessed - Feb 18, 2010)
[3] http://www.centennialofflight.gov (accessed - Feb 18, 2010)

growth in the cargo market and the expansion of the jet cargo fleet in the late 1960s (ATA 1967) added to the rapid growth of jet aircraft in the U.S Fleet.

Tech Case II: Regional Jets in the 1990s

The dynamic of diffusion of regional jets (i.e. 50 to 90 seat jet powered aircraft) starting at the beginning of the 1990s also exhibited a S-curve dynamic. Figure 9 shows the historical evolution of the number of regional jets registered in the United States from 1993 to 2008.

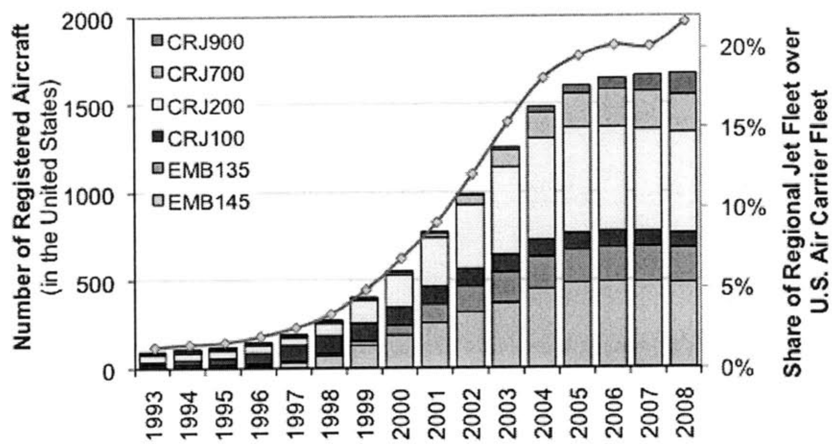

Figure 9: Historical evolution of regional jets registered in United States from 1993 to 2008

(Data source: FAA Aircraft Registry Database)

During the 1990s, a very slow rate of growth of regional jets was observed starting with the introduction of the Bombardier CRJ100. Due to pilot scope clauses (A. H. Mozdzanowska 2003) and the improved performance of regional jets (i.e. range, speed, cabin noise) compared to turboprop aircraft, regional jets became increasingly attractive to airlines. This resulted in a rapid growth from 1998 to 2005. From 2006 onwards, the rate of diffusion into the system decreased since the airline organizational structure was changing (i.e. removal of pilot scope clauses) and the increasing cost of fuel was starting to have a significant impact on operating regional jets as compared to more fuel-efficient turboprops.

Tech Case III: Blended Winglets

Blended winglets are wingtip devices that are an efficient way of introducing effective wingspan (increase aspect ratio) that reduces drag by limiting wingtip vortices. Figure 10 illustrates the cumulative number of orders (all aircraft types) placed with Aviation Partners (the sole supplier of winglets) and reflects the adoption of the technology by the industry.

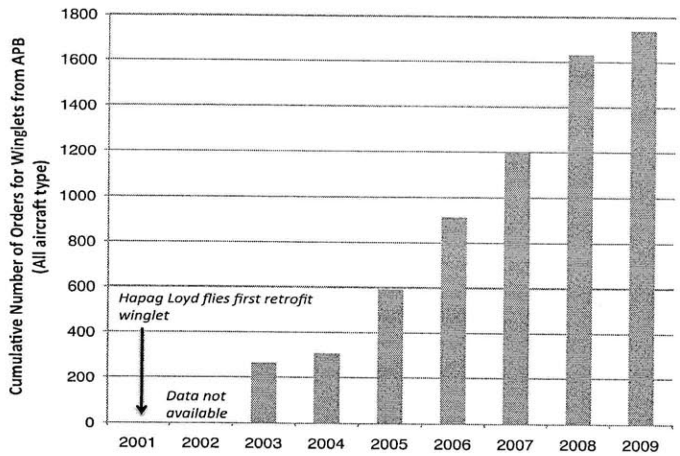

Figure 10: Adoption of Blended Winglets
(Data source: Aviation Partners)

In 1999, Aviation Partners Boeing (APB) formed a joint venture to offer blended winglets to Boeing aircraft after receiving FAA approval in 1993. The first supplemental type certificate (necessary certification to retrofit blended winglets on existing aircraft) was awarded in 2001 for the 737-800 and South African and Hapag-Lloyd were the early adopters. Boeing also started offering factory-installed winglets. Adoption of the blended winglet was initially slow because supplemental type certification was required for each model of aircraft. Rapid diffusion started once significant fuel savings from using blended winglets were reported and airlines accepted winglets as a retrofit option to save on fuel costs. Diffusion of winglets followed two pathways – entry with new aircraft as OEM and entry as a retrofit option.

4.2 Patterns of Diffusion of Operational Procedures

Ops Case I: E-Tickets

An electronic ticket is used to represent the purchase of a seat on a passenger airline, usually through a website, by telephone, airline ticket offices or travel agencies. This form of airline ticket has rapidly replaced the old multi-layered paper tickets. The growth pattern in the use of electronic tickets has also exhibited S-curve dynamics as shown in Figure 11.

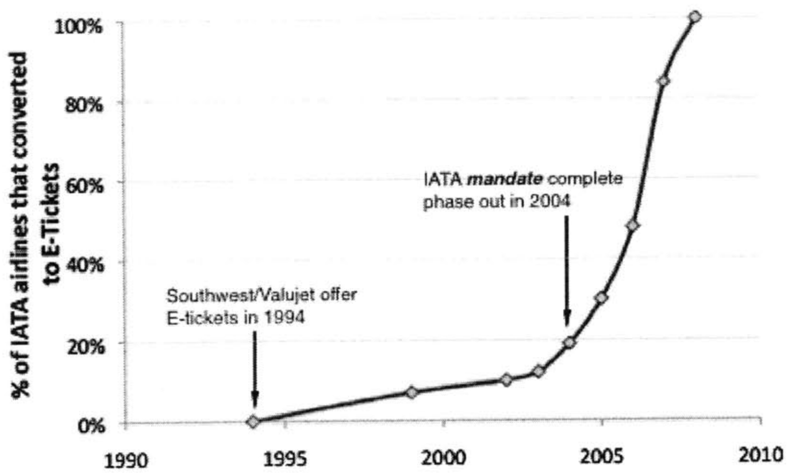

Figure 11: Historical adoption of e-tickets by IATA airlines
(Data sources: IATA and (Peter P. Belobaba 2009))

The transition from paper tickets to e-tickets was driven by two major dynamics – the reduced cost to airlines (e-tickets cost 10% the cost of a paper ticket) and the rapid growth of the Internet distribution channels (Peter P. Belobaba 2009). In the United States, Southwest and ValuJet were the first airlines to offer an e-ticket option in 1994. The initial adopters were shorter-haul and leisure travelers that had simple itineraries and were less likely to connect to other airlines and make changes to their tickets. Business travelers who had more flexible schedules were reluctant to adopt since an e-ticket issued by one airline was not accepted by another (i.e. lack of common IT communication infrastructure). In the late 1990s and early 2000s, once the IT barriers were removed, the increasing popularity of Internet based booking services resulted in rapid diffusion of e-tickets. Increased use of e-tickets allowed the passengers to gather more information online about ticket prices and gave them greater flexibility in travel planning. Passenger acceptance reinforced quick adoption. A spillover benefit for the airlines was better revenue management – filling empty seats or 'distressed inventory' tickets. Finally an IATA mandate, set for a complete phase out of paper tickets by 2008, led towards a full adoption of e-tickets.

Ops Case II: Reduced Vertical Separation Minimum (RVSM)

Aircraft are expected to maintain a minimum vertical separation to ensure safety. Historically, standard vertical separation was 1000 feet from the surface to FL290, 2000 feet from FL290 to FL410 and 4000 feet above this. This was because the accuracy of the pressure altimeter decreased with height. With improvement in altitude measurement instruments, it was found that the 2000 feet separation was overly cautious. The objective behind implementing Reduced Vertical Separation Minimum (RVSM) was to reduce vertical separation between flight levels 290 and 410 from 2000 ft to 1000 ft. This allowed the aircraft to fly optimum cruise levels, reducing fuel burn and increasing capacity. Figure 12 shows the historical evolution of cumulative area of coverage with Reduced Vertical Separation Minimum (RVSM) across the world.

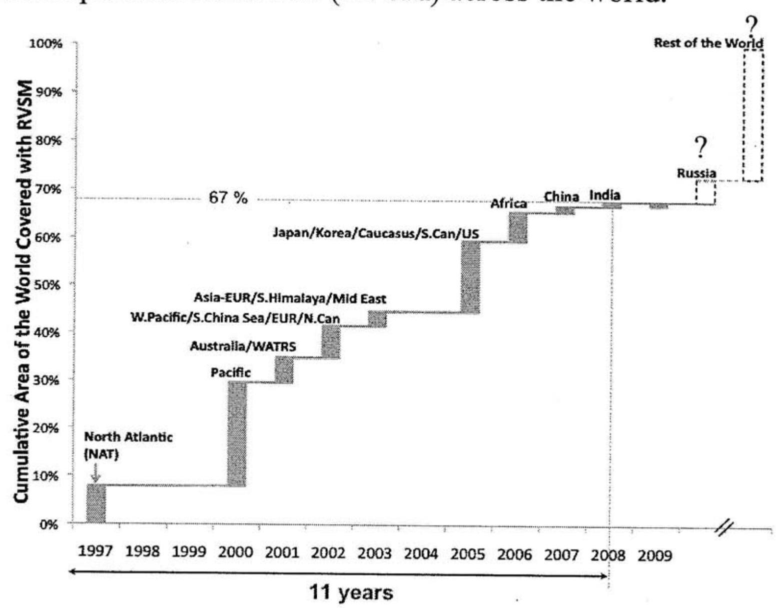

Figure 12: RVSM Implementation worldwide
(Data: FAA 2007, ICAO 2008)

It took 11 years to achieve 67% RVSM worldwide coverage. The implementation and diffusion of RVSM was initially slow because of the high cost for upgrading aircraft that were difficult to justify for 2-3% fuel savings (Mclaren 2005). The adoption was also slowed down due to barriers such as the development and deployment of new avionics to monitor aircraft separation and the design of accurate altitude indicators. In addition, there were safety concerns with aircraft wake vortices and interactions with other system components such as Traffic Collision Avoidance System (TCAS) which resulted in an increased frequency of alerts. This procedural change required the training of air traffic controllers and setting standards when transitioning airspaces to RVSM.

A key enabler to the implementation of RVSM over the North Atlantic Tracks (NAT) was the large trans-oceanic fleet that could be upgraded at a fast rate for which benefits could accrue rapidly.

4.3 Patterns of Diffusion of Alternative Fuels

Alt. Fuels Case I & II: Adoption of Ethanol in the US and Brazil

Alternative fuels hold the potential to reduce the carbon footprint of aviation, mostly because of their reduced life-cycle (i.e. well-to-wake) carbon content. The adoption dynamics of ethanol in the automotive industry in the United States and Brazil were investigated to gain insights into the drivers and constraints of transitioning away from petroleum-based jet fuels used in the airline industry. Figure 13 shows the trend of ethanol production in the United States and Brazil from 1975 to 2004. It took approximately 11 and 26 years for Brazil and the United States respectively to reach similar levels of ethanol production.

Figure 13: Historical evolution of ethanol use in Brazil and the US
(Data: EIA, 2008)

These cases illustrate the effect of countries infrastructure and capabilities, regulations and incentives on the time of diffusion:

In Brazil, the ethanol industry is more than 30 years old and had been stimulated with the launch of the 1975 National Alcohol Program that guaranteed low-interest loans to construct distilleries, guaranteed purchase of ethanol by the state owned oil companies and incentivizing flex-fuel vehicles. In 1977, the government also mandated a 20% mix of ethanol with gasoline. This led to the rapid development and diffusion of the ethanol industry.

In the United States, ethanol is distilled from corn which is less efficient than producing it from sugarcane (compared to Brazil). Ethanol production competes with food and fodder use of corn, and has been the source of controversy. In the United States, the buildup of production capabilities was significantly slower despite a federal subsidy of 40 to 60 cents per gallon since 1978. Distribution of biofuels to end-use markets have been hampered by several factors – limited rail and truck capacity, location of all distilleries near the Midwest (to reduce raw material transportation costs) which is far from major biofuel consumption centers (East and West coasts), limited number of fueling stations and the general murky regulatory environment that surrounds use and distribution at retail centers[1]. The uptake of ethanol as a flex fuel in the US has therefore not been at par with that in Brazil.

Summary and Discussion of Key Barriers and Drivers

The examples discussed in this chapter have illustrated the patterns of change in the aviation industry and the long time constants of diffusion associated with every change. They also indicate that S-curves are one way of modeling the diffusion modes for the industry. Every case has unique dynamics – driven by sets of barriers, enablers and adopters. Several key barriers and dynamics were observed that have the potential to delay the implementation of CO_2 emission reduction measures through the following mechanisms.

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[1] Biofuels in the U.S. Transportation Sector, EIA, February 2007.

a) Barriers

Cost of adoption

High capital costs or the need for expensive upgrades/retrofits can delay the rate of adoption of measures significantly – particularly in cases where the benefits are uncertain. In the case of RVSM for example, high costs for instrumentation upgrades and design costs were a barrier to implementation. Similarly, adoption of early generation jet aircraft by airlines was delayed because of extremely high capital costs. High costs of equipment also lead to slow fleet turnover – airlines utilize aircraft for a long period of time. Entry of new and efficient aircraft is blocked.

Coordination and standards setting

Approval processes that require coordination amongst stakeholders and require setting standards can delay implementation of changes. The approval of RVSM across airspaces required coordination amongst stakeholders involved in the process, civil aviation authorities, air navigation service providers, air traffic controllers, pilots and air navigation engineers/technicians. Safety concerns increased the implementation time. The diffusion of e-tickets was initially slow because of the lack of coordination amongst different airlines – a ticket issued by one airline was not accepted by another that led to poor passenger service quality.

Certification

There are stringent certification requirements by the civil aviation authorities (FAA) before any system change is implemented to ensure public safety. To meet the safety standards, stakeholders have to undergo certification tests – like the type certification for new aircraft. Winglets, for example, have to be certified for each aircraft model and this adds on to the time to full adoption in the fleet.

Requirement for equipage

The need to equip aircraft, air traffic control stations or ground infrastructure with instruments to achieve operational capabilities can delay the implementation process. This was illustrated in the case of RVSM where upgrades to the TCAS system and deployment of accurate altitude indicators preceded the approval of the operational change.

Production capability build-up

Technology and alternative fuel solutions generally require the development of production capabilities, which is not instantaneous due to the need for infrastructure build-up. Comparison of the adoption of ethanol in the US and Brazil show that the lack of infrastructure for distribution of the biofuel to end-use markets hampered the uptake by the consumers in the US.

Maintenance cycles (window of opportunity for retrofits)

Most of the aircraft retrofit measures are performed during aircraft maintenance visit (i.e. D-checks), which happens approximately every 5 years. As a result, it may take several years before an aircraft becomes available for a retrofit. Winglets diffuse into the aircraft fleet through new aircraft as well as through retrofits. It will take at least 5 years before there is a window of opportunity to retrofit all aircraft in an airline fleet to achieve fuel efficiency improvements.

b) Drivers

Technology spillover

The commercial aircraft industry has derived spillover benefits from other sectors. The evolution of the jet aircraft has been brought about by the research and development conducted by the military. The adoption of E-tickets was accelerated because of the existence of a well-established information technology infrastructure that Internet distribution channels could take advantage of.

Passenger preference

Passenger preference plays a significant role in the rate of adoption of changes in the air transportation system. One of the primary factors behind the transition to a 'jet age' is the preference for passengers for faster modes of travel (ATA 1965,1966). Increased use of e-tickets allowed passengers greater flexibility to plan their travel and reinforced quick adoption.

Policies and mandates

Transitions in the air transportation system can be significantly accelerated through policies and mandates. The IATA mandate in 2004 that demanded a complete phase out of paper tickets by 2008 was instrumental in the moving towards a fully e-ticket based reservation system. The National Alchohol Policy enacted in Brazil and a guaranteed market stimulated ethanol as an alternative automobile fuel. Pilot scope clauses led to the development of regional jets.

c) Distribution of costs and benefits across stakeholders

Marais and Weigel (Marais and Weigel 2006) showed that while the overall cost benefit analysis for a transition may be favorable, individual stakeholders may not derive equal value from the transition. Stakeholders that are asked to bear a larger share of the costs while reaping little benefit can be reluctant to cooperate with the transition effort. Push back from stakeholders tends to be acute when changes exhibit asymmetrical costs and benefits (A. Mozdzanowska 2008).

CHAPTER 5

CONCEPTUAL DYNAMICS OF IMPLEMENTATION OF MITIGATING MEASURES

5.1 Literature Review of Technology Diffusion

The implementation of a new technology or a procedure generally follows an S-curve over time (Geroski 2000). In the consumer electronics industry for example, there is a development phase during which a measure is being developed, evaluated and certified. The diffusion phase begins with a phase of slow adoption driven by early adopters (first movers or innovators). Then, reinforcing dynamics accelerate the adoption process to a phase of maximum diffusion when most of the barriers are overcome and the measure is generally accepted. This phase is followed by slower adoption by laggards and exhibits diminishing returns.

There are two types of technology evolution. First and the most common transition is one of sustained development with incremental improvements in performance (Henderson and Kim 1990). The second type is that of a disruptive technology (Christensen, 1997) that requires altering the current mode of behavior of the services enabled by the innovation (Moore 1999).

Adoption of new technology or operational measures in air transportation, through all phases of the life-cycle, is determined by how the transition can be used to **create, capture** and **deliver** value to stakeholders (Campos 2008). An S-curve model can be used to describe the path followed by technology development, showing the relationship between levels of improvement in performance over time (see Figure 14). The returns to improvements diminish as technology limits are reached (Utterback, 1994). At this point disruptive new technology can enter the system. At first, transitioning into a new technology may appear less efficient and more costly than the current technology. However, after a period of maturation, the new technology can outperform the current one (Foster, 1986).

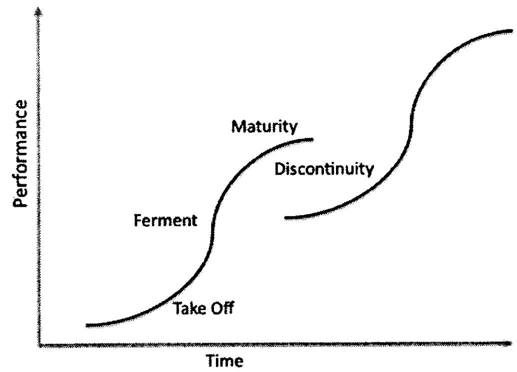

Figure 14: Technology life cycle as an S-curve
Source: (R. Henderson 2005)

Technology diffusion in air transport can also be analyzed using Roger's market segmentation dynamics, where adopters are classified into: innovators, early adopters, early majority, late majority and laggards (Campos 2008). There are very few adopters under the category of innovators but their endorsement is fundamental to reassure stakeholders that the technology is viable (Campos 2008). Early adopters buy into a technology only to seek specific benefits from it. Approximately one third of the adopters belong to the third category i.e. the early majority. Members in this segment will follow a wait and see strategy and evaluate how a technology is beneficial to others before deciding to adopt it. A strong baseline of proven benefits and the infrastructure to support the technology are necessary to encourage this group to invest (Campos 2008). Another third of the adopters falls under the fourth group - the late majority. They will wait until the technology becomes an established standard and will try to maintain the status quo unless change is necessary. The technology laggards represent the last segment. Stakeholders in this category are not interested in adopting a new technology if given the choice. This group is generally not particularly worth pursuing with targeted incentives (Moore 1999).

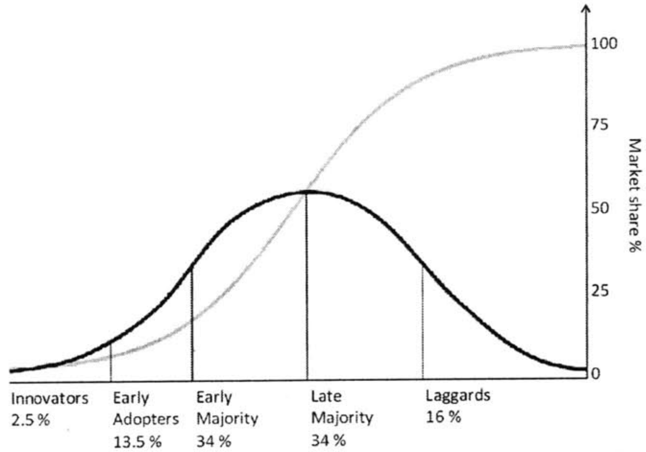

Figure 15: S-curve market segmentation
Source: (Everett 1983)

Another framework for investigating the diffusion of innovations is to derive a list of factors that can be expected to influence adoption and diffusion dynamics (Hall and Khan 2003). The factors can be classified into four main groups of factors that affect:

(1) benefits achieved

(2) the costs of adoption

(3) industry or regulatory environment and

(4) uncertainty and information problems.

These factors contribute directly to the speed of diffusion (Hall and Khan 2003)

<u>Benefit received from the new technology</u>

The improvement of the new technology over the existing technology is the most critical determinant of benefits. When a new technology is introduced, the relative advantage is often relatively small but increases with learning and when adapted to different environments to attract a different set of adopters (Rosenberg 1972). This implies that the benefits increase over time and diffusion often appears delayed because learning increases the size of the adopting population. Network effects where the consumer and the firms benefit from the fact that other consumers and firms have also chosen the same technology play a critical role in the speed of adoption as well. (Hall and Khan 2003) classify this effect into two groups – direct and indirect benefits. Direct benefits allow the adopter to communicate/operate with other adopters using the same technology whereas indirect benefits lead to a particular standard being used by greater number of adopters and therefore survive. Standard setting accelerates adoption in multiple ways – ease of communication and consumer learning being foremost (Hall and Khan 2003).

Costs of adopting the new technology

The second main class of factors affecting the decision to adopt new technology is those related to its cost. This includes not only the price of acquisition, but more importantly the cost of the complementary investment and learning required to make use of the technology. Such investment may include training of operators and the purchase of necessary capital equipment (whose diffusion is therefore affected by the same factors). Firm investment in new technologies is also sensitive to financial factors. The decision to adopt new technology is fundamentally an investment decision made in an uncertain environment, and therefore relationship between sources of finance and choice of investment strategy has a role to play (Hall and Khan 2003). In hazardous market conditions when liquidity is a concern, firms may be extremely risk averse, thereby restricting adoption of new technologies by limiting investment.

Market size, industry environment and market structure

Large dominant firms can spread the costs of adoption over more units, but also may not feel the pressure to reduce costs that leads to investment in new technologies. Along with market size and structure, the general regulatory environment will have an influence, tending to slow the rate of adoption in some areas due to the relative sluggishness of regulatory change and increasing it in others due to the role of the regulator in mandating a particular technical standard. As an example of accelerating the adoption, Mowery (Mowery and Rosenberg 1981) described the extent to which airline regulation by the Civil Aeronautics Board in the United States was responsible for promoting the adoption of new innovation in airframes and jet engines, in its role as standard setter and coordinator for the industry.

Information and uncertainty

The choice to adopt a new technology requires knowledge that it exists and some information about its suitability to the potential adopter's situation. Therefore an important determinant of diffusion is information about the new technology and experience. Upfront costs and long time lags to recover benefits and uncertainty surrounding them will often slow diffusion (Hall and Khan 2003)

5.2 The Bass Diffusion Model

The Bass Diffusion model (Bass 2004) is a conceptual representation that captures diffusion dynamics that result in S-curves. This model allows for asymmetric S-curve growth between the early adoption period and the later imitation period and is therefore more applicable to growth dynamics (i.e. "first mover advantage") seen in the aviation industry. The model states that the ratio of the fraction of the adopters to the fraction of those who are still to adopt is a linear function of the cumulative number of adopters. This is mathematically represented as:

$$\frac{f(t)}{1-F(t)} = p + \frac{q}{M}F(t)$$

$$f(t) = \frac{dF(t)}{dt}, F(t) = \frac{A(t)}{M}$$

Equation 2

where,

f(t) is the adopting fraction i.e. fraction of the potential market that adopts at time 't'

F(t) is the adopter fraction, i.e the fraction of the potential market that has adopted up to time 't'

A(t) is the cumulative number of adopters till time 't'

'p' is the innovation coefficient and accounts for the early adoption dynamics

'q' is the imitation coefficient and accounts for new adoption influenced by older adopters

'M' is the total number of potential adopters or market size

Figure 16 illustrates the different stages of implementation of a technology using the Bass diffusion model. (τ_1) denotes the development phase after which the technology is ready for market adoption. At this juncture (called the Start Time of Diffusion) the technology has gone through the innovation, R&D, prototype testing and certification process. From that point onwards, adoption is driven by early movers and then by imitators (see Bass diffusion equation).

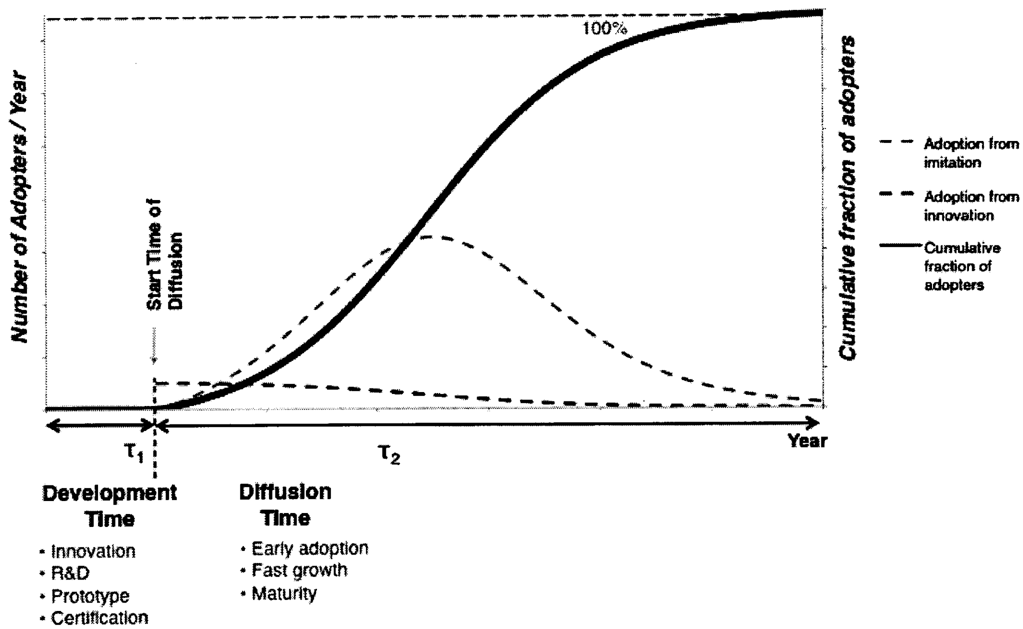

Figure 16: Conceptual representation of the Bass diffusion model

The total time to full adoption is called the Diffusion Time (τ_2). For the purpose of this study, the total period of development (τ_1) and diffusion (τ_2) is referred to as the implementation period. Figure 16 shows rate of adoption by innovation and imitation (i.e. left ordinate axis). The cumulative number of adoptions as a fraction of the total possible adoptions is plotted along the right ordinate axis. The overall dynamic can be completely represented using three parameters: (1) **the development time** (or *start date of diffusion*), (2) the **diffusion time** and (3) the **full adoption potential** (scales to total number of adopters).

5.3 Frameworks for Identifying, Categorizing and Evaluating Measures

Framework 1: Systematic grouping of mitigating measures

Section 1.1 (Equation 1) introduced the modified Breguet range equation to decompose the total CO_2 emissions from the aviation industry. The equation is used as the first framework for identifying the different levers for emissions abatement. The main categories are:

1. New Technologies: Entry with new aircraft models
    a. Propulsion improvements
    b. Aerodynamic improvement
    c. Weight reduction
    d. Retrofit existing aircraft
2. Operational improvements
    a. Ground operations
    b. Air Traffic Management (ATM) operations
    c. Airline operations
3. Alternative Fuels

Framework 2: The Bass Diffusion Model

Section 5.2 introduced the bass diffusion model as one way of conceptualizing the S-shaped growth that has been observed in past changes in the aviation industry. It lays the framework for determining the implementation characteristic of each mitigating measure based on three parameters: 1)Start Time of Diffusion (i.e. Entry Into Service) 2) Diffusion Time (i.e. time constant from first entry into service to market saturation) 3)Potential for CO_2 reduction (when full adoption is achieved).

Using the two frameworks, each mitigating measure can be identified as belonging to one of the three key areas of improvement and their impact on reducing system-wide carbon emissions can be evaluated based on the three parameters that define the implementation of characteristic of the measure.

CHAPTER 6

IDENTIFICATION AND CATEGORIZATION OF MITIGATING MEASURES

A broad range of technological and operational measures and fuel alternatives are available to the aviation industry to reduce its carbon emissions. Each measure, have unique development times, diffusion time constants and the potential to reduce emissions.

This chapter develops a portfolio of technology and operational measures, and alternative fuels that are currently available or anticipated in the future. Measures are categorized and analyzed using the frameworks developed in Section 4.3.

6.1 Methodology for Identification and Categorization of Mitigating Measures

The first step to develop the portfolio of measures was to conduct a literature survey of journals, conference papers and presentations, annual reports, websites, press releases etc. The review identified 95 mitigating measures. The list is shown in Appendix A: List of Mitigating Measures.

The second step was a filtering and aggregation process that led to the construction of a portfolio of 41 unique measures. Technologies or concepts that have not reached maturity were filtered out. The set of measures was further synthesized by aggregating measures that were achieving similar goals (e.g. carrying less food and water, switching to electronic flight bags, reducing duty free goods were all aggregated into a single empty and payload weight reduction measure).

6.2 Estimation of the Diffusion Characteristics of Mitigating Measures

The discussion on S-curve type implementation showed three key parameters that defined the dynamics of the process. The parameters are re-defined for the purpose of this analysis and to better suit the aviation industry.

(1) ***The start time of diffusion*** is defined as the time of entry into service of the measure when diffusing into the system can begin,

(2) ***The diffusion time*** is defined as the amount of time required to reach market saturation and when most of the potential for improvement is achieved,

(3) ***The percentage CO_2 emission reduction potential*** scales to the total impact on the system when full adoption is achieved. For the purpose of this research, this percentage is defined for an individual measure and assumes that there are no other changes to the system apart from the adoption of this particular measure. As shown with Equation 3, a baseline of 2006 was used for estimations of emissions reduction potential.

$$Potential\ CO_2\ Emission\ \mathrm{Re}duction\ Potential = \frac{CO_2Emission_{2006} - CO_2Emission_{fulladoption}}{CO_2Emission_{2006}}$$

Equation 3

Estimation of the start time of diffusion

Based on program timelines and schedules gathered from the literature review, estimates of start date of availability or certification were obtained. When multiple sources were available a range of start time of availability is reported. It should be noted that due to the nature of the forecasting exercise of program planning, these dates are likely to change (i.e. start date being delayed). The reported numbers can therefore be seen as being optimistic estimations of the start time of diffusion.

Assumptions for the diffusion time

The diffusion time of mitigating measures was based on direct quotes from literature sources when available as well as assumptions based on past changes of similar nature. Several measures involve the retrofit of components on existing aircraft. The window of opportunity for retrofits is dictated by D-check maintenance, which is generally performed every 5 years. Because of production capability build-up constraints, retrofit solutions (e.g. new engine, winglet) are not necessarily available to replace all the aircraft that are scheduled for D-check during the first years of diffusion. As a result, it is assumed that within two D-check cycles (i.e. approx. 10 years) retrofit measures should be able to diffuse throughout the fleet.

The diffusion of new aircraft was assumed to take 20 years based on historical cases. As shown on Figure 8 it took approximately 15 years for jet aircraft to diffuse through the system. Given the disruptive character of this product, this is an optimistic number. The regional jet took slightly longer to diffuse (while not fully replacing the aircraft in its category).

Estimation of percentage of CO_2 emission reduction potential

Estimates of the percentage of CO_2 emission reduction potential obtained from the literature review were of two types:

(1) improvements with effects on a portion of the system (e.g. reduction in ground emissions, new aircraft type that only account for a fraction of the total fleet) and

(2) improvements with system wide effects. Both types of information are reported in Table 1 (Column 4 and 5) as verbatim from the literature.

In order to compare measures on the same basis, the measures that targeted one segment of the fleet or a portion of the flight stages were scaled to system-wide potential using 2006 BTS Form 41 data. For the purpose of scaling potential improvements, it was assumed that the fleet size and its general composition would remain constant over time. As an illustration, the NASA N+1 concept that is expected to replace the Boeing 737 is reported to have a potential for CO_2 emission reduction of 33% compared to current generation aircraft. Given the 2006 fleet composition, its system wide impact is expected to be 12%. Similarly, queue management and controlled pushback techniques that reduce ground emissions by 60% are scaled to system-wide impacts by approximating the percentage of fuel burnt taxiing on the ground compared to the total fuel burnt during all phases of operations.

Due to the forecasting nature of this exercise, the reported estimates exhibit some level of uncertainty. An evaluation of the degree of confidence in the numbers quoted was performed and is largely based on its correlation to the status of development or adoption of the measures (see Column 9 in Table 5). Confidence in estimates for measures in concept/R&D phase is generally low as compared to estimates for measures that are already being implemented.

6.3 Evaluation of the Diffusion Characteristics of Mitigating Measures

The portfolio of mitigating measures were divided into three main categories:

- technology applications for new aircraft and retrofit technologies for existing aircraft,
- operational improvements through ground, airline and air traffic management and the
- use of alternative fuels.

A short description of the mitigating measures is included in Table 3.

Table 3: Brief Description of Technology Measures

Area of Improvement			Mitigating Measure	Description
Technology	New Aircraft		B787/A350	The Boeing 787 Dreamliner is a mid-sized, wide-body, twin-engine jet airliner developed by Boeing Commercial Airplanes. The Airbus A350 is a long-range, mid-size, wide-body family of airliners currently under development.
			Bombardier C-series/Mitsubishi RJ	The C-series and the MRJ are the next generation regional jet aircraft powered by the PW geared turbofan engine
			N+1 NASA Subsonic	N+1 is a concept aircraft one generation after the current B737NG/A320 (single aisle tube architecture)
			N+2 NASA Subsonic	N+2 is two generations after the B777 and is a blended wing concept aircraft
			N+3 NASA Subsonic	N+3 is a concept aircraft three generations after the current B737NG/A320
	Components (introduced with New Aircraft)	*Propulsion*	Material, coatings, cooling technology for engines	Reduce weight and increase operating temperature of the combustion chamber of engines
			Engines - GTF	Planetary gear arrangement that allows fan and LP Turbine rotate at optimum speeds
			Engines - Open rotor	Unducted fan mounted on the same axis as the compressor blades.
			Variable fan nozzle	Better aerodynamic flow matching at off design conditions
			No bleed architecture	Bleed air is taken from the engines to provide cabin air services and support other systems. By removing this requirement the engines can operate more efficiently, reducing fuel consumption.
			Develop 'all-electric/more-electric' planes	Shift to all-electric architecture for most systems to save weight and improve efficiency
			New Engine Core	Advanced aerodynamic blades for compressors and turbine cascade (3D blades, low solidity, higher loading), twin annular preswirl combustors (TAPS)
			Embedded distributed multi-fan	Use of many small size turbofan engines along the airframe for lower fuel burn and noise
			Next generation high bypass ratio engine	Develop next generation HBR Engines (e.g. GE LEAP-X program) – includes new engine core, LP compressor aerodynamics, new materials and monitoring systems
			Replace APU's with fuel cells	Replace APU with Solid Oxide Fuel Cells
			Ubiquitous composite engines	Use of composites (ceramic matrix) to reduce the weight of engines
		Aerodynamics	Non-planar wings	Winglets, Box-wings, Multi-wings that reduce vortex drag.
			Laminar nacelles	Achieve laminar flow over engine nacelles (e.g. shaping the nacelle and applying uniform grey paint on the B787) and reduce airframe drag.
			Riblets	Apply thin grooved layer of plastics to airswept surfaces – reduces skin friction drag from the turbulent boundary layer
			Hybrid Laminar Flow(HLF) control	(HLFC) is an active form of control employing a combination of suitable aerofoil shaping and boundary layer suction. Its objectives are to achieve the characteristics of natural laminar flow designs at higher values of chord Reynolds number and leading edge sweep - ie a wing with laminar flow and reduced friction over its forward surfaces, giving rise to reduced profile drag through reduced turbulent boundary layer growth over the rear of the wing
			Higher aspect ratio wings	Use higher aspect ratio wings to reduce induced drag
			Morphing airframe	An aircraft able to change shape during flight, for example a wing able to adapt itself for different aerodynamic characteristics in flight, for optimisation and effective aerodynamic control
			Variable Camber wings	Variable camber control of the wing for drag reduction throughout the flight envelope
			Laminar flow wing profile	Shaping the wing profile so as to maintain gently accelerating flow over the forward 50% or so of both upper and lower wing surfaces, thereby maintaining laminar boundary layers over the first half of the wing and reducing the pressure drag associated with rapid boundary layer growth in the decelerating flow over the rear of the wing
		Weight	Lightweight material, composites etc	Structural weight reduction using advanced composite materials
			Advanced fly by wire technology	Replacement of bulky and heavy hydraulic circuits with electrical power circuits
			Fly by light technology	Utilization of fiber optics instead of electrical circuits for data transfer to reduce weight
			Friction stir welding (FSW)	FSW is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as far as possible. This process is primarily used on aluminum, and most often on large pieces which cannot be easily heat treated post weld to recover temper characteristics.
			Laser beam welding (LBW)	LBW is a welding technique used to join multiple pieces of metal through the use of a laser. The beam provides a concentrated heat source, allowing for narrow, deep welds and high welding rates
			Reduce OEW	Reduce empty and payload weight by using lighter weight carpets, seats, cargo containers etc

Table 4: Brief Description of Mitigating Measures; Technology (Retrofit), Operational Improvements and Alternative Fuels (cont.)

Area of Improvement			Mitigating Measure	Description
Technology	Retrofit solutions for Existing Aircraft	*Propulsion*	Retrofit engines	Retrofit existing aircraft with higher efficiency engines
			Technology insertion- Upgrade core	Replace engine core with more efficient technology insertion (e.g. TECH56 program)
		Aerodynamics	Winglets	Wingtip devices that reduce lift-induced drag from wingtip vortices
			Riblets	Apply thin grooved layer of plastics to airswept surfaces – reduces skin friction drag from the turbulent boundary layer
			Laminar Nacelles	Achieve laminar flow over engine nacelles (e.g. shaping the nacelle and applying uniform grey paint on the B787) and reduce airframe drag.
		Weight	Reduced use of paint on airframes	Reduce extra weight of paint on airframe by polishing instead of painting
Operational improvements		*Ground ops*	Fixed electric ground power instead of APU	Provide fixed electric ground power (FEGP) and preconditioned air (PCA) to aircraft at terminal gates
			Single engine taxi	Shutting down one or more engines during taxi
			Implement queue management and controlled pushback	Limit build up of queues and congestion through improved queue management. Improve coordination on the surface though information sharing and collaborative planning
			Ground towing with diesel tugs instead of engine power	Tow aircraft to runway rather than use engine power. Start engines 5 mins before departure
		ATM ops	Fly at optimum cruise level	Fly at optimal altitude for minimum cruise fuel burn
			Use continuous descent approaches (CDA)	Continuous descent uses less engine thrust than stepped descent (prevailing practice)
			Fly optimized routes	Current airspace system requires flight plans to be defined in terms of predetermined routes. Airlines can save cost by flying wind-optimal routes that minimize flight time or fuel burn and flying great circle routes
		Airline ops	Reduce cabin dead-weight	Reduce empty and payload weight
			Engine washing	Clean up deposits on engine blades to improve compressor efficiency
			Fly at lower cruise speed	Fly at 'maximum range cruise' speed instead of long range speed
Alternative Fuels			2nd Generation Biofuel (Nature by-products/waste)	Mostly cellulosic material (that does not compete with feedstock) converted to biofuel using the Fischer Tropsch process
			3rd Generation Biofuel (algae, switch grass, jatropha, babassu and halophytes)	Drop-in jet fuel from renewable resources like algae, switchgrass etc

The portfolio of mitigating measures is shown in Table 5: Column 3 enumerates the references; Column 4 and 5 enumerates the percent CO_2 emissions reduction; Column 6 scales Column 4 to system-wide impact or uses Column 5 as is; Column 7 and 8 shows assumed start time of diffusion and time to full diffusion based on estimates from literature; Column 9 shows the current stage of implementation – the earlier the state, the less confidence in the numbers.

Table 5: Portfolio of mitigating measures to reduce CO_2 emissions and estimates of the diffusion characteristics (References: see Appendix B)

1			2	3	4	5	6	7	8	9
Area of Improvement			Mitigating Measure	Number of Sources Reviewed and [References]	Quoted % CO_2 Emissions Reduction from Literature		System-wide %CO_2 Emissions Reduction Potential	Assumed Start Time of Diffusion	Assumed Time to 100% Diffusion (Rounded to 5yrs)	Status of Implementation of Measure (degree of confidence shaded***)
					Individual	System-wide				
Technology	New Aircraft		B787/A350	3 [1,2,3]	20-25%		7-9%	2010	20	Certification
			Bombardier C-series/Mitsubishi RJ	3 [4,5,6]	25-30%		2-3%	2013	20	Prototype
			N+1 NASA Subsonic (*)	4 [7,8,10,11]	33%		12%	2015	20	Concept
			N+2 NASA Subsonic (*)	3 [10,11,12]	40%		12%	2018-2020	20	Concept
			N+3 NASA Subsonic (*)	3 [10,11,13]	70%		25%	2030-2035	20	Concept
	Components (introduced with New Aircraft)	Propulsion	Material, coatings, cooling technology for engines	2 [14,15]		3-5%	3-5%	2010	Diffusion with new aircraft**	Certification
			Engines - GTF	3 [6,14,16,17]	12%		12%	2013		Prototype
			Engines - Open rotor	6 [9,14,18-21]	25-30%		13-15%	2015-2017		Prototype
			Variable fan nozzle			1-2%	1-2%	2010		Prototype
			No bleed architecture	2 [22,23]	1-2%		0.5-1.5%	2010		Prototype
			Develop 'all-electric/more-electric' planes	2 [22,23]		3%	3%	2010		Prototype
			New Engine Core	3 [14,16,24]	5-7%		1.5-2.5%	2015		R&D
			Embedded distributed multi-fan	1 [67]		1%	1%	2020		R&D
			Next generation high bypass ratio engine	3 [15,16,24]	16%		16%	2015-2016		R&D
			Replace APU's with fuel cells	3 [25,26,27]		0.2-0.8%	0.2-0.8%	2015		R&D
			Ubiquitous composite engines	1 [67]		10-15%	10-15%	2020		Concept
		Aerodynamics	Non-planar wings	2 [28,29]		1-2%	1-2%	2008		Adoption
			Laminar nacelles	4 [14,30,31,32]		0.8-1%	0.8-1%	2010		Prototype
			Riblets	3 [14,33,46]		1-2%	1-2%	2015-2020		Prototype
			Hybrid Laminar Flow(HLF) control	3 [14,33,34]		10-20%	10-20%	2015-2020		Prototype
			Higher aspect ratio wings	2 [35,36]		7-16%	7-16%	2030-2035		Concept
			Morphing airframe	1 [67]		5-10%	5-10%	2020		R&D
			Variable Camber with new control surfaces	1 [67]		1-5%	1-5%	2010		R&D
			Laminar flow wing profile	2 [31,33]		1-2%	1-2%	2015		R&D
		Weight	Lightweight material, composites etc	3 [36,37,38]		10-20%	10-20%	2010		Certification
			Advanced fly by wire technology	1 [39]		1-3%	1-3%	2010		Certification
			Fly by light technology	1 [67]		1-3%	1-3%	2010		Prototype
			Friction stir welding	1 [67]		1%	1%	2010		Prototype
			Laser beam welding	1 [67]		1%	1%	2010		Prototype
			Wireless flight control system	1 [67]		1-3%	1-3%	2020		R&D
			Reduce OEW	2 [39,40]		1%	1%	2010		Near Term
	Retrofit solutions for Existing Aircraft	Propulsion	Retrofit engines	1 [14]	2-7%			2008	10	Adoption
			Technology insertion- Upgrade core	2 [41,42]	1-3%		0.25-0.75%	2007	10	Adoption
		Aerodynamics	Winglets	5 [14,43,44,45,46]		1-6%	1-6%	2004	10	Adoption
			Riblets	3 [14,33,46]		1-2%	1-2%	2015	10	Prototype
			Laminar Nacelles	4 [14,30,31,32]		1%	1%	2010	10	Prototype
		Weight	Reduced use of paint on airframes	3 [14,36,37]		0.3-0.8%	0.3-0.8%	2008	5	Adoption
Operational improvements		Ground operations	Fixed electric ground power instead of APU	3 [46,48,49]		0.6%	0.6%	2008	10	Adoption
			Single engine taxi	4 [40,48,49,51]		0.4%	0.4%	2004	10	Adoption
			Implement queue management and controlled pushback	3 [51-53]	60%		2%	2010	10	Prototype
			Ground towing with diesel tugs instead of engine power	2 [14,51]	60%		2%	2010		Prototype
		ATM operations	Fly at optimum cruise level	2 [54,55]		0.3-0.5%	0.3-0.5%	2008	10	Adoption
			Use continuous descent approaches (CDA)	4 [56-59]		1-2%	1-2%	2007	10	Adoption
			Fly optimized routes	4 [52,58,60,61]		1-2%	1-2%	2015	10	R&D
		Airline operations	Reduce cabin dead-weight	4 [14,39,40,54]		1%	1%	2005	5	Adoption
			Engine washing	2 [46,62,63]		0.4-1.2%	0.4-1.2%	2007	5	Adoption
			Fly at lower cruise speed	3 [40,46,54]		1%	1%	2005	10	Adoption
Alternative Fuels			2nd Generation Biofuel (Nature by-products/waste)	4 [68, 64-66]	40%		20%	2011-2014	15	Prototype
			3rd Generation Biofuel (algae, switch grass, jatropha, babassu and halophytes)	4 [68,64-66]	60-100%		30-50%	2018-2023	15	Prototype

Notes:

(*) N refers to current generation aircraft with tube and wing architecture. In the NASA subsonic research program, N+1 is a concept aircraft one generation after the current B737NG/A320 (single aisle tube architecture). N+2 is two generations after the B777 and is a blended wing concept aircraft. N+3 is a concept aircraft three generations after the current B737NG/A320.

(**) Technology components introduced in a new aircraft diffuse with a time constant of 20 years (like new aircraft). However in order to diffuse through the entire fleet, these components have to be embedded in airraft types across the spectrum. Since the first delivery dates of all types of new aircraft do not happen simultaneously, there is a phased delay in the actual diffusion of a particular component across the system. As a result, the total diffusion time can be as long as 30 years

(***) Degree of confidence generally scales with status of implementation of a measure. Degree of confidence is colored coded with darker shaded depicting higher degree of confidence.

A representation of the mitigation measures on a temporal chart is shown in Figure 17 where the vertical axis is Diffusion Time and the horizontal axis is Start Time of Diffusion. The area of the bubble represents the percent CO_2 emissions reduction. Component technologies that diffuse with new aircraft are not included in this plot.

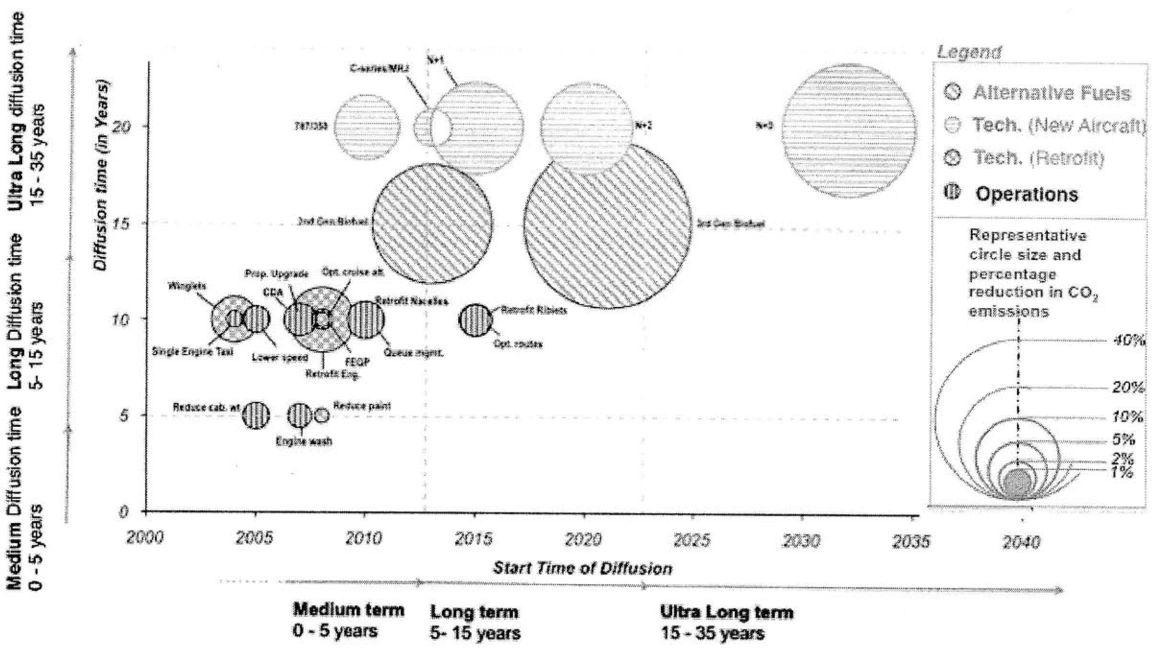

Figure 17: Distribution of Mitigating Measures based on Start Time and Diffusion Time

From Figure 17 several categories of mitigating measures can be identified depending on the time horizon of their estimated start of diffusion and diffusion time:

Measures that can provide rapid improvements in the medium term (i.e. *medium-term start date and medium diffusion time)* are mostly operational (e.g. reducing payload weight and engine washing). They have relatively low potential for improvements ranging from 0.5 to 2%.

Measures with *medium-term start date and long diffusion time* include retrofitting new engines on older aircraft, using laminar nacelles, upgrading the core of engines and adding winglets. Within this category, operational measures were also identified (e.g. single engine taxiing, queue management and controlled pushback and Continuous Descent Approaches, ground towing, using fixed electric ground power instead of APU and flying at optimum cruise levels and lower cruise speeds). The potential for reducing CO_2 emissions range from 0.5 to 7%.

Measures with *medium-term start date and ultra long diffusion time* include among others using composites for structures to reduce weight of aircraft, using no bleed architecture and developing new all (or more)-electric planes. The reductions in emissions from individual measures range from 1 to 20%.

Measures with *long-term start date of implementation and medium diffusion time* include a technology measure (riblets) and an operational measure (flying optimized routes). These measures have the potential to reduce emissions by 1 to 2% per measure.

Measures with *long-term start date and ultra long diffusion time* include technology measures such as new engines (e.g. geared turbofan, open rotor), next generation high bypass ratio engines, laminar flow airframes as well as N+1 and N+2 subsonic NASA aircraft. Second and third generation biofuels also exhibit these diffusion characteristics and have a significant potential for CO_2 lifecycle savings.

Measures with *ultra long-term start date and ultra long diffusion time* that tend to be less certain include new aircraft technologies like NASA N+3 aircraft and higher aspect ratio wings.

Component technologies that are expected to enter into the technology mix with next generation aircraft design are shown in Figure 18.

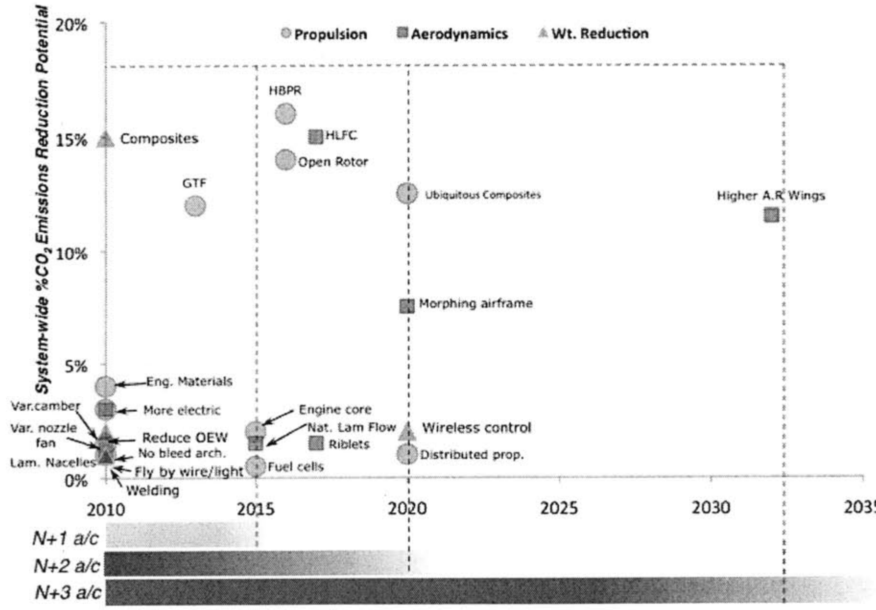

Figure 18: Estimated availability of component technologies for new aircraft designs (e.g. NASA N+1, N+2, N+3 programs) and their relative CO_2 emissions reduction potential

The largest reduction in emissions from the N+1 generation aircraft is expected to come from (1) next generation engines (like the GTF, HBPR or Open Rotor) and (2) the use of composite materials. Natural laminar flow wings, increased use of electric architecture, fly by wire systems are expected to have marginal effects on fuel consumption reduction. The N+2 generation aircraft could be developed using component technologies such as distributed propulsions, riblets along with the N+1 technologies; hybrid laminar flow control is expected to have the largest impact on improving fuel efficiency. Morphing airframes, ubiquitous composites and high aspect ratio wings are expected to be introduced within the N+3 generation aircraft.

Figure 18 also poses a strategic decision point for aircraft manufacturers. The design of the next generation single-aisle aircraft that will replace the Boeing 737/Airbus 320 will depend on the availability and the maturity of component technologies that reduce emissions. Between 2015 and 2020, several technologies become available that can significantly reduce fuel burn of the aircraft (e.g. HLFC). Aircraft manufacturers will have to trade-off between an early design freeze (i.e. early entry into service) and a later design freeze that will incorporate higher performance technologies. The decision does not solely depend on the availability of technologies but also on the market drivers – development cost, competition, economic conditions and the regulatory environment (e.g. imposition of CO_2 standards).

6.4 Cumulative estimation of the potential for CO_2 emissions reduction by category of measures

Based on the portfolio of measures presented in Table 5, an assessment of the relative potential for CO_2 emission reduction over time (by category of measures) was conducted. Using the Bass diffusion model presented in Chapter 5, S-curves were generated for each of the measures listed in the four categories of (1) *technology improvements through new aircraft*, (2) *technology improvements through the retrofit of components of existing aircraft* (3) *operational improvements* and (4) *alternative fuels*. Technology measures that are components and will be introduced with new aircraft were not included since they are accounted for in the potential reductions from new aircraft. Each S-curve was constructed using the parameters presented in columns 6-8 in Table 5 and formed the basis of an aggregate model to estimate potential fleet wide reduction in CO_2 emissions.

Several assumptions were made for the construction of the aggregate CO_2 reduction system model. For estimating the benefits, the baseline for system-wide fuel consumption (and CO_2 emissions) was set at the levels of the 2006 US fleet. The benefits from the four categories of measures were assumed independent from each other i.e. the adoption of one category of measure did not affect the uptake of another category.

To model the improvements from new aircraft introduction, the fleet itself was divided into four non-overlapping categories, based on the number of seats. In order to exclude the effects of changes in demand and therefore keep the total fleet size constant, each new aircraft was assumed to replace an older aircraft in one of these categories. The C-series/MRJ replaced aircraft in the 50-120 seat range, N+1/N+3 in the 120-200 seat range, B787/A350 in the 200-300 seat range, and N+2 in the 300 and above seat range. The N+3 aircraft replaced N+1 aircraft after entry into service. In-production aircraft from 2006 onwards entered the system till a newer generation aircraft in that seat category was available.

Retrofitting older aircraft with new technology was assumed to have two key diffusion dynamics: a) engines and engine cores were replaced on 10-year-old airframes and winglets, riblets and laminar nacelles were retrofitted on 5-year airframes during the first D-check and b) retrofits (and one time operational improvements such as reducing cabin weight) stay in the system till the older aircraft are replaced with newer aircraft. It was assumed that no new aircraft is retrofitted.

With regard to the diffusion of biofuels, the use of second-generation biofuels was assumed to continue till the third-generation biofuels are available. Both biofuels were used as 50-50 blends with regular jet fuel.

Figure 19 shows the cumulative reductions of CO_2 emissions from four categories of measures. The model suggests that retrofits and operational improvements have the potential to contribute to reductions in CO_2 emissions in the short to medium term. Significant reductions in emissions will only come from the adoption of new generation aircraft and alternative fuels once they reach the stage of fast diffusion (post 2025).

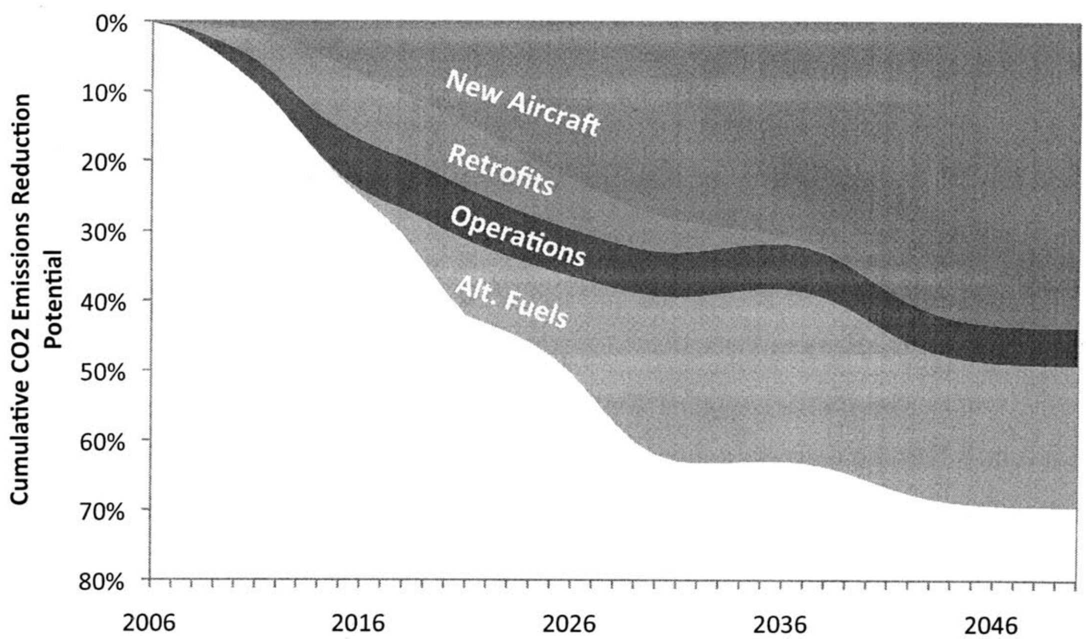

Figure 19: Cumulative Potential Reductions in CO_2 Emissions from 2006 to 2050

CHAPTER 7

MODELING THE DYNAMICS OF NEW AIRCRAFT DIFFUSION

7.1 Introduction

As shown in Section 6.4, technology improvement, specifically the adoption of new fuel-efficient aircraft, has the potential to significantly reduce aviation's emissions. However, transforming these potential benefits into actual benefits is dependent upon the rate of entry of new vehicles and the retirement of older generation aircraft that tend to stay in the fleet for a long time (average life of an aircraft is on the order of 25-30 years).

Chapter 5.2 showed that these benefits will depend on the complex trades between (1) technology/vehicle fuel efficiency improvement or *percent CO_2 reduction potential*, (2) the entry into service (EIS) of new technology/vehicle or the *start time of diffusion* and (3) the rate of entry into the fleet or the *diffusion time.*

As a result, there is the need to understand how the fleet efficiency will be influenced by the entry of various generations of aircraft with different levels of performance as well as the trades between the characteristic S-curve parameters.

In order to assess these trades, an Aircraft Diffusion Dynamic Model (ADDM) was developed using System Dynamics modeling approaches and techniques. The model was used to evaluate outcomes of several future potential scenarios as well as to perform sensitivity analyses of the S-curve parameters.

This chapter first presents the architecture of the model followed by the results of its calibration for the US narrow-body jet aircraft family. It then presents the input and assumptions for several potential scenarios and sensitivity analyses. Finally, it discusses the results from the analysis and their implications for future technology development, entry into the system and diffusion.

7.2 Description of the Aircraft Diffusion Dynamic Model (ADDM)

Architecture of the Aircraft Diffusion Dynamic Model

The objective behind constructing the aircraft diffusion dynamics model is to capture the dynamics of aircraft infusion and fleet turnover - entry, life and exit of aircraft from the fleet. The model will be used to analyze scenarios of complex trades between the S-curve parameters and to perform sensitivity analysis.

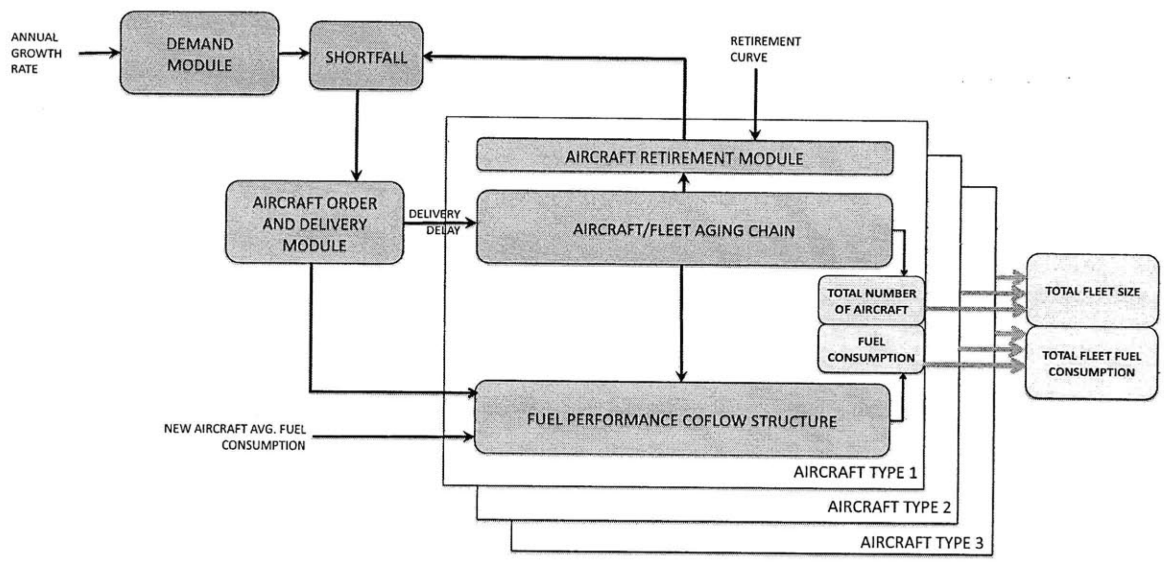

Figure 20: Architecture of the Aircraft Diffusion Dynamic Model (ADDM)[1]

As shown in Figure 20 the model is composed of five key components with four exogenous inputs:

(1) ***Aging chains*** are used to capture the dynamics of the rate of change of stocks as a function of the age of the stock. (Sterman 2001). In the airline industry, aircraft are generally retired from the fleet based on their age. The retirement module simulates the exit of aircraft from the system based on retirement curves. A retirement curve plots the cumulative probability of survival of an aircraft in the fleet. Figure 21 is a conceptual retirement curve that shows that the probability of survival of an aircraft of age 25 or lower is 80%.

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[1] The Aircraft Diffusion Dynamic Model was implemented in Vensim® DSS for Windows (Version 5.9e)

(2) ***Coflow*** structures are used to keep track of attributes of the stocks in the system. In this model they track the fuel consumption of aircraft stocks as they age and new aircraft with improved fuel consumption enter the system.

(3) ***Orders and Deliveries module*** capture the dynamics of aircraft entry and exit rates that are affected by the cyclical nature of the airline industry.

(4) ***Aircraft demand module*** that model the capacity needs from airlines to meet external demand for air transportation.

(5) ***Multi-layered fleet*** tracks fuel performance from different generations of aircraft in the fleet.

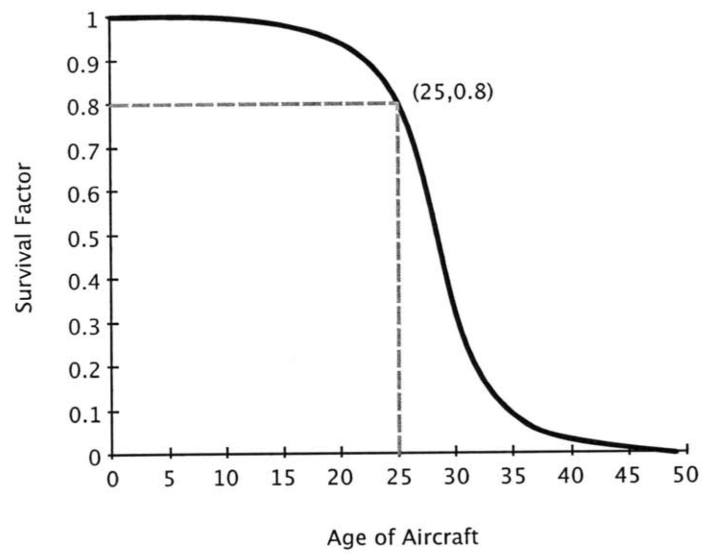

Figure 21: Conceptual retirement curve

Description of the Components of the Aircraft Diffusion Dynamic Model

i. Aging Chain Structure and Retirement Module

The Aircraft/Fleet aging chain module is based on 5 aircraft aging chain stocks (0-10 year old aircraft, 10-20 year old aircraft, 20-30 year old aircraft, 30-40 year old aircraft and 40 year and above aircraft. Figure 22 illustrates two such stocks. New aircraft enter into the 0-10 year old aircraft stock and the average time period of stay in the stock is 10 years after which aircraft enter the 10-20 year old aircraft stock. The total fuel consumption of each stock changes with the inflow and outflow of aircraft from the stock and is a function of the average fuel consumption of the stock.

Aircraft are retired from each aging chain stock based on their survival factor. For modeling purposes, the survival factor of the mid-range age aircraft is chosen to represent the stock of which it is a part (i.e. 25 year old aircraft represents 20-30 year stock). It should be noted that the conversion of retired aircraft into freighters or parking of aircraft during periods of low demand is not considered in this study.

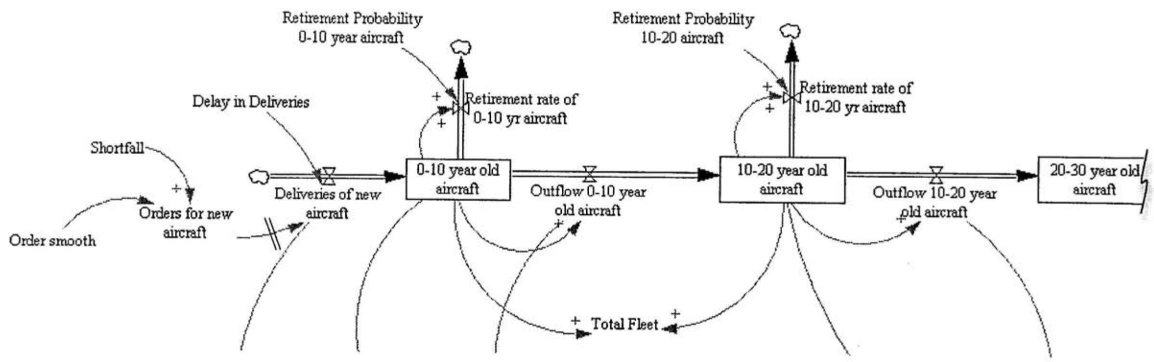

Figure 22: Aging chain structure

ii. Coflow Structure

In a coflow structure, each entity flowing into the stock adds the marginal attribute to the total attribute. Each unit flowing out removes the average attribute. As shown in Figure 23, the model uses the coflow structure to keep track of the fuel consumption of each aging aircraft stock. The assumption that each aircraft unit leaving the main stock removes marginal average fuel consumption of that stock is an approximation and a more accurate model would require higher order aging chains.

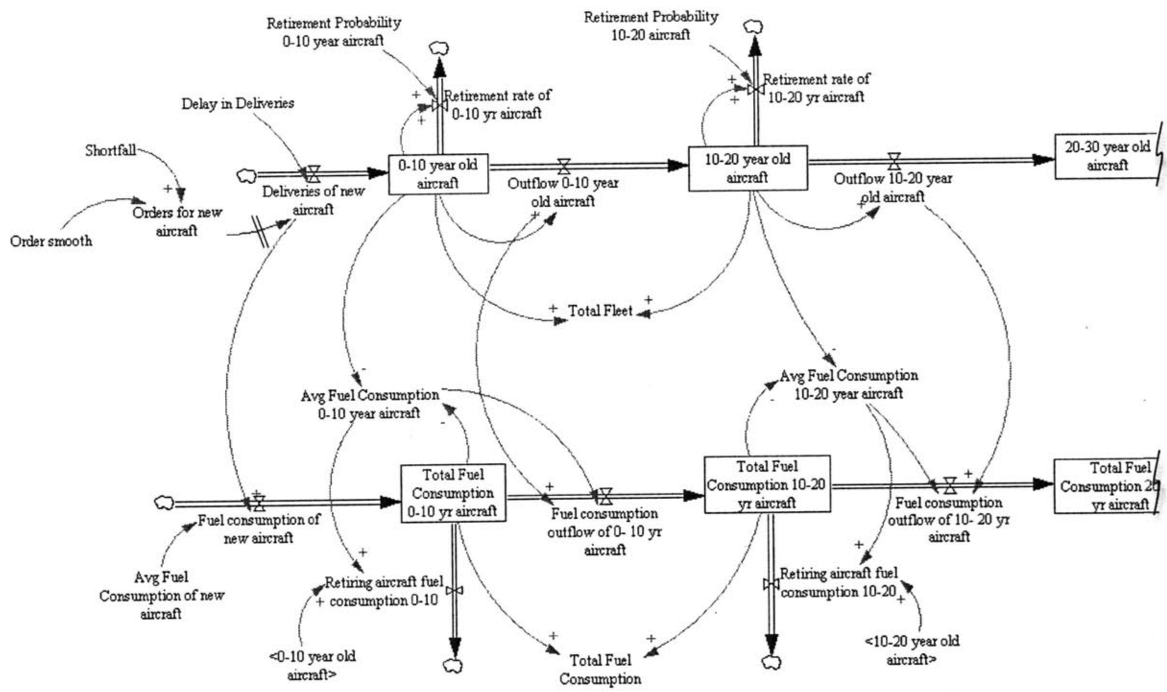

Figure 23: Fleet aging chain with fuel performance co-flow structure

iii. Orders/Deliveries Module

The entry of new aircraft is dependent on the airline orders and manufacturer deliveries. Section 7.4 illustrates the cyclical nature of the industry (i.e. orders and deliveries) that can be modeled using standard system dynamic delays. The model uses a two-step approach to model the dynamic delays – 1) It uses a first order delay to trend the exponential growth in demand and 2) uses a third order delay function to account for manufacturing and supply chain time lags (Sterman 2001) to model the industry cycle. The variable 'Order smooth' represents the aggressiveness of order placement. Higher order smooth values reflect lower aggressiveness to reduce the risk of errors from forecasting.

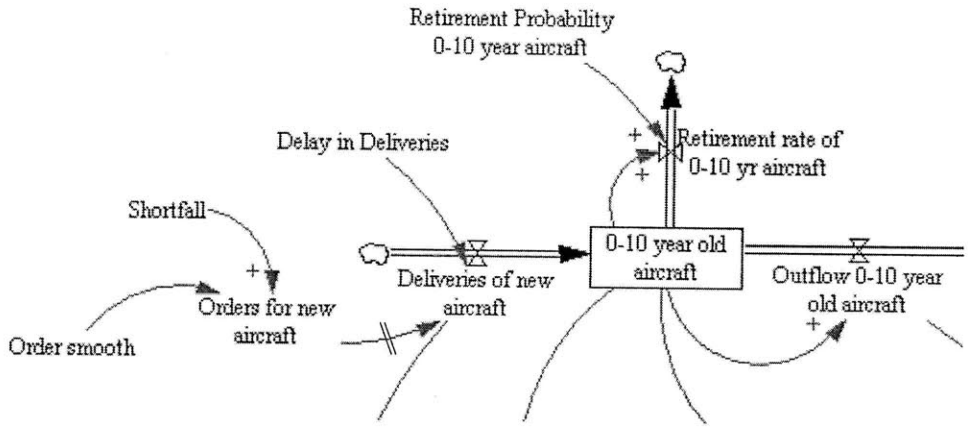

Figure 24: Orders/Deliveries and Retirement

iv. Aircraft Demand module

Demand for aircraft is modeled as an exponential function with a constant growth rate. The shortfall is the difference between the demand for new aircraft and the total fleet size. Shortfall is driven by retirements from the fleet and the growth in demand.

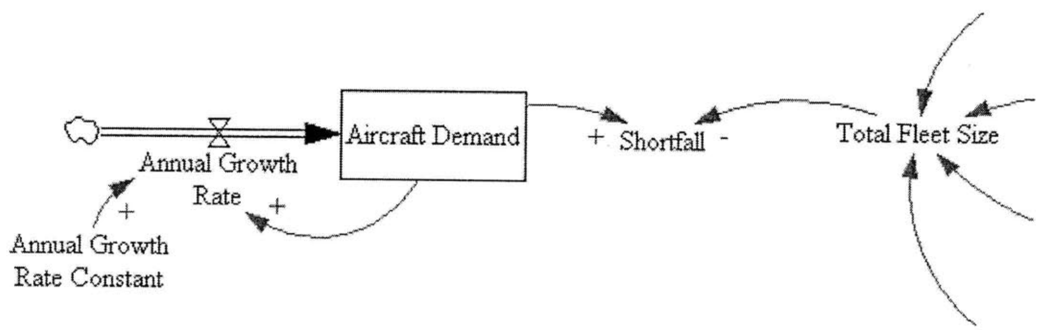

Figure 25: Demand module

v. Multi-Aircraft Type Layered Model

The fleet wide fuel performance at any time is dependent on the fleet mix that consists and will be composed of several generations of aircraft. Modeling each aircraft type with an aging chain and coflow structure captures the heterogeneity in the fleet mix. Four layers of aircraft types are used to represent four generations of aircraft:

- ***Current 2006 fleet*** that is made of older generation Boeing 737 and A320 models
- ***'In-Production' fleet*** i.e. models (new and re-engined B737/A320) being manufactured and delivered 2006 onwards,

- ***Next generation narrow body fleet (Gen +1)*** following the 'In-Production' generation
- ***Next to Next generation (Gen+2) narrow body fleet*** following the Gen+1 generation.

The complete multi-layered model is shown in Appendix C: Single Aisle SD Model – Causal Loop Diagram

vi. *Output of the Aircraft Diffusion Dynamic Model*

At any point in time, the fleet wide fuel consumption is given as:

$$FleetwideFuelConsumption = \sum_{FleetType} \#ofAircraft_{FleetType} \times Avg\,FuelConsumption_{FleetType}$$

where, $FleetType$ = {2006 aircraft, In production aircraft, Gen+1 aircraft, Gen+2 aircraft}

The scenario analyses use 2050 fleet fuel consumption as a metric to evaluate the sensitivity of the inputs. The total fuel consumption of the fleet at a particular time can be expressed as:

$$TotalF.C_{year} = TotalFleet_{year} \times AvgFleetF.C_{year}$$

$$= TotalFleet_{2006} \times e^{GR \times t} \begin{bmatrix} \%2006Aircraft_{year} \times 2006AvgF.C + \%In\Pr odAircraft_{year} \times In\Pr odAvgF.C + \\ \%Gen+1Aircraft_{year} \times Gen+1AvgF.C + \%Gen+2Aircraft_{year} \times Gen+2AvgF.C \end{bmatrix}$$

Equation 4

where , GR = Growth rate

F.C = Fuel Consumption

%Gen+1$Aircraft_{year}$ = Fraction of Gen+1 aircraft in the fleet

Gen+1Avg. F.C = Average fuel consumption of a Gen+1 aircraft

Based on the formulation of S-curves in 5.2, the fraction of a particular type of aircraft will be a function of growth rate (overall market size), diffusion time and the start time of diffusion.

$$\%Gen+1Aircraft_{year} = fn(GR, DiffusionTime, StartTime)$$

The average fuel consumption of the Gen+1 aircraft is also a function of the start time of diffusion as shown in Figure 34 i.e.

$$Gen+1Avg\,F.C = fn(StartTime)$$

Therefore, the response of the model to sensitivity scenarios will consider the output to the following variables:

1. Fleet composition i.e. number of aircraft in the fleet by aircraft type
2. Net fuel consumption of the fleet and each aircraft type normalized by 2006 fleet wide fuel consumption
3. Total normalized fleet wide fuel consumption and
4. Normalized fuel intensity defined as fleet wide fuel consumption/Fleet size

Given that most of the long-term industry CO_2 emission reduction use 2050 as a target date, the performance of the fleet is assessed in 2050.

Also, Fuel consumption ratio (FCR) = 2050 Fleet Fuel Consumption/2006 Fleet Fuel Consumption.

7.3 Scope of the Aircraft Diffusion Dynamic Model: Application to the Single Aisle Aircraft Category

The modules discussed above are generic and can be applied to study the evolution of any type of aircraft fleet provided the exogenous constants are known. Given the importance of the single aisle aircraft category (see Figure 26) in terms of number of aircraft and contribution to fleet wide emissions and potential for improvement, this study will focus on the US single aisle aircraft fleet. It specifically investigates the evolution of this category of aircraft in the context of the entry of the next generation fuel-efficient aircraft that will replace the current aging narrow body fleet.

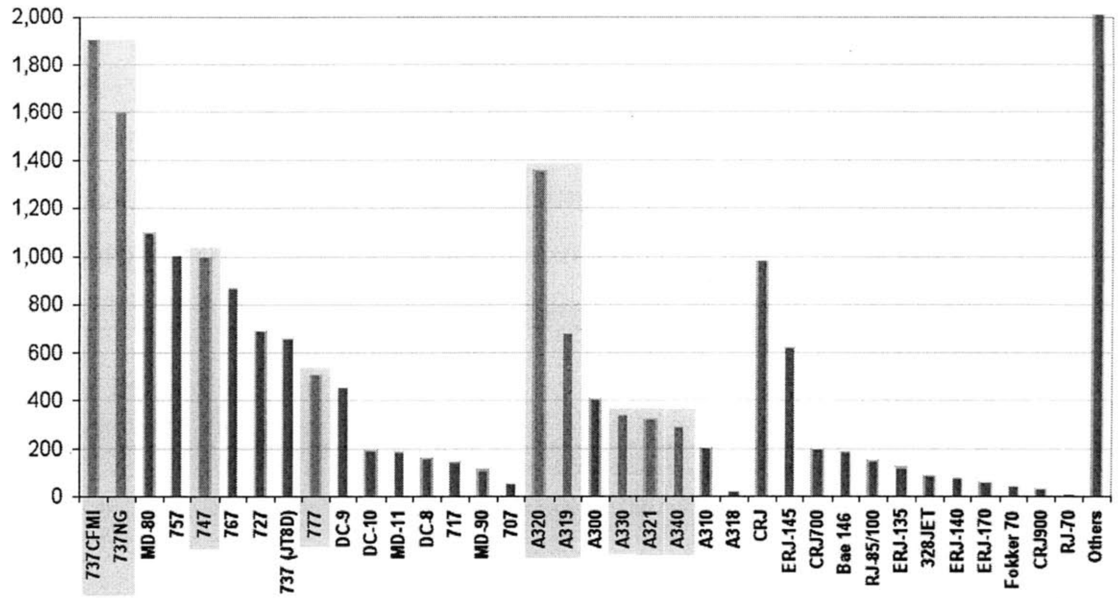

Figure 26: World Airline Fleet
(Source: ATW, data from Airclaims 2005)

7.4 Assumptions for the Calibration of the Aircraft Diffusion Dynamic Model

vii. Reference Fleet

The 2006 single aisle fleet information was extracted from BTS Form 41 Schedule B 43 database that reports data of airframe inventories by model type, number of seats and date of entry into service. Figure 27 shows the distribution of number of aircraft by age.

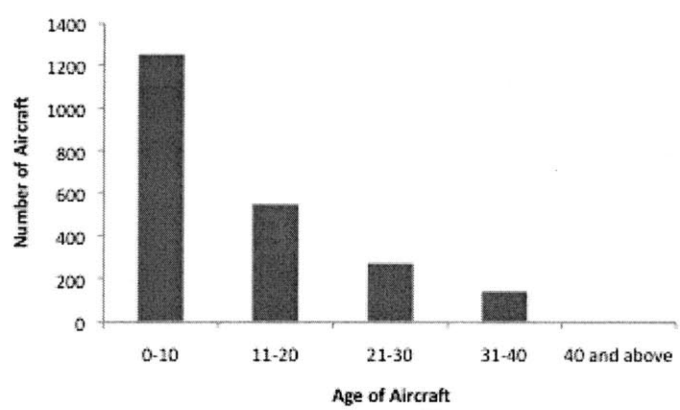

Figure 27: Distribution of 2006 single aisle fleet by age

viii. Reference Fleet Fuel Consumption

The average fuel consumption for each stock of the 2006 fleet in the aging chain model is calculated based on Piano-X (Lissys Ltd 2010) data of a representative aircraft model[1] and then normalized to the fuel efficiency of aircraft that are 0-10 years old in 2006. Efficiency changes from aging and maintenance is not considered in the model.

Table 6: Average fuel efficiency

Age (yrs)	Representative aircraft	Fuel Efficiency = Energy Fuel Burn / Payload*Distance	Normalized Fuel Efficiency*
0-10	737-800/900/A321-200	0.007	1.0
10-20	737-500/600/A320-200	0.009	1.3
20-30	737-300/400	0.009	1.3
30-40	737-200	0.010	1.4
40 and above	727	0.014	2.0

* Normalized to 0-10 yr old Fuel Efficiency

ix. Fleet Retirement

The dynamic of aircraft retirements are generally captured in aircraft retirement curves that describe the survival factor as a function of the age of the aircraft. The survival factor is defined as the cumulative probability of an aircraft less than or equal to a particular age, that will survive in the fleet. For the purpose of this model, the retirement curve for the 'All Others' category from Figure 28 was used because the Boeing 727 occupy a small percent of the 2006 fleet and the other aircraft fall in the wide-body category.

[1] http://www.boeing.com/commercial/737family/background.html

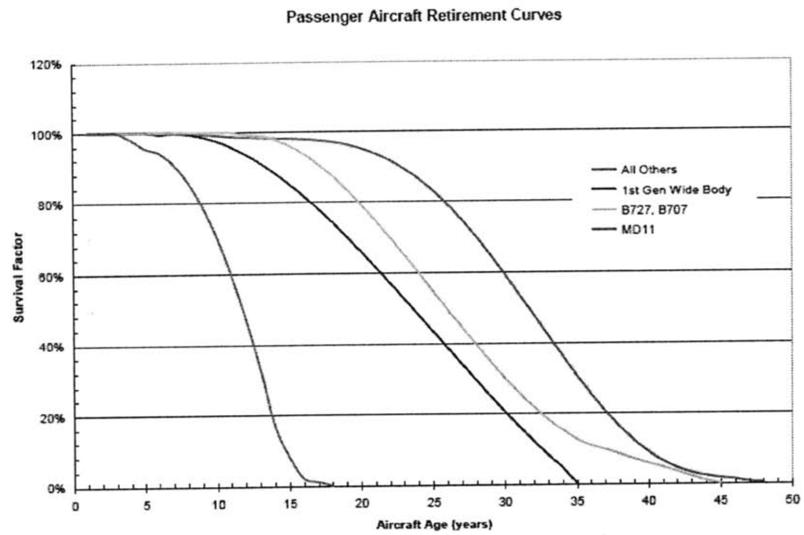

Figure 28: Passenger aircraft retirement curves
(Source: CAEP/8 Modeling and Database Task Force)

The ICAO Committee on Aviation and Environmental Protection (CAEP) published aircraft retirement curves in its *Fleet and Operations Module* (ICAO 2007) that is used as inputs to the retirement probability for each aging stock in the Aircraft Diffusion Dynamic Model.

To use this aircraft retirement curve as input to the model, the following ICAO equation was used with the coefficients shown in Table 7

$$Survival\ Factor = Const + Ax + Bx^2 + Cx^3 + Dx^4 + Ex^5 + Fx^6$$

Table 7: ICAO regression constants for retirement curve (ICAO 2007)

Constants	Const	A	B	C	D	E	F
Value	0.7912	0.0975	-0.0168	0.00135	-0.000053636	9.7731E-07	-6.58E-09

7.5 Calibration of the Aircraft Diffusion Dynamic Model

The world airline industry has been subject to boom and bust cycles. The cyclical nature of the industry is driven by the delays between the orders placed by airlines and the deliveries. As shown in Figure 29, airlines tend to place orders when they are profitable (airline profitability and orders exhibit high correlation). However, due to production lead times, the deliveries only occur several years after the orders are placed (see Figure 29). This mismatch between the need for capacity –when airlines are profitable- and the actual introduction of additional capacity from new deliveries drives the instability in the system and the profitability cycle.

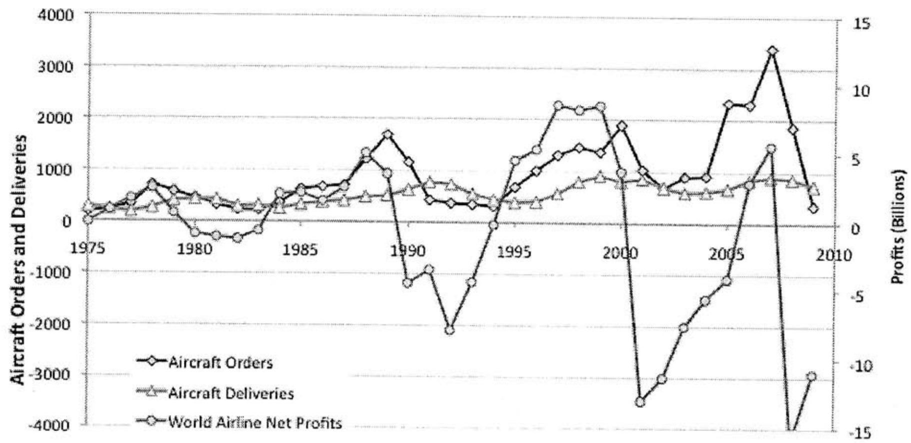

Figure 29: Boeing and Airbus orders and deliveries
(Data source: Orders & Deliveries: ICAO 2009, Financial: ICAO 2009 reported by ATA)

The profitability cycle in the industry is extremely uncertain to predict in the long term (i.e. 20-30 years) and the model uses a first order delay between the orders and deliveries, which does not produce cycles, to explore long term trends. To study the effects of the cycle in the short term on fleet performance, the model uses a third order delay between the orders and deliveries that generates a cycle. Historical data of orders and deliveries of Boeing 737 and Airbus 320 (all models) to the US airlines are used to calibrate the model and obtain estimates of the 'order smooth' and 'delay in deliveries' that provide the best fit for the data. These two models of aircraft represent approximately 85% of the single aisle fleet and can therefore approximate the fleet evolution. Yearly data for orders and deliveries of Boeing 737 and Airbus 320 aircraft only to US Airlines were obtained from two different sources: (1) Boeing database[1] and (2) Airbus data[2]

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[1] Database available at
http://active.boeing.com/commercial/orders/index.cfm?content=userdefinedselection.cfm&pageid=m15527

[2] Data from OAG – FleetiNet database (Courtesy of Simon Pickup, Business Operations Director, Airbus)

x. Model Calibration

The model was set up for calibration for two different purposes – 1) to represent the long-term trends in the industry and 2) capture the short-term industry cycles.

Figure 1 has shown the exponential growth trend in aviation worldwide over a period of 40 years. This trend was captured using a first order delay between orders and deliveries in the model shown in Figure 31 and was calibrated using the data from Figure 30. Short term effects from the airline cycle was modeled using a third order delay between orders and deliveries in the model and was calibrated using the same data from Figure 30. The model was calibrated using the automated optimization routine in Vensim that minimizes the square of the difference between the actual data and the model output for each time step by varying the exogenous variables.

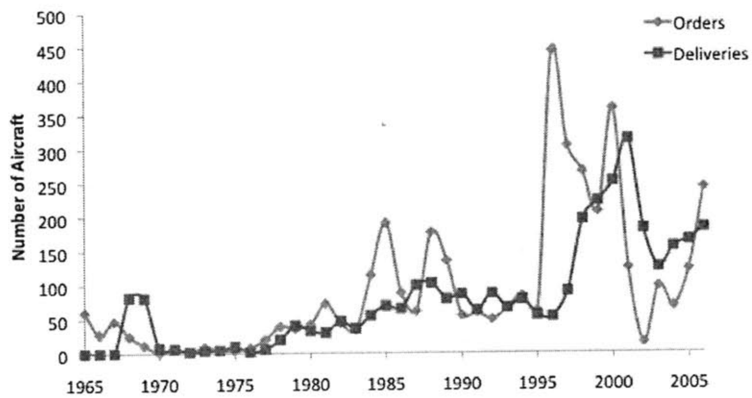


Figure 30: Boeing 737 family and Airbus 320 family orders and deliveries to U.S airlines

(Data Sources: Boeing, Airbus)

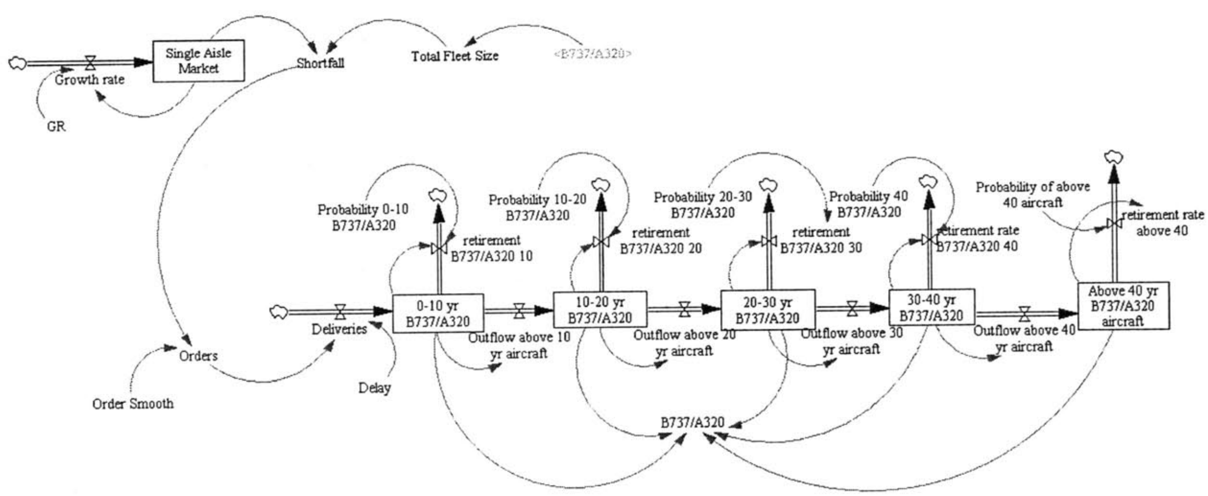
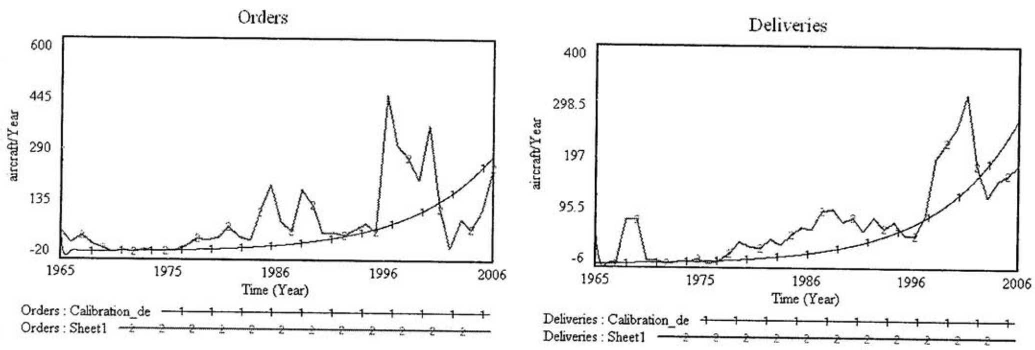


Figure 31: Model to estimate calibration constants – 'order smooth' and 'delay'

The output for the best fit is shown in Figure 33 and the following constants were obtained from the calibration exercise:

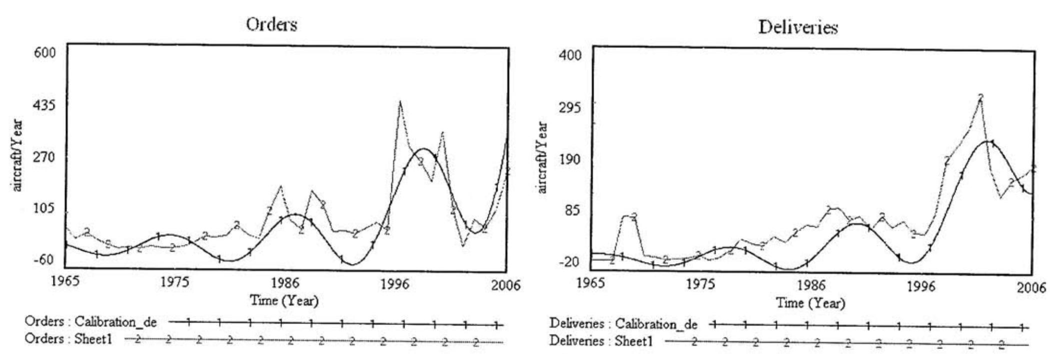
1st Order Delay (No cycle)



Variables	Values for Minimum Payoff
Order smooth	0.22
Delay	0.21 years
Number of Simulations	229
Payoff	-556303

Figure 32: Results of calibrating the Aircraft Diffusion Dynamic Model with historical data using first order fits

3rd Order Delay (With cycle)



Variables	Values for Minimum Payoff
Order smooth	0.86
Delay	3.85 Years
Number of Simulations	108
Payoff	-307129

Figure 33: Results of calibrating the Aircraft Diffusion Dynamic Model with historical data using third order fits

7.6 Definition of Assumptions and Scenarios

The model is used to examine the future fleet wide fuel consumption for a variety of scenarios:

- First, the effects of two technology improvement paths are assessed.
- Second, the effects of demand growth rates on fleet mix and performance are examined.
- Third, the impacts of early and late retirement on fleet performance are evaluated.
- Fourth, the effects of industry cycles on aircraft adoption rates and the fleet performance are tested and

A set of sensitivity analyses was then conducted to evaluate the effects of varying the dates of entry into service of new aircraft.

The list of technology options (i.e. re-engining and new aircraft designs) is presented in Table 8.

Table 8: Summary of technology mitigating measures

Mitigating Measure	Designation	Description	Assumptions
New Engine	RE-ENGINE	Re-engine B737/A320 with GTF	-12% in 2015
New Aircraft	N_{30}	Next generation single aisle aircraft with 30% efficiency improvement	-30% in 2020
New Aircraft	N_{50}	Next generation single aisle aircraft with 50% efficiency improvement	-50% in 2023
New Aircraft	N_{70}	Next generation single aisle aircraft with 70% efficiency improvement	-70% in 2035

RE-ENGINE refers to the option of upgrading the power plants of current generation In-Production aircraft with the next generation engines like the Geared Turbofan. N_{30}, N_{50} refer to the next generation narrow body (Gen+1) aircraft that are 30% and 50% more efficient than current generation planes and N_{70} refers to the next to next generation (Gen+2) aircraft that is 70% more efficient than current generation aircraft. Figure 34 presents the technology options in the context of historical evolution of fuel efficiency of the industry and also constructs two possible technology paths – i) *Emphasis on early entry into service of available technology* and ii) *Delayed entry into service for more fuel efficient technology*. These two scenarios capture the *entry into service vs. fuel efficiency improvement* trade-off. In one case, a less efficient aircraft may be introduced earlier whereas, in the other case, aircraft manufacturers may decide to wait and delay the entry into service for higher fuel efficiency.

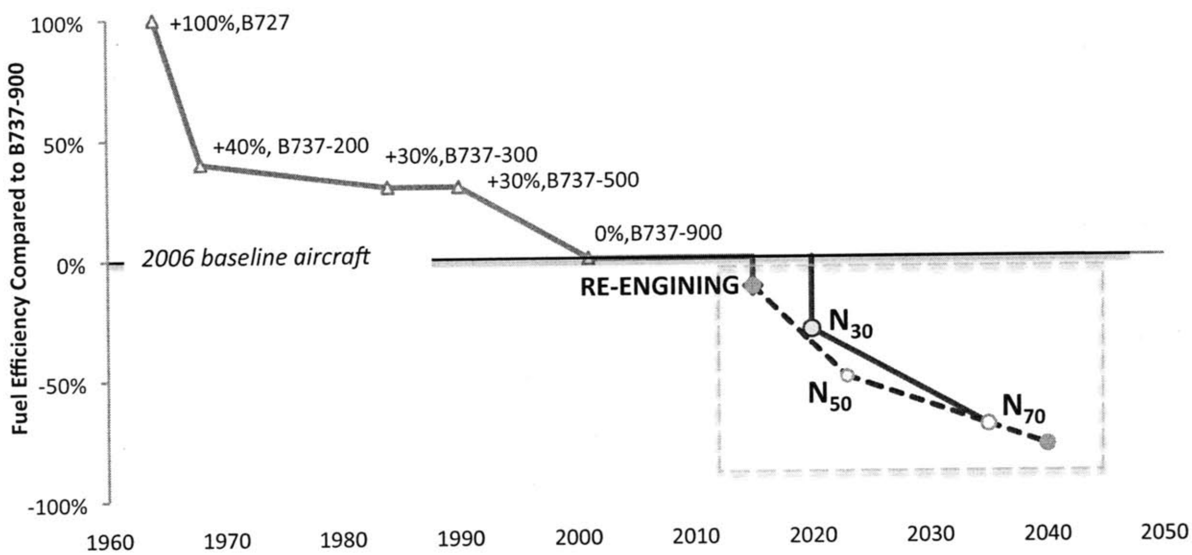


Figure 34: Historical evolution of single aisle aircraft fuel efficiency by entry into service dates and two technology improvement pathways (Inset – see Figure 35) (Data sources: Boeing, Piano X for historical data, and author's projections for future aircraft)

Scenario Analyses

This section describes the what-if scenarios and sensitivity analysis that are going to be tested using the Aircraft Dynamic Diffusion Model. The scenarios are a combination of technology, demand growth, fleet management (retirement) and industry cycles that are going to impact the adoption of new aircraft and influence the fleet fuel performance. Table 9 summarizes the list of scenarios that will be considered and the combinations that make up each scenario. Details of each scenario are provided in the section below.

Table 9: Scenario Assumptions

		Technology Path		Annual Demand Growth Rate			Shift in Retirement Curve			Type of Delay	
		Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
		RE-ENGINE, N_{50} and N_{70}	*N_{50} and N_{70}*								
WHAT-IF SCENARIOS	Tech. Path	✔			✔			✔		✔	
			✔		✔			✔		✔	
	Demand	✔		✔				✔		✔	
		✔			✔			✔		✔	
		✔				✔		✔		✔	
	Fleet Retirement	✔			✔		✔			✔	
		✔			✔			✔		✔	
		✔			✔				✔	✔	
	Cycle	✔			✔			✔			✔
SENSITIVITY ANALYSIS	Tech. Path	✔			✔			✔		✔	
			✔		✔			✔		✔	

xi. Effect of Technology Path on Fleet Performance

Next generation fuel-efficient narrow-body aircraft are expected to replace the current generation Boeing 737/Airbus 320 fleet. The fleet fuel performance will be determined by the relative efficiency improvement from the adoption of new technologies as detailed in Figure 18. While the fuel efficiency of the next generation aircraft is uncertain, estimates can be drawn from the NASA subsonic fixed wing program[1] and engine upgrades that manufacturers are considering to make current production aircraft more efficient. This research considers the following technology strategies constructed on decisions taken by the manufacturer about the time of entry of the next generation narrow body aircraft/engines:

<u>Emphasis on early entry into service of technology:</u>

In this scenario, the manufacturers re-engine the In-Production aircraft with the geared turbofan engine in 2015 and introduce an early version of the N_{70} aircraft – the N_{50} in 2023. This aircraft is consistent with recent MIT findings of "a version that could be built

[1] http://www.aeronautics.nasa.gov/fap/subfixed.html

with conventional aluminum and current jet technology that would burn 50 percent less fuel and might be more attractive as a lower risk, near-term alternative" (Bettex 2010). The N_{70} is introduced in 2035 as the Gen+2.

Strategy of delayed entry into service with more fuel-efficient technology:

Under this scenario, the manufacturers do not re-engine the In-Production aircraft in 2015 but introduce a more 'technology mature' next generation aircraft the N_{30} in 2020 that is 30% more fuel-efficient than the Boeing 737-900 aircraft. The next to next generation aircraft –the N_{70} is introduced in 2035 with 70% less fuel burn than the 737-900.

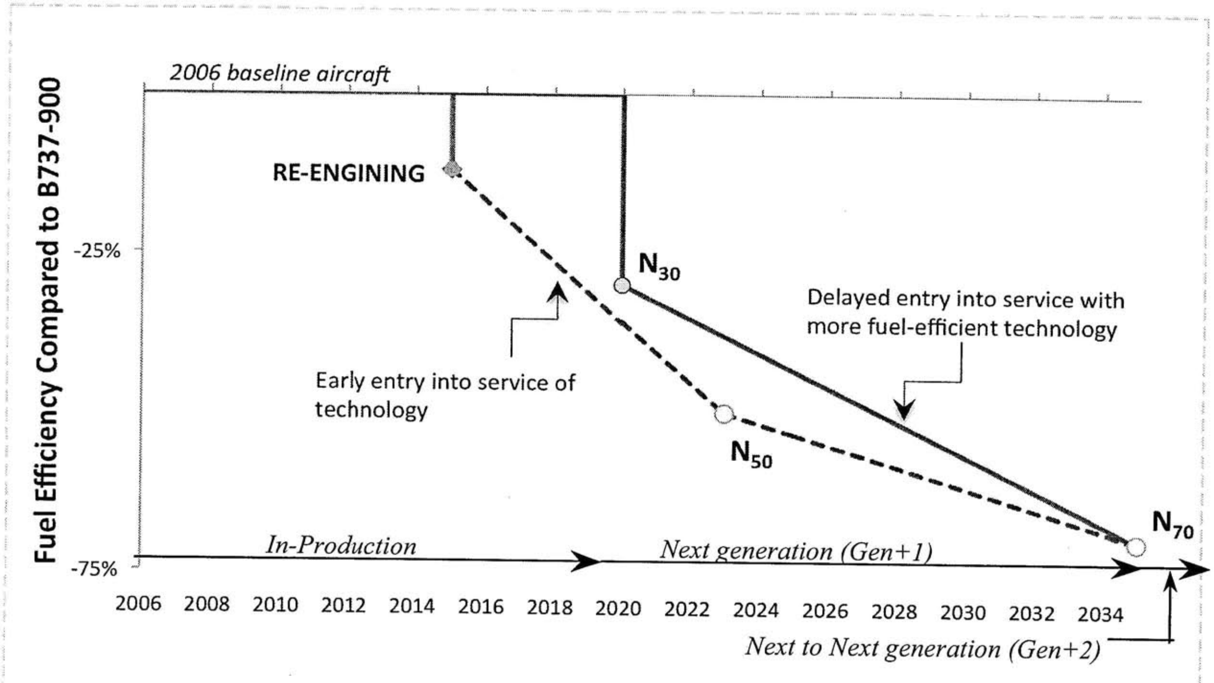


Figure 35: Aircraft technology improvement scenarios by generation of aircraft

xii. *Effect of Demand Growth on Fleet Performance*

The ADDM is tested with three different demand scenarios – annual growth rates of 1, 3 and 5% as shown Figure 36. The three scenarios are placed in the perspective of historical demand growth since the 1990s.

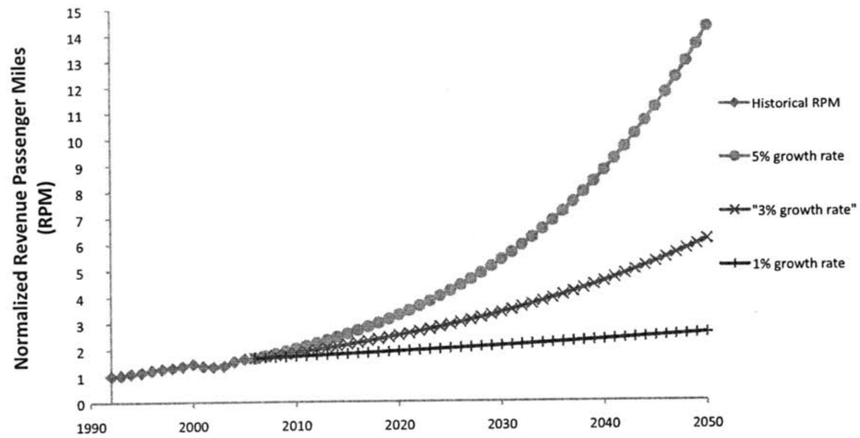


Figure 36: Exponential demand growth scenarios in scheduled revenue passenger miles

The effect of demand growth rate is tested on the re-engining and late but more efficient entry scenario technology path for a baseline retirement case and without industry cycles.

xiii. *Effect of Fleet Retirement on Fleet Performance*

The impact of different retirement rates on the fleet performance is tested. The baseline retirement curve is shifted by ±10% to get faster and slower fleet turnover as shown in Figure 37. The effects on fleet performance are tested using the Aircraft Diffusion Dynamic Model on the *Early entry into service of technology* scenario.

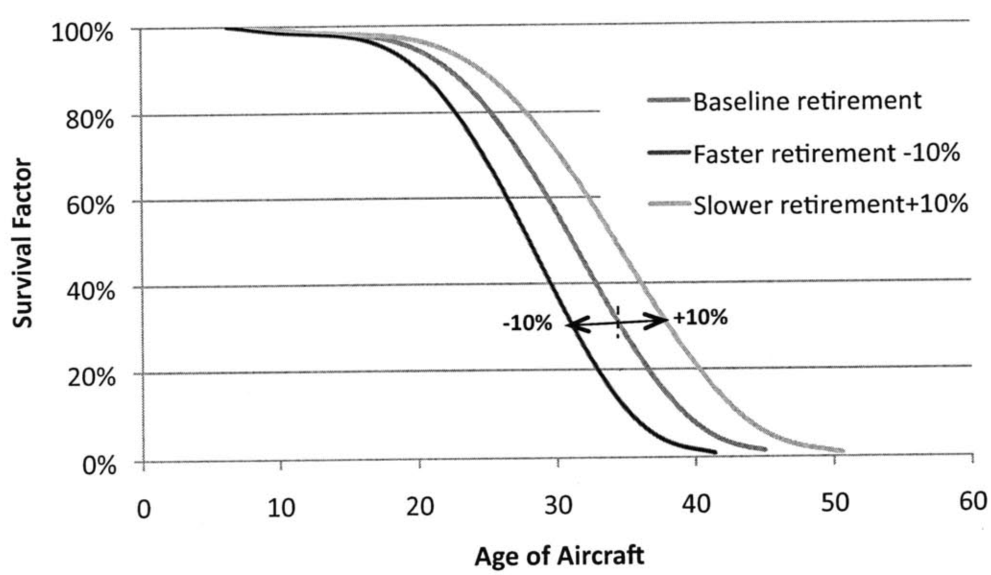


Figure 37: Retirement curve scenarios

xiv. Effect of Industry Cycle on Fleet Performance

In this scenario, the effect of industry cycles on aircraft diffusion rates and fleet performance is tested. The cycle is generated using the constants extracted from the calibration exercise shown in Figure 33.

xv. Sensitivity of New Aircraft Entry into Service on Fleet Performance

Aircraft entry dates for the aggressive entry intro service scenario is varied to test the sensitivity on fleet wide fuel consumption. When testing the sensitivity, it is assumed that the efficiency changes linearly, depending on the entry dates as shown in Figure 38.

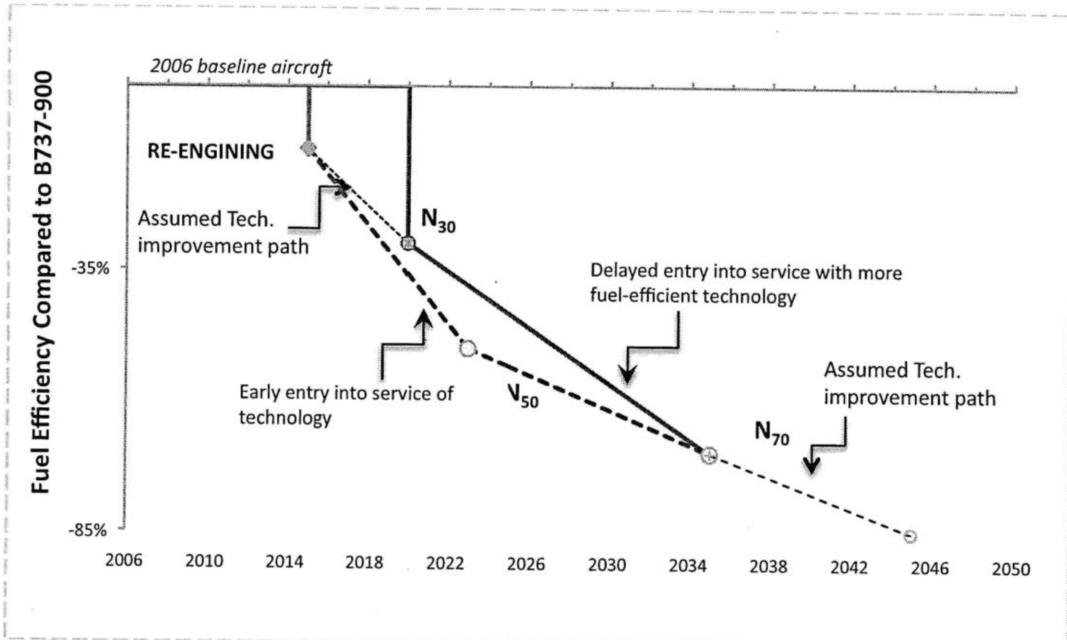


Figure 38: Assumed variation of performance with entry into service dates for sensitivity analysis

The following ranges are tested –

<u>Early entry into service of technology:</u>

Entry into service of N_{50}: 2020 to 2030

Entry into service of N_{70}: 2030 to 2045

<u>Delayed entry into service with more fuel-efficient technology:</u>

Entry into service of N_{30}: 2015 to 2030

Entry into service of N_{70}: 2030 to 2045

7.1 Simulation Results

xvi. *Effect of Technology Path on Fleet Performance*

Setup:

	Technology Path		**Annual Demand Growth Rate**			**Shift in Retirement Curve**			**Type of Delay**	
	Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
	RE-ENGINE, N_{50} and N_{70}	*N_{30} and N_{70}*								
Tech. Path	✔			✔			✔		✔	
		✔		✔			✔		✔	

The comparison of fleet fuel consumption for the two technology path scenarios shows that the *early entry into service of technology* case has better fuel performance in the 2050 time frame (Figure 39). Introducing the N_{50} aircraft in 2023 allows more time for the In-production re-engined aircraft to diffuse into the fleet and they occupy a larger percentage of the fleet in 2050 as compared to the 'Delayed entry into service of technology' scenario. The difference in fuel burn from the in-production fleet between these two scenarios is not large because of the higher efficiency of the re-engined aircraft. At the same time, introducing the N_{30} in 2020 as compared to the N_{50} in 2023 causes a higher number of inefficient (30% vis-a-vis 50%) next generation aircraft in the 2050 fleet. This results in a better fuel performance of the *early entry into service of technology* case.

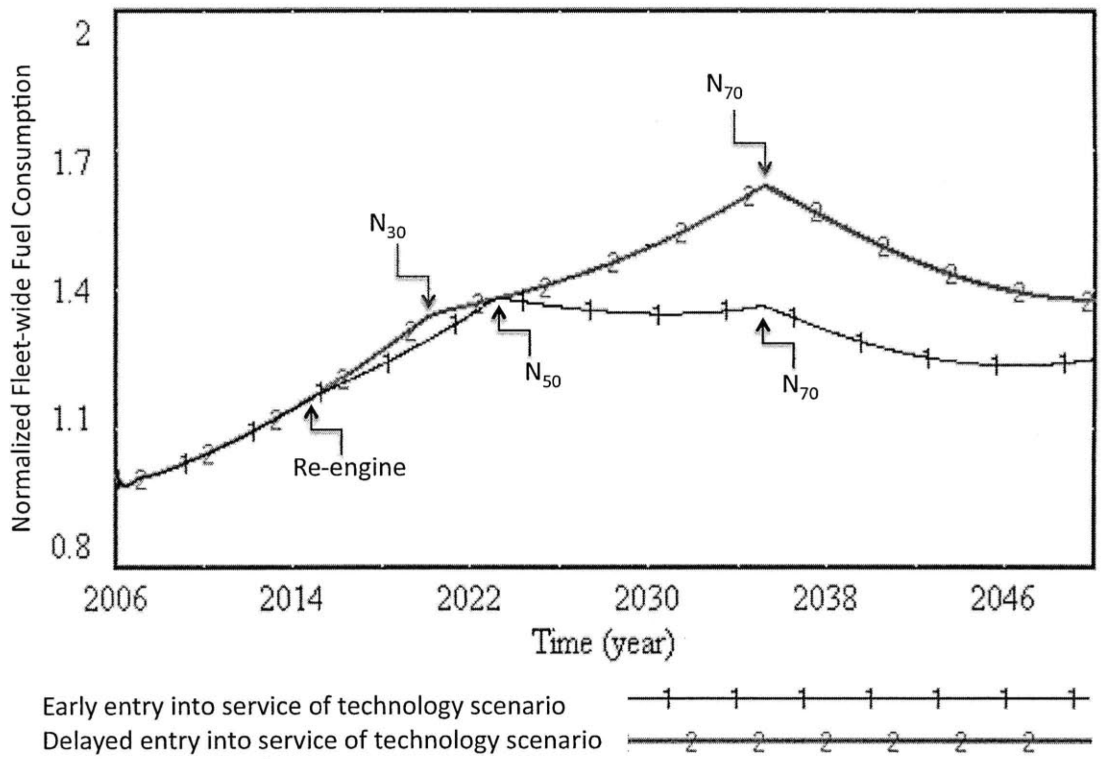


Figure 39: Normalized fleet fuel consumption under 'Early entry into service of technology' and 'Delayed entry into service with more fuel-efficient technology' scenarios

xvii. Effect of Demand Growth on Fleet Performance

Setup:

	Technology Path		Annual Demand Growth Rate			Shift in Retirement Curve			Type of Delay	
	Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
	RE-ENGINE, N_{50} and N_{70}	*N_{30} and N_{70}*								
Demand	✔		✔				✔		✔	
	✔			✔			✔		✔	
	✔				✔		✔		✔	

Figure 40 shows the normalized fleet fuel consumption under three annual demand growth rates. Fleet fuel consumption is below 2006 levels only for a 1% demand growth scenario.

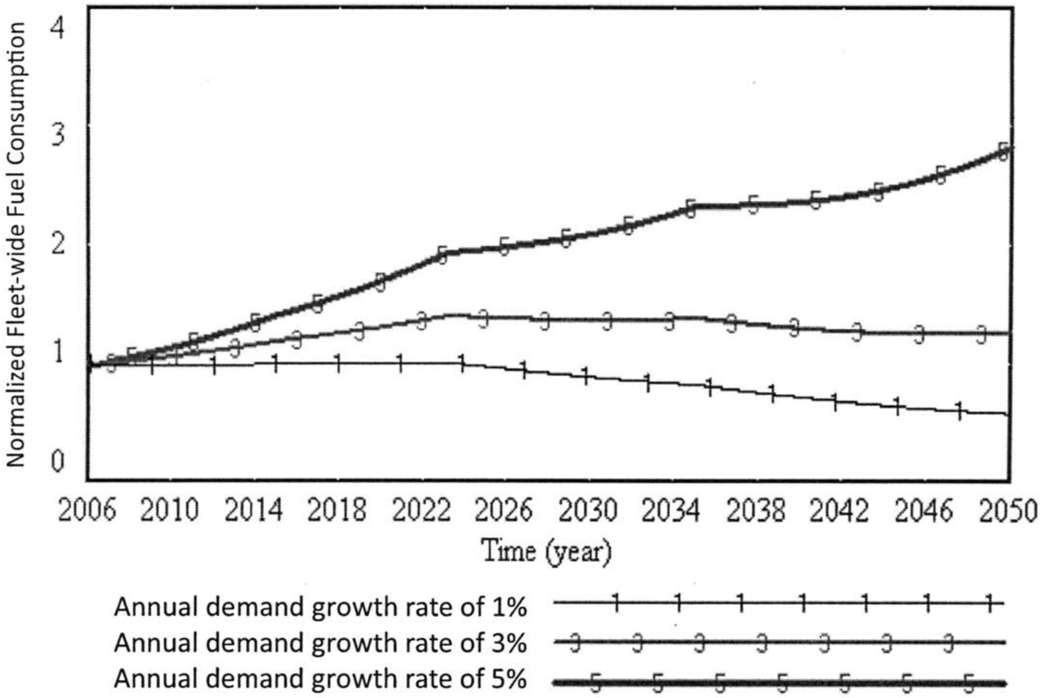


Figure 40: Normalized fleet consumption for 1, 3, 5% annual demand growth scenarios

The diffusion of an aircraft type in the fleet is sensitive to the growth rate as shown in Figure 41. The higher the growth rate the shorter the time to diffuse. This can be explained by considering the example of diffusion and retirement of the N_{50} and N_{70} aircraft. The Gen+1 aircraft continues to be ordered till the N_{70} becomes available. If the growth rate is higher, and the N_{70} is not available, a larger number of N_{50} aircraft will be ordered to meet demand and N_{50} will occupy a higher percentage of the fleet mix. Also, when there is a larger percentage N_{50} aircraft in the fleet, there will be a higher number of retirements that are N_{50} aircraft. The growth rate affects the fleet mix at any instant of time by increasing diffusion and in turn retirement rates. Figure 42 tracks the fuel intensity of the fleet (normalized to the 2006 fleet fuel intensity) over time. Higher annual demand growth rate reduces the fleet fuel intensity by enforcing increased diffusion of the more efficient aircraft - the N_{70}.

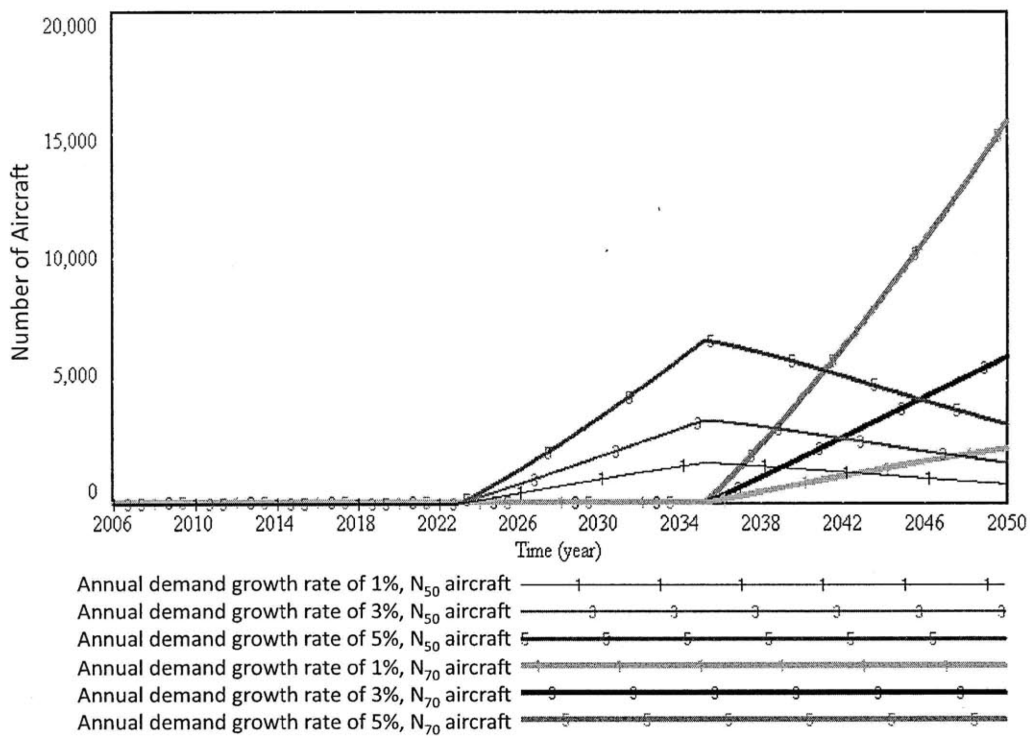


Figure 41: Effect of annual demand growth rate on the diffusion of N_{50} and N_{70} aircraft

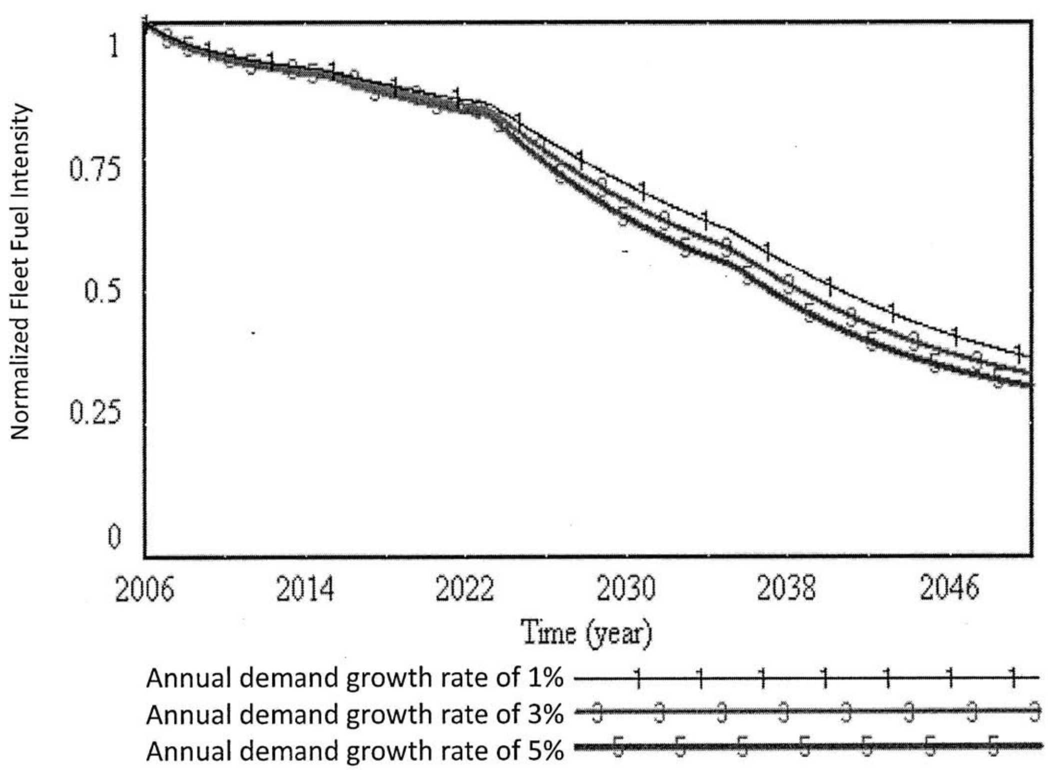


Figure 42: Normalized fuel intensity for 1%, 3% and 5% annual demand growth rate

Setup:

	Technology Path		Annual Demand Growth Rate			Shift in Retirement Curve			Type of Delay	
	Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
	RE-ENGINE, N_{50} and N_{70}	*N_{30} and N_{70}*								
Fleet Retirement	✔			✔		✔			✔	
	✔			✔			✔		✔	
	✔			✔				✔	✔	

In this scenario, the fleet mix determines the fuel consumption in 2050 (Figure 43) since the efficiency improvement is kept constant with the time of entry of new aircraft. With higher retirement rates, the 2006 fleet expectedly declines faster. This creates a shortfall in the industry that is taken up by higher orders and deliveries of In-production aircraft. Similar dynamic is exhibited by the take-up of N_{70} aircraft with higher N_{50} retirement. With faster retirement, the fleet is 2% more fuel efficient in 2050 than the baseline scenario. With slower retirement, the fleet is 1.8% less fuel efficient in 2050.

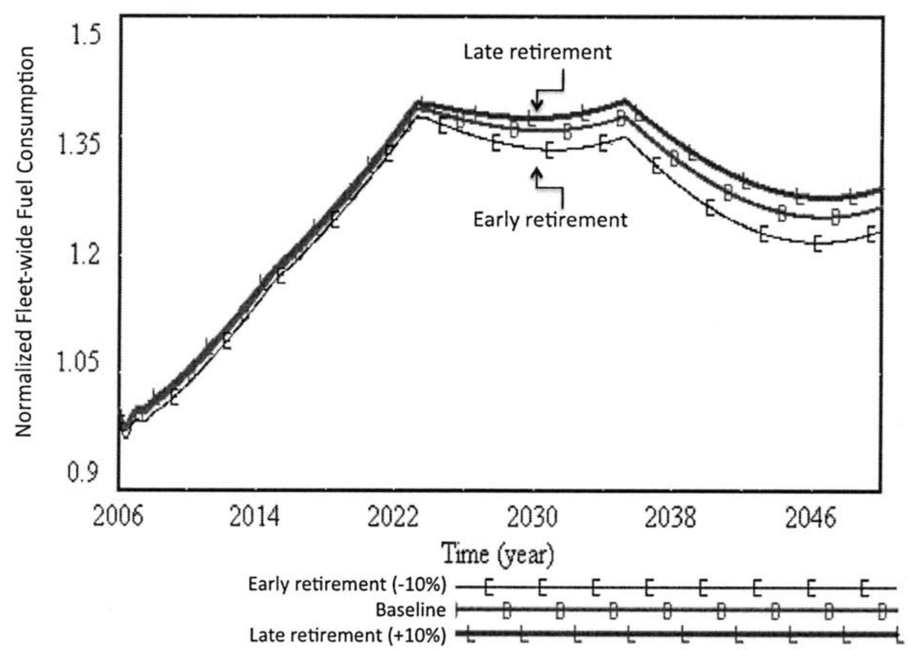


Figure 43: Normalized fuel consumption for early, baseline and late retirement scenarios

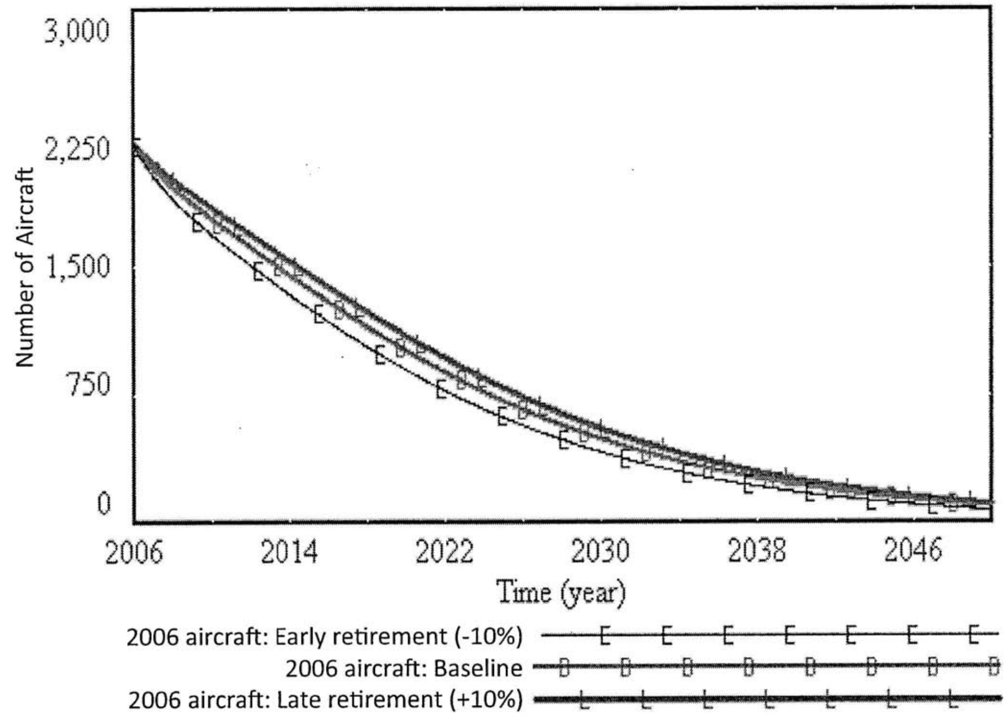


Figure 44: Effect of retirement rates on the diffusion and retirement of the 2006 fleet

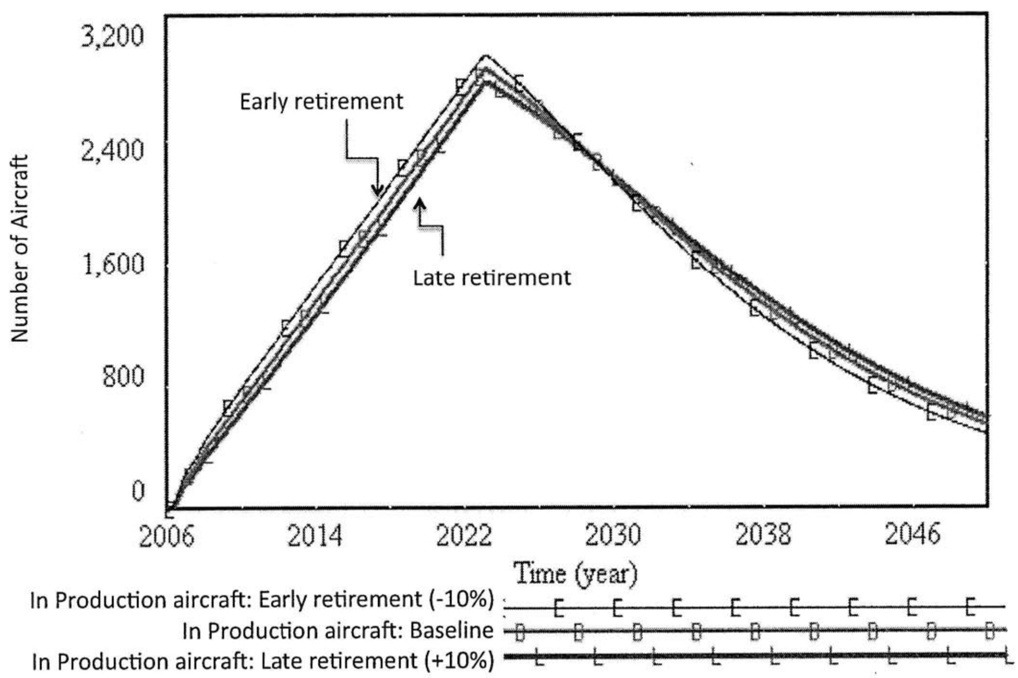


Figure 45: Effect of retirement rates on the diffusion and retirement of the In-Production fleet

xix. *Effect of Industry Cycle on Fleet Performance*

Setup:

	Technology Path		Annual Demand Growth Rate			Shift in Retirement Curve			Type of Delay	
	Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
	RE-ENGINE, N_{50} and N_{70}	*N_{30} and N_{70}*								
Cycle	✔			✔			✔			✔

The effect of the airline industry cycle on the fleet wide fuel burn is shown in Figure 46. While it is difficult to predict the cycle in the long term, its effect on the adoption of new aircraft in the short to medium term cannot be de-emphasized. The timing of the new aircraft entry into service with respect to and upturn or downturn in the industry cycle is vital to its fast adoption.

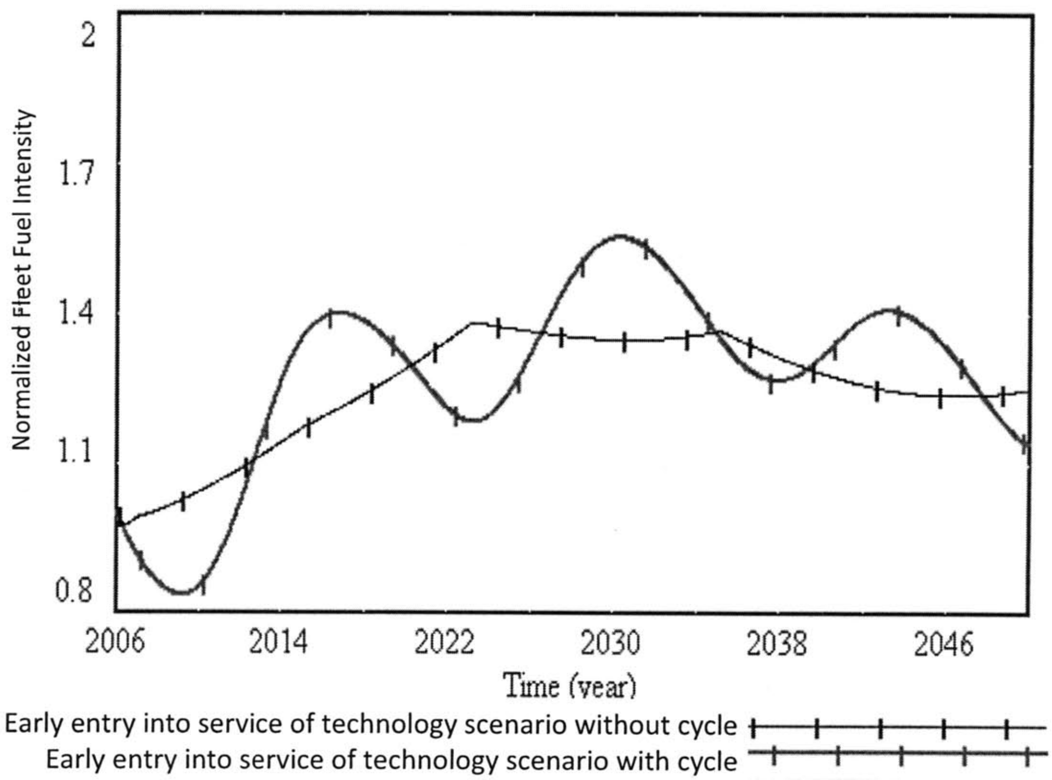


Figure 46: Effect of airline industry cycle on normalized fleet fuel consumption

Industry down cycles can, in some cases, significantly delay the diffusion rate (see In-production and Gen+1 aircraft adoption in Figure 48) and timing of the aircraft entry into service has to be synchronized with the cycle for maximum penetration (i.e. a trade exists between the timing and the diffusion rate). The timing of the introduction of new aircraft also determines the retirement of inefficient generations of aircraft. The order rate for new aircraft (i.e. the diffusion rate) depends on the retirements from the fleet. One example of a trade-off is: retiring the In-Production aircraft faster by introducing the Gen+1 earlier can lead to a high number of Gen+1 aircraft in the fleet. The long time that the Gen+1 aircraft stays in the fleet can block the fast adoption of Gen+2 aircraft and adversely affect the 2050 fleet wide fuel consumption.

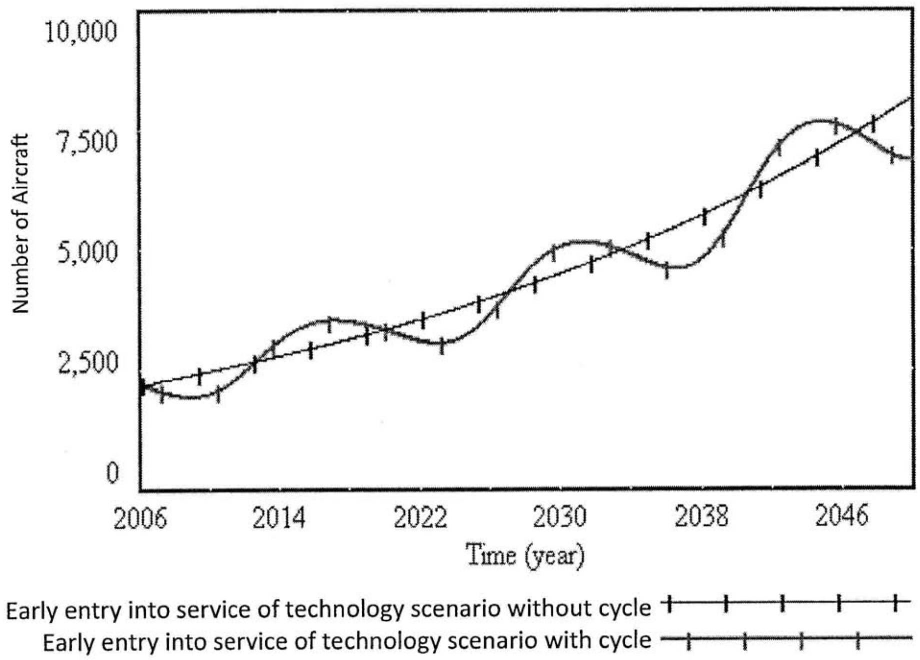


Figure 47: Airline industry cycle and fleet evolution

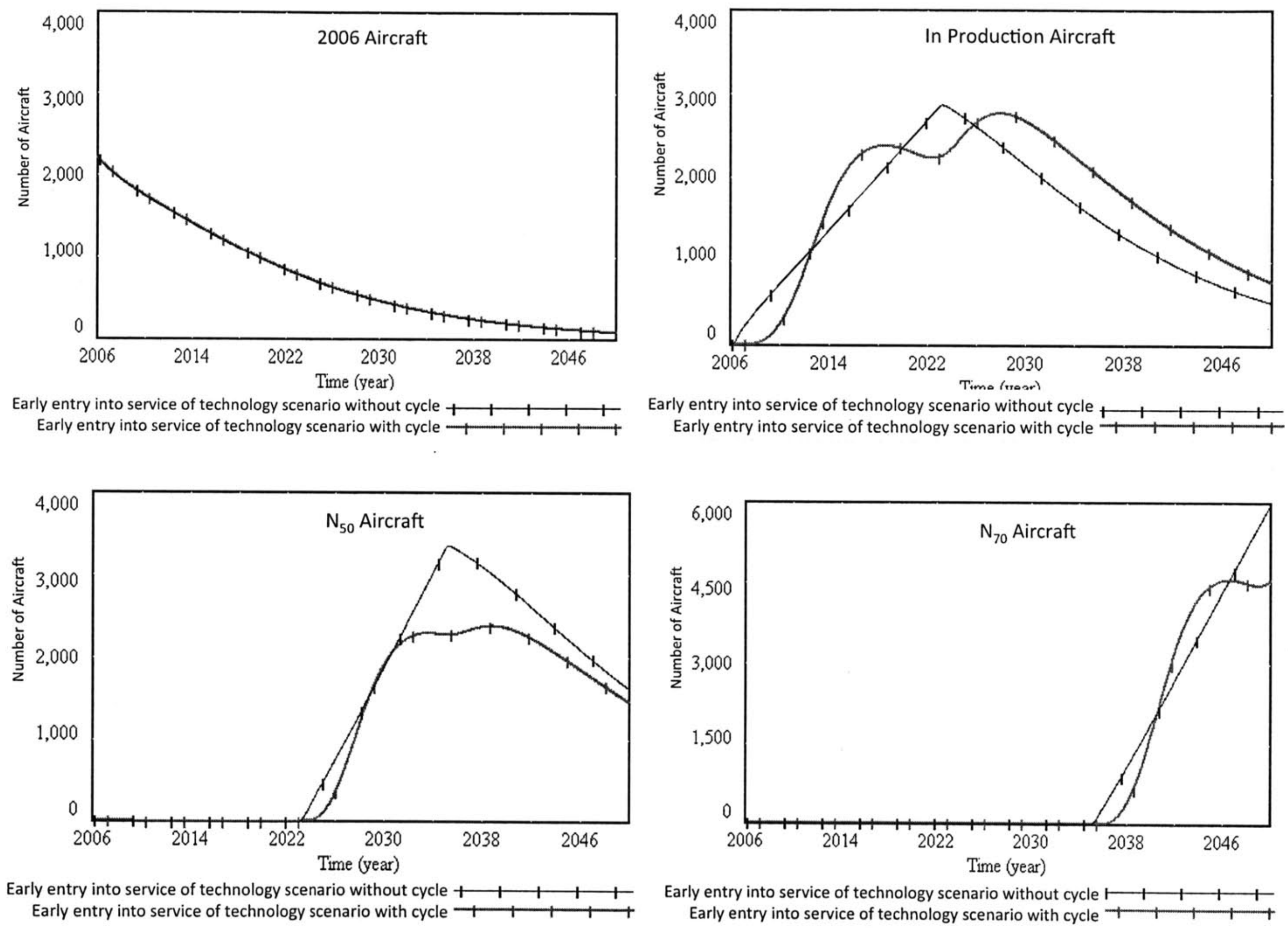


Figure 48: Airline industry cycle and fleet mix

xx. Sensitivity of New Aircraft Entry into Service on Fleet Performance

Setup:

	Technology Path		Annual Demand Growth Rate			Shift in Retirement Curve			Type of Delay	
	Early entry into service of technology	Delayed entry into service with more fuel-efficient technology	1%	3%	5%	-10%	0%	10%	1st order	3rd order
	RE-ENGINE, N_{50} and N_{70}	*N_{30} and N_{70}*								
Tech. Path	✔			✔			✔		✔	
		✔		✔			✔		✔	

The following ranges are tested –

<u>Early entry into service of technology:</u>

Entry into service of N_{50}: 2020 to 2030

Entry into service of N_{70}: 2030 to 2045

<u>Delayed entry into service with more fuel-efficient technology:</u>

Entry into service of N_{30} : 2015 to 2030

Entry into service of N_{70} : 2030 to 2045

The results from the two sensitivity scenarios are shown in Figure 49 and Figure 51 and can be explained using Equation 4 and the dynamics of fleet evolution.

For the best performance in terms of fleet wide fuel consumption in 2050, the fleet has to be ideally composed of the most efficient aircraft (the Gen+2) and the lowest number of the inefficient aircraft. This can be achieved by: introducing the most efficient aircraft early and retiring the inefficient aircraft. However, the coupled nature of the fleet turnover system gives rise to trade-offs in the following way:

1. <u>Trade between Efficiency and Start time:</u> The efficiency of the aircraft is a function of when it is introduced into the fleet. Thus, introducing an aircraft early can make it occupy a larger share of the fleet but only at the cost of efficiency (See Figure 38).
2. <u>Trade between Start time and Diffusion time:</u> The share of the fleet that the aircraft occupies depends on the time that it has to diffuse.

3. <u>Trade between Start time and Diffusion rate:</u> The timing of the introduction of new aircraft determines the retirement of inefficient categories of aircraft. The order rate for new aircraft (i.e. the diffusion rate) depends on the retirements from the fleet. One example of a trade-off is: retiring the In-Production aircraft faster by introducing the Gen+1 earlier can lead to a high number of Gen+1 aircraft in the fleet. The long time that the Gen+1 aircraft stays in the fleet can block the fast adoption of Gen+2 aircraft and adversely affect the 2050 fleet wide fuel consumption.

Case: <u>Early entry into service of technology:</u>

The results from the sensitivity analysis are shown in Figure 49. The minimum fleet fuel burn in 2050 is attained when the entry of the N_{50} and N_{70} aircraft are at 2027 and 2040 respectively. Delayed entry of the next generation of aircraft result in a higher number of In-Production aircraft to diffuse into the fleet. Around the 2040 time period a significant number of this category of aircraft retire, abetting the diffusion of the more efficient N_{70}. The minimum point of entry is reached for an optimal combination of fleet mix and efficiency as shown in Equation 4. The evolution of the fleet wide fuel consumption for the baseline entry (i.e. 2023 and 2035) is plotted against the optimal entry (2027,2040) in Figure 50. Delayed entry of the N_{50} and the N_{70} causes higher fuel burn in the short term but the fleet has better fuel performance in the long run. This result also shows that the optimal choice of entry dates will be strongly affected by the choice of horizon at which minimum fuel burn is being calculated.

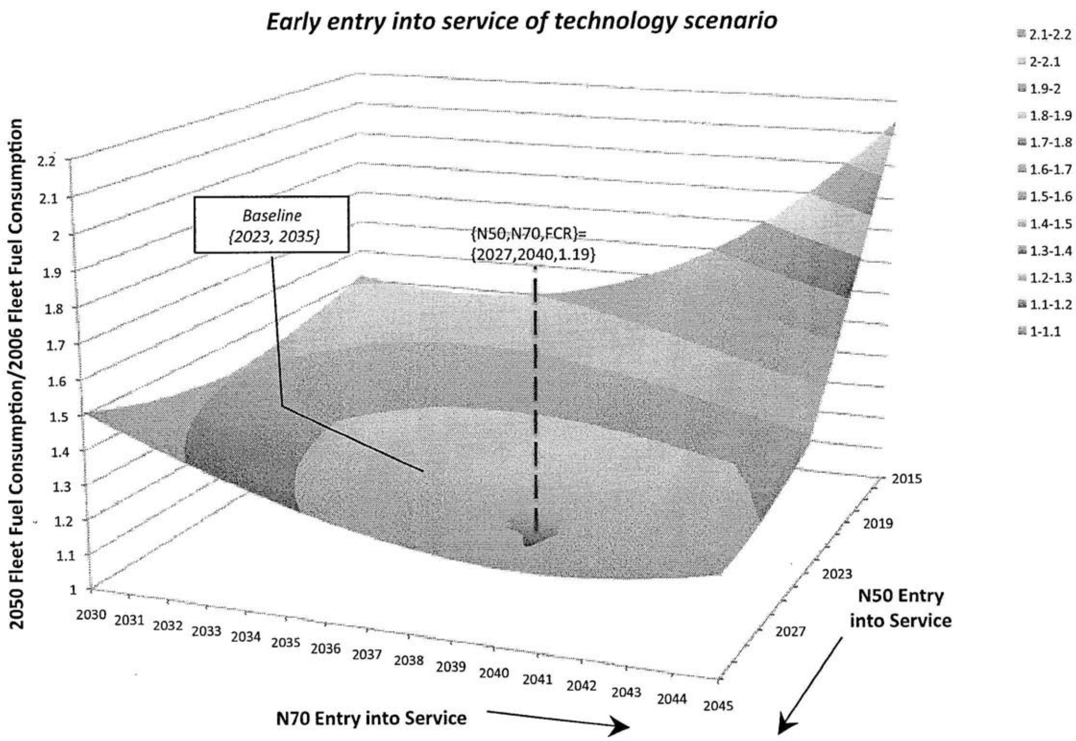


Figure 49: Effect of entry dates for N_{50} and N_{70} aircraft on 2050 fleet fuel consumption for 'Early entry into service of technology' scenario

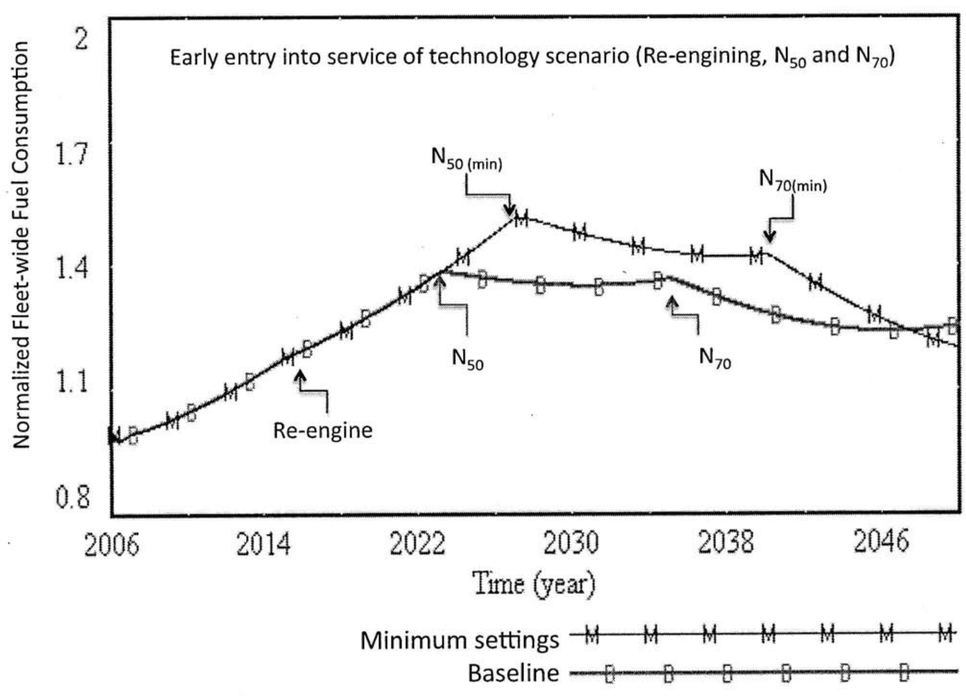


Figure 50: Normalized fleet fuel consumption for minimum settings and baseline for 'Early entry into service of technology' scenario

Case: <u>'Delayed entry into service with more fuel-efficient technology' :</u>

Under this technology path, the minimum fleet fuel burn in 2050 is attained when the entry of the N_{30} and N_{70} aircraft are at 2028 and 2039 respectively. Similar arguments (as in the previous case) about the impacts of delayed entry on fleet evolution hold in this case. Compared to the 'Early entry into service of technology' technology path, this scenario has 8% higher fuel burn at the optimal point.

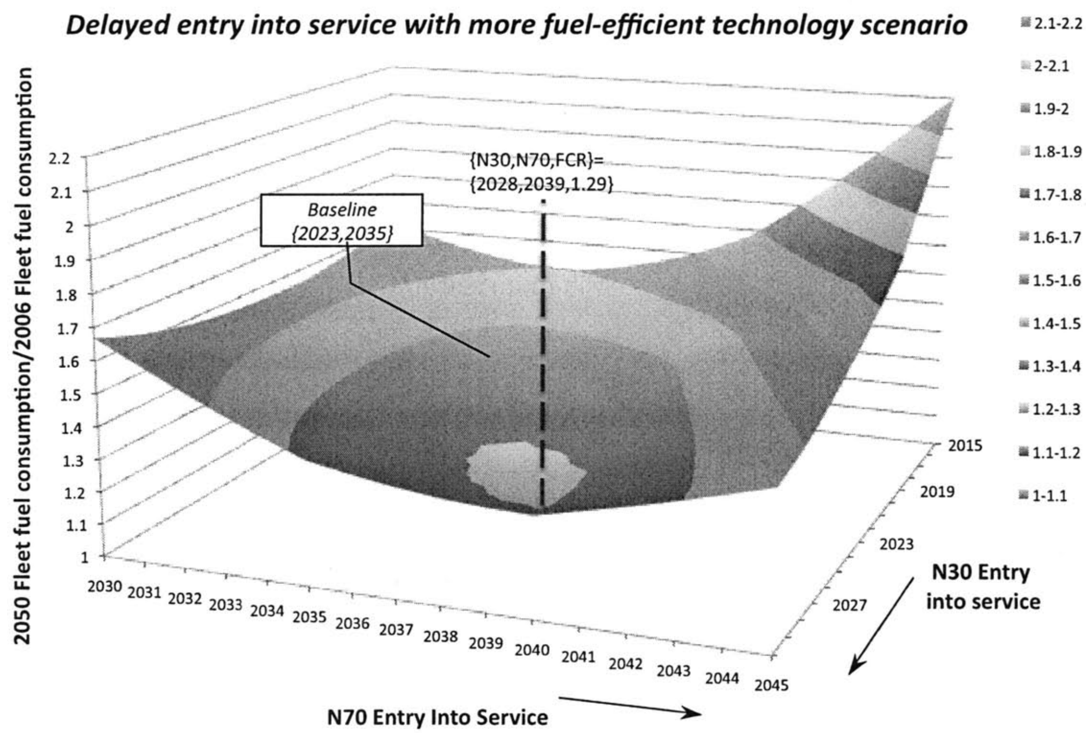


Figure 51: Effect of entry dates for N30 and N70 aircraft on 2050 fleet fuel consumption for 'Delayed entry into service with more fuel-efficient technology' scenario

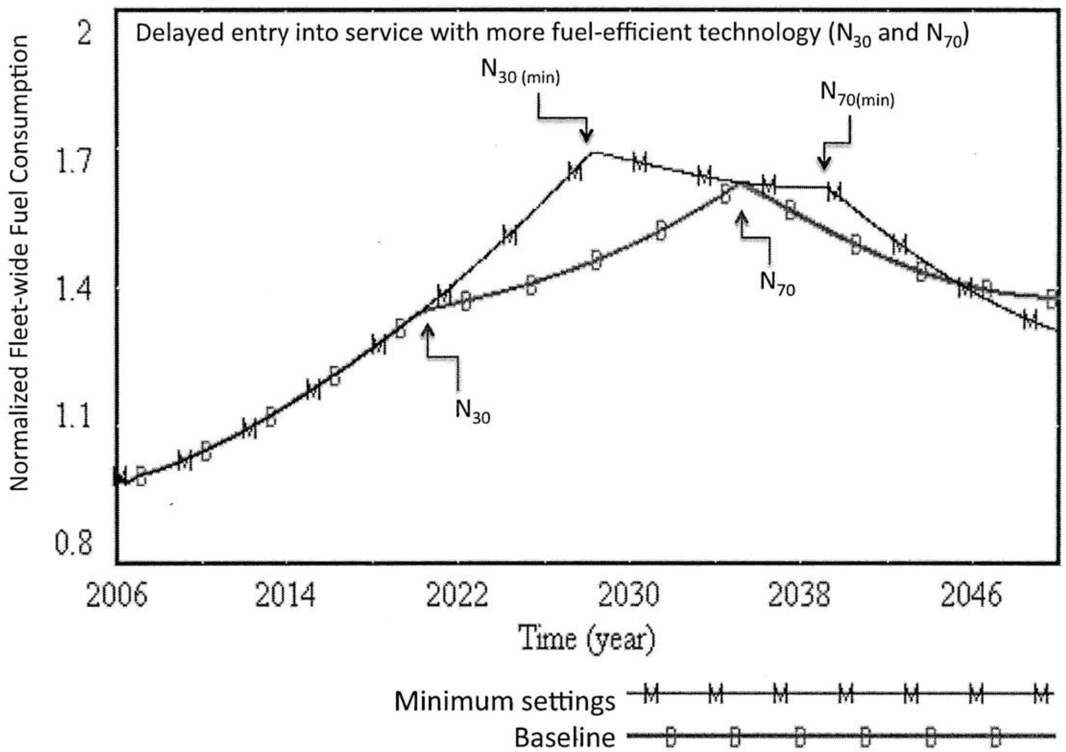


Figure 52: Normalized fleet fuel consumption for minimum settings and baseline for 'Delayed entry into service with more fuel-efficient technology' scenario

Comparison of the two scenarios indicates that there are steep penalties in fuel burn if the N_{30} or N_{50} aircraft is not introduced at the optimal point of entry. The fuel penalty is less pronounced for the N_{70} entry into service (even less so for the 'Early entry into service of technology' scenario). From a purely environmental standpoint, the challenge for the airline industry will be to time the entry of the aircraft not only based on optimal fleet fuel burn but also on the industry cycle.

Both scenarios indicate that the entry of the N_{30} /N_{50} aircraft and the N_{70} aircraft should be in the range of 2027-2028 and 2039-2040 respectively, for minimum fuel burn performance in 2050. Figure 50 and Figure 52 also show that while these dates of entry into service minimize fuel burn in 2050, the cumulative fuel consumption is significantly higher. As a result, the cumulative fuel burn should be considered as a metric alongside fleet performance, when evaluating the environmental impacts of the entry into service of next generation fuel-efficient aircraft.

7.1 Discussion and Implications for Aircraft Manufacturer Strategies and Public Policy

This chapter has investigated the possibilities of improving the fuel efficiency performance of the single-aisle fleet by inducting the next two generations of single aisle aircraft. Fleet turnover dynamics was modeled using System Dynamic techniques and various scenarios were tested.

The results show that the 'Early entry into service of technology' scenario is a better alternative to reducing aviation CO_2 emissions as compared to an 'Delayed entry into service with more fuel-efficient technology' scenario. Retiring older aircraft from the fleet also improves the fleet fuel performance but only moderately. Under high demand growth scenarios, introducing new aircraft is not sufficient to curb rising emissions because the technology improvement is not sufficient to mitigate the increase in fuel burn from a larger number of aircraft. Results also show that the industry cycle can adversely impact the adoption of new aircraft and thereby affect fleet performance. Sensitivity analysis for the entry into service dates of the next and next to next generation aircraft indicate that fleet fuel burn can be minimized in 2050 by suitably selecting the date of entry. However, this might be lead to higher cumulative fuel burn till 2050.

The results have several implications for implementing policies to combat the high carbon emissions growth scenario from aviation as predicted by forecasts. CO_2 emissions from the aviation industry is an externality and there are several approaches to tackling it:

1. Internalize the cost of the externality – cap and trade and fuel tax
2. Reduce externality at the source – use efficient aircraft, reduce demand for air travel
3. Command and control – impose standards for CO_2 emissions and enforce compliance

Fleet turnover dynamics has an impact on each approach and is discussed below.

Technology:

<u>CO_2 Standards:</u> The Aircraft Diffusion Dynamic Model has shown that drastic technology improvements as in the 'Early entry into service of technology'scenario is the best alternative to reduce fuel burn. A CO_2 standard for new and in-production aircraft can help incentivize the introduction of technology. The policymakers have to be careful about designing the standard. If it is made applicable to new aircraft only, manufacturers will *delay* the introduction of new models and continue with incremental improvements on existing production lines. This can also incentivize re-engining the in-production aircraft. At the same time, if the standard is designed too stringently for in-production aircraft, it can encourage re-engining to meet the standards in the short run and also delay the introduction of new aircraft.

<u>Implications for Aircraft Manufacturers:</u> Developing a new aircraft is a risky undertaking. The onus is on the aircraft manufacturers to timely bring new and fuel efficient aircraft to the market. With an estimated demand growth of 3% the ideal time of entry for the Gen+1 aircraft (like the Boeing Y1[1] and the Airbus NSR[2]) is in the 2028/2029 time frame. Given that an aircraft development program lasts over 10 years before entry into service(Clark 2007), the Gen+1 program has to start in the 2017 time frame.

The 'Early entry into service of technology' scenario with a 50% efficiency improvement by 2023 has proved to be the best technology improvement pathway that can reduce fuel burn in the long run. If the next generation single aisle aircraft is to enter into service in 2023, the design freeze will have to occur much earlier (see Figure 53 for average timelines of new aircraft development). Technology development to meet the 'Early entry into service of technology' path has to be accelerated.

The timing of the Gen+1 and Gen+2 entry will also impact the total number of aircraft that are sold by the manufacturer. Early introduction of the Gen+1 and the Gen+2 will cannibalize the sales of In-production and the Gen+1 models respectively.

The industry cycle is also an important consideration for the manufacturers for short-term strategies. The simulation predicts that the current downturn in the cycle will

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[1]http://www.flightglobal.com/articles/2006/03/03/205223/boeing-firms-up-737-replacement-studies-by-appointing.html
[2]http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=comm&id=news/aw070207p3.xml&headline=Airbus%20May%20Not%20Do%20A320%20Replacement%20Alone

end by 2014, which is approximately co-incidental with the expected entry of the re-engined single aisle aircraft. The timing will be right for fast adoption of the re-engined aircraft. On the other hand, the industry is predicted to enter into another downturn in the 2020-2024 time frame. This can significantly delay the sales of the new next generation narrow body aircraft. Going strictly by the cycle, the manufacturers are more likely to re-engine the in-production aircraft and delay the introduction of the next generation narrow body.

The growing demand for aircraft has encouraged new manufacturers to eye the single aisle market. This has competitive implications for the two largest manufacturers – Airbus and Boeing. If they do not develop the Gen+1 aircraft and resort to re-engining as a strategy, manufacturers like Bombardier (C-Series) and Comac (C919) can derive competitive advantage with better technology offerings as well from imminent regulations.

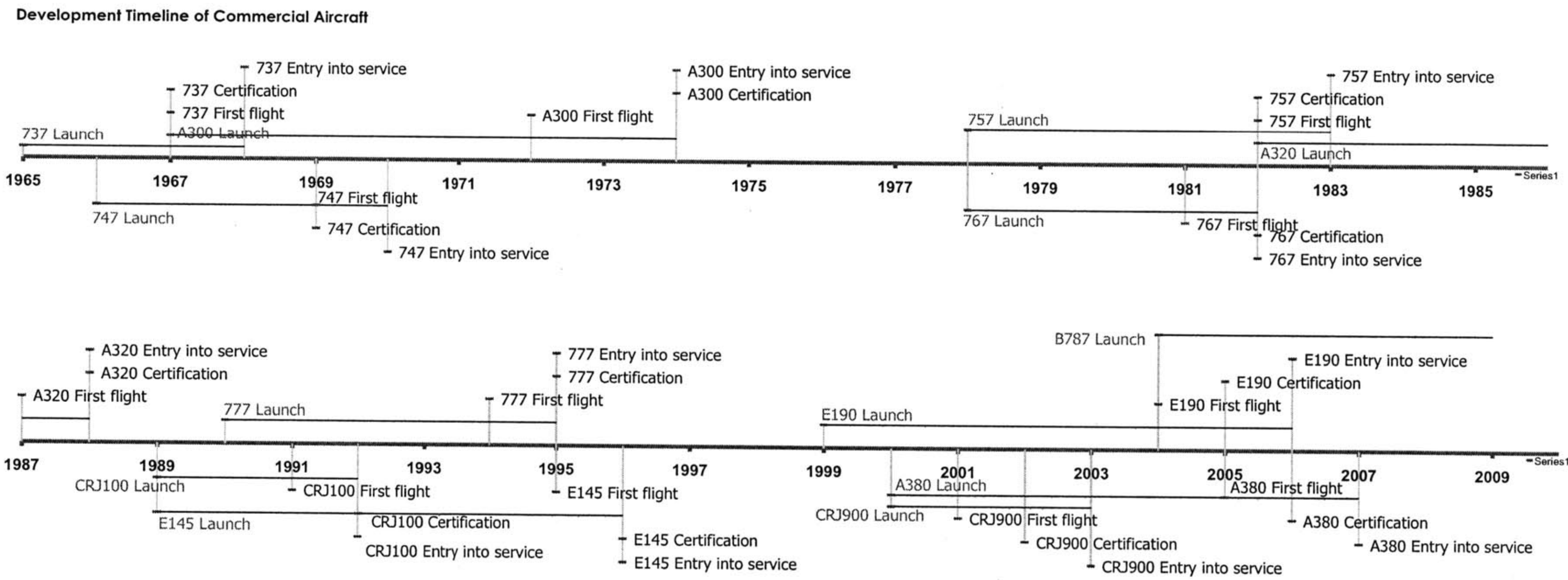

Figure 53: Launch to entry into service timelines for different aircraft types
(Source: Flightglobal.com, crj900.com, Embraer, aviastar.com, airliners.net, BBC, b737.org, Boeing)

Demand:

Adoption of new aircraft will not be sufficient to counterbalance the rise in fuel consumption from growth in demand. A market-based mechanism that imposes a cost on carbon emissions (like fuel tax or cap and trade) is expected to increase the price of air travel and reduce demand. Reduced demand influences fleet dynamics in multiple ways – influencing the industry cycle that has second order effects on reduced orders of new aircraft and slow diffusion rates.

Retirement:

CO_2 Standards and taxes on older aircraft: The retirement curves can be influenced by imposing taxes or by emission standards and older aircraft will retire at a faster rate (i.e., the curve shifts to the left). The Aircraft Dynamic Diffusion Model has shown that aircraft from the 2006 fleet will retire at a faster rate but this will increase the orders for in-production aircraft to meet demand. In the short run, this can reduce fleet fuel consumption if the in-production aircraft are made more efficient by imposing CO_2 standards.

CHAPTER 8

CONCLUSIONS

Increasing demand for air transportation worldwide and growing environmental concerns motivate the need to implement mitigating measures to reduce CO_2 emissions. The maximum potential of benefits can only be realized after full adoption of the measures by the industry.

Case studies of historical changes in the air transportation industry have shown that implementation and diffusion of technology or operational changes generally follow S-curve type dynamics with relatively long time–constants. Each study indicated key barriers and enablers in the implementation process that could impact the diffusion time of future mitigating measures. This research developed a portfolio of CO_2 emission mitigating measures, analyzed their diffusion characteristics and their relative contribution to cumulative system wide improvements. First, a literature review identified over 90 proposed mitigating measures, which were aggregated into 41 unique measures, including: (1) technological improvements, (2) operational improvements, and (3) use of alternative fuels. It was found that in the near term, operational changes have the highest potential for improvements but are unlikely to significantly reduce CO_2 emissions. In the medium term, both technology retrofit and operational measures have the potential to reduce emissions. In the long term, the use of 2nd and 3rd generation of biofuels have significant potential for reducing the carbon footprint of aviation but are likely to have long diffusion times and may not be available exclusively to the aviation sector and in sufficient quantities due to demand from and competition with other industry sectors. Technology measures such as next generations of aircraft have the highest potential for reducing CO_2 emissions but only in the long term due to slow turnover dynamics of the fleet.

An Aircraft Diffusion Dynamic Model (ADDM) was developed using System Dynamics modeling approaches and techniques that could evaluate the fleet efficiency with the entry of various generations of aircraft at different levels. The model could also perform the trades between the characteristic S-curve parameters. It was found that new aircraft diffusion was strongly influenced by a) the annual growth rate in demand, b) the industry cycle and c) the retirement of older aircraft.

Results from the model showed that strategies that emphasize the early entry into service of available technology, as opposed to waiting and delaying entry for more fuel-efficient technology, have greater potential to improve fleet fuel-burn performance. Also, strategies that incentivize early retirement of older aircraft have marginal potential for reducing fuel burn. The timing of the entry of the newer generation aircraft has a significant impact on the fleet fuel performance in 2050. Sensitivity analysis for the entry into service dates of the next and subsequent generation aircraft indicate that fleet fuel burn can be minimized in 2050 by suitably selecting the date of entry. However, this might be lead to higher cumulative fuel burn till 2050. As a result, the cumulative fuel burn should be considered as a metric alongside fleet performance, when evaluating the environmental impacts of the entry into service of next generation fuel-efficient aircraft.

Future demand scenarios have also shown that the infusion of fuel-efficient aircraft alone, is unlikely to reduce emissions below 2006 levels. Instead, a portfolio of measures that include operational improvements, demand reduction mechanisms and adoption of alternative fuels will be needed for tackling the emissions growth problem.

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Appendix A: List of Mitigating Measures

Area of Improvement			Mitigating Measure
	New aircraft		B787/A350
			Bombardier C-series/Mitsubishi RJ
			N+1 NASA Subsonic
			N+2 NASA Subsonic
			N+3 NASA Subsonic
			Hydrogen Cryoplane
Technology	Components (introduced with new aircraft)	*Propulsion*	Material, coatings, cooling technology for engines
			Engines - GTF
			Engines - Open rotor
			Variable fan nozzle
			Variable geometry chevron
			No bleed architecture
			Develop 'all-electric/more-electric' planes
			New Engine Core
			Embedded distributed multi-fan
			Next generation high bypass ratio engine
			Replace APU's with fuel cells
			Ubiquitous composite engines
			Variable and adaptive cycles
			Pulse detonation engines
		Aerodynamics	Non-planar wings
			Laminar nacelles
			Riblets
			Hybrid Laminar Flow(HLF) control
			Higher aspect ratio wings
			Morphing airframe
			Variable Camber wings
			Laminar flow wing profile
			Develop laminar surfaces using coatings and paintings
			Utilize slotted cruise airfoils
			Ski-jump shaped wheel fairing
			Use Leading Edge Droop
			Redesign engine mount to reduce interference drag
			Implement better design methodology like PAI, Multi-objective optimization and integrative design
			Design laminar vertical tailplane and horizontal tailplane
			Use shock wave/boundary layer devices (like micro-vortex generators)to reduce stagnation pressure loss
		Weight	Lightweight material, composites etc
			Advanced fly by wire technology
			Fly by light technology
			Friction stir welding (FSW)
			Laser beam welding (LBW)
			Reduce OEW
			Use lightweight alloys on secondary load bearing structures
			Use lighter cabin seats
			Remove passive interior noise treatment (wall bags, environment control ducts)by active noise control technology
			Use fewer coats of paint
			Use anti-corrosion coating instead of paint
			Use lighter carpet
			Make lavatories out of composite material
			Use light weight life jackets
			Use light weight tires
			Use light weight cargo containers
			Use databus for electrical systems
			Change to electronic freight bags from paper manuals in the cockpit
			Integrate avionics - merge multiple systems
			Use composite wiring and connectors
			Replace windshield wiper with rain repellant coating
			User lighter carbon brakes (Boeing next gen 737)

Area of Improvement			Mitigating Measure
Technology	**Retrofit solutions for existing aircraft**	*Propulsion*	Retrofit engines
			Technology insertion- Upgrade core
			Use improved air-conditioning and pressurization systems that use less engine bleed
			More efficient APU
			Lithium batteries for secondary power
		Aerodynamics	Winglets
			Riblets
			Laminar Nacelles
			Raked Wingtips
		Weight	Reduced use of paint on airframes
			Install zonal driers to reduce moisture trapped in the insulation between the outer skin and cabin lining
			Use LED lighting
Operationnal improvements		*Ground ops*	Fixed electric ground power instead of APU
			Single engine taxi
			Implement queue management and controlled pushback
			Airframe washing
			Use starting grids
			Use alternative fuels for ground tugs
			Improved operations at closely spaced runways
			Ground towing with diesel tugs instead of engine power
		ATM ops	Fly at optimum cruise level
			Use continuous descent approaches (CDA)
			Fly optimized routes
			RNAV and RNP
			Reduced horizontal seperation to 3 miles
		Airline ops	Reduce cabin dead-weight
			Engine washing
			Fly at lower cruise speed
			Use optimal take-off power
			Optimize climb/descent (flap settings, engine power etc)
			Use idle reverse thrust instead of maximum reverse thrust after landing
			Do not use A/C Pacs in high flow
			Do not use unnecessary cargo heat
			Conduct formation flying
			Do not use unnecessary anti-ice
			Air to Air refueling
Alternative Fuels			2nd Generation Biofuel (Nature by-products/waste)
			3rd Generation Biofuel (algae, switch grass, jatropha, babassu and halophytes)
			Hydrogen
			Coal to liquid
			Gas to liquid
			Hydrogenated oil/fat

Appendix B: References for Table 5

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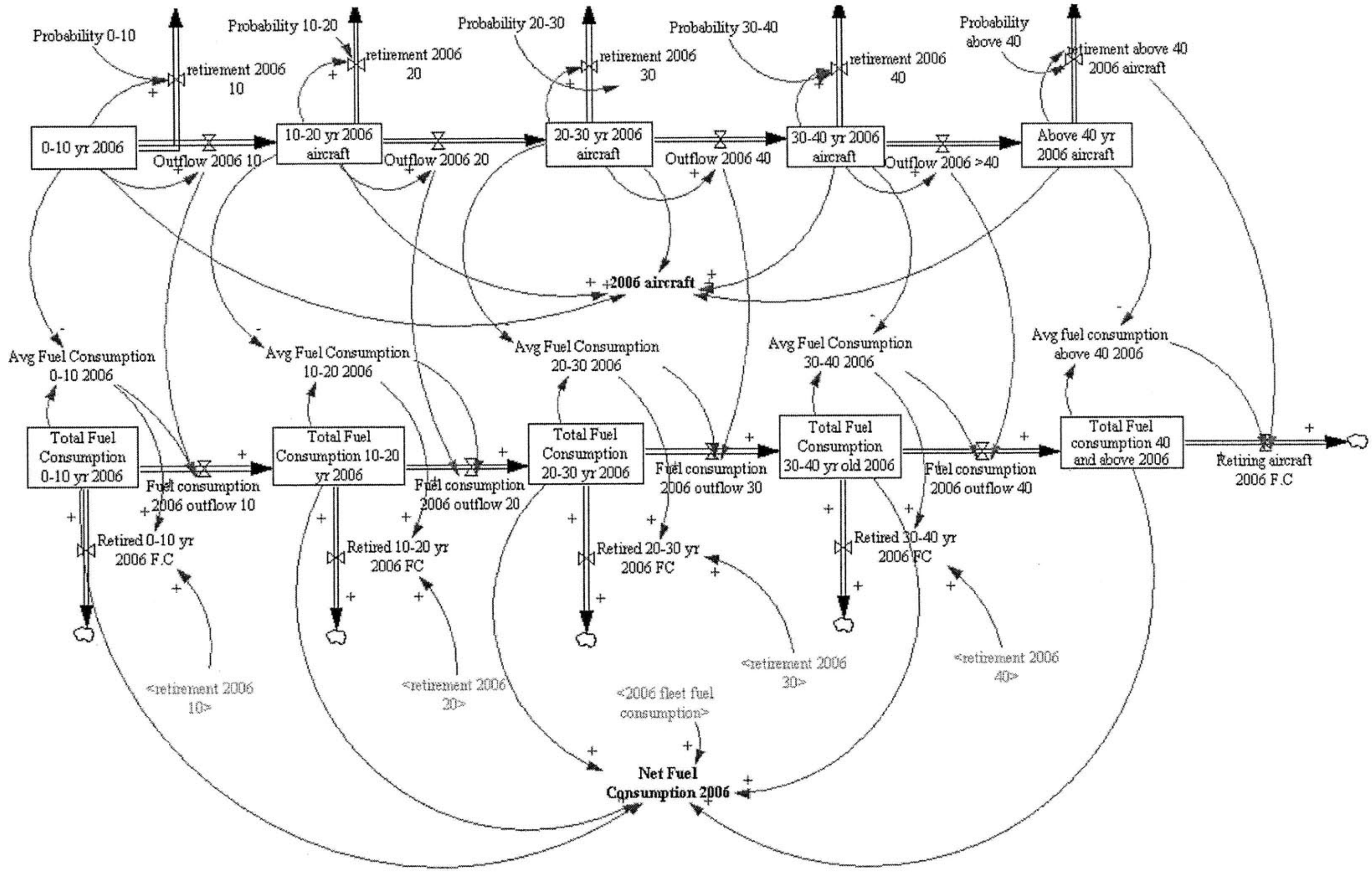
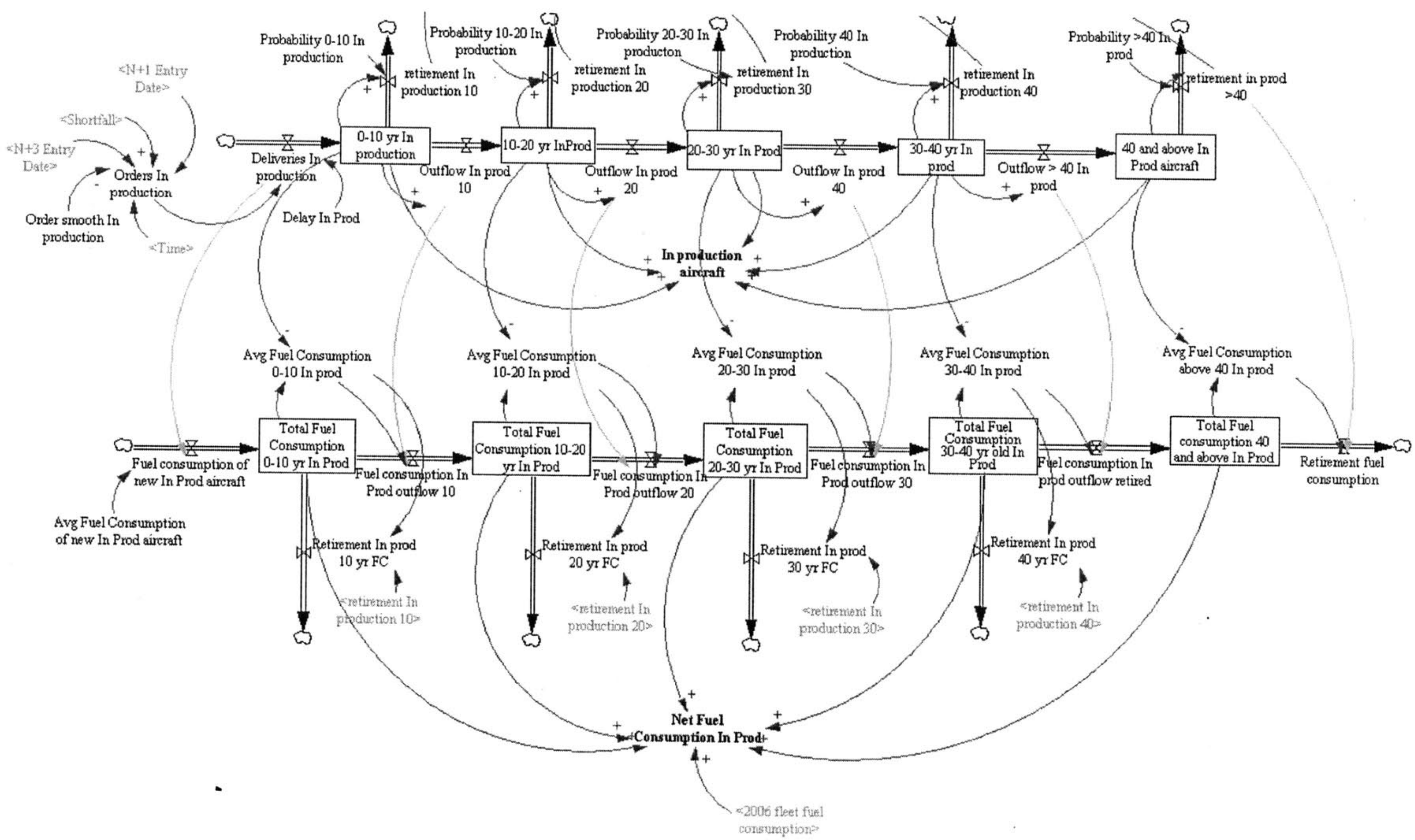
Appendix C: Single Aisle SD Model – Causal Loop Diagram

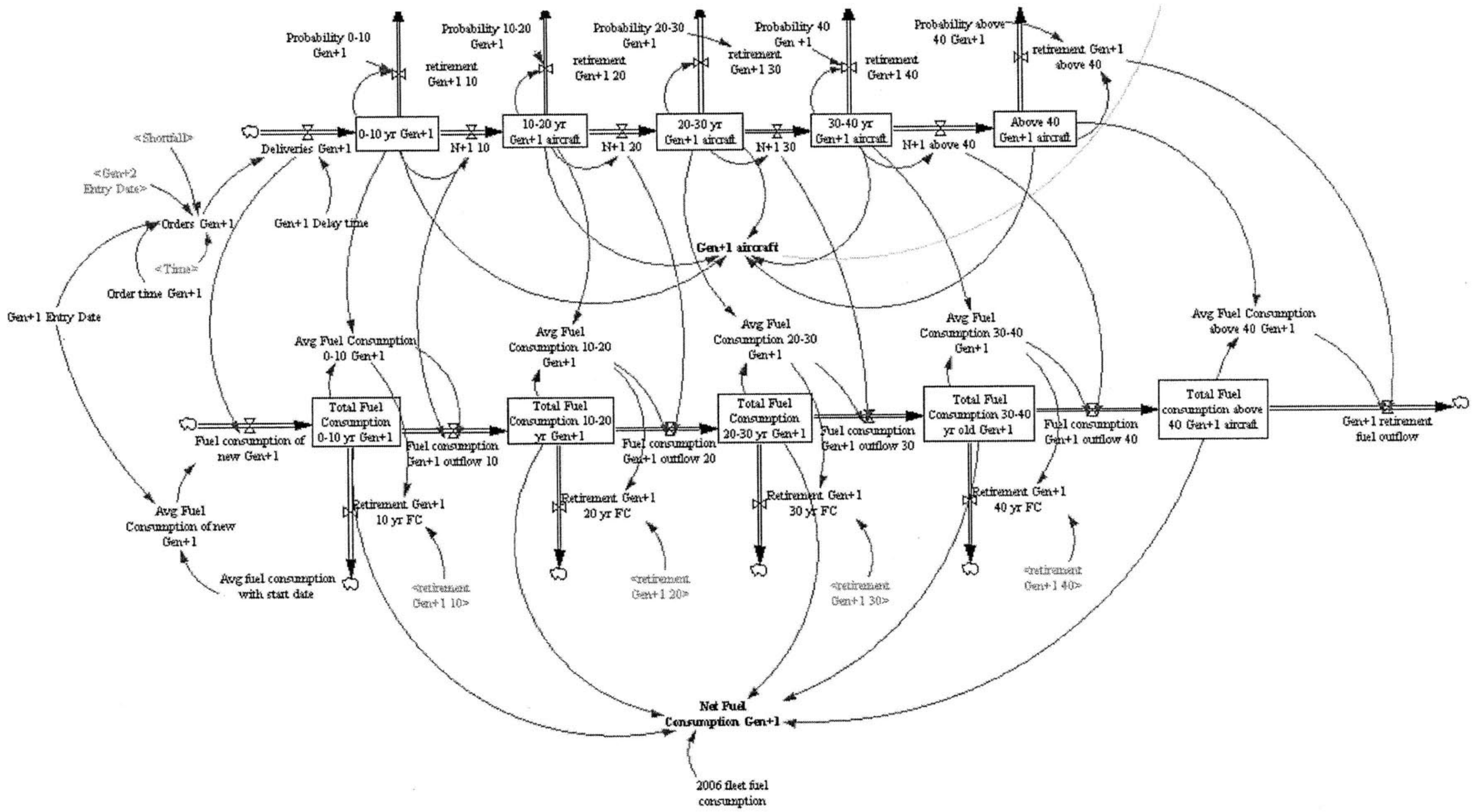
2006 Fleet Turnover Model:



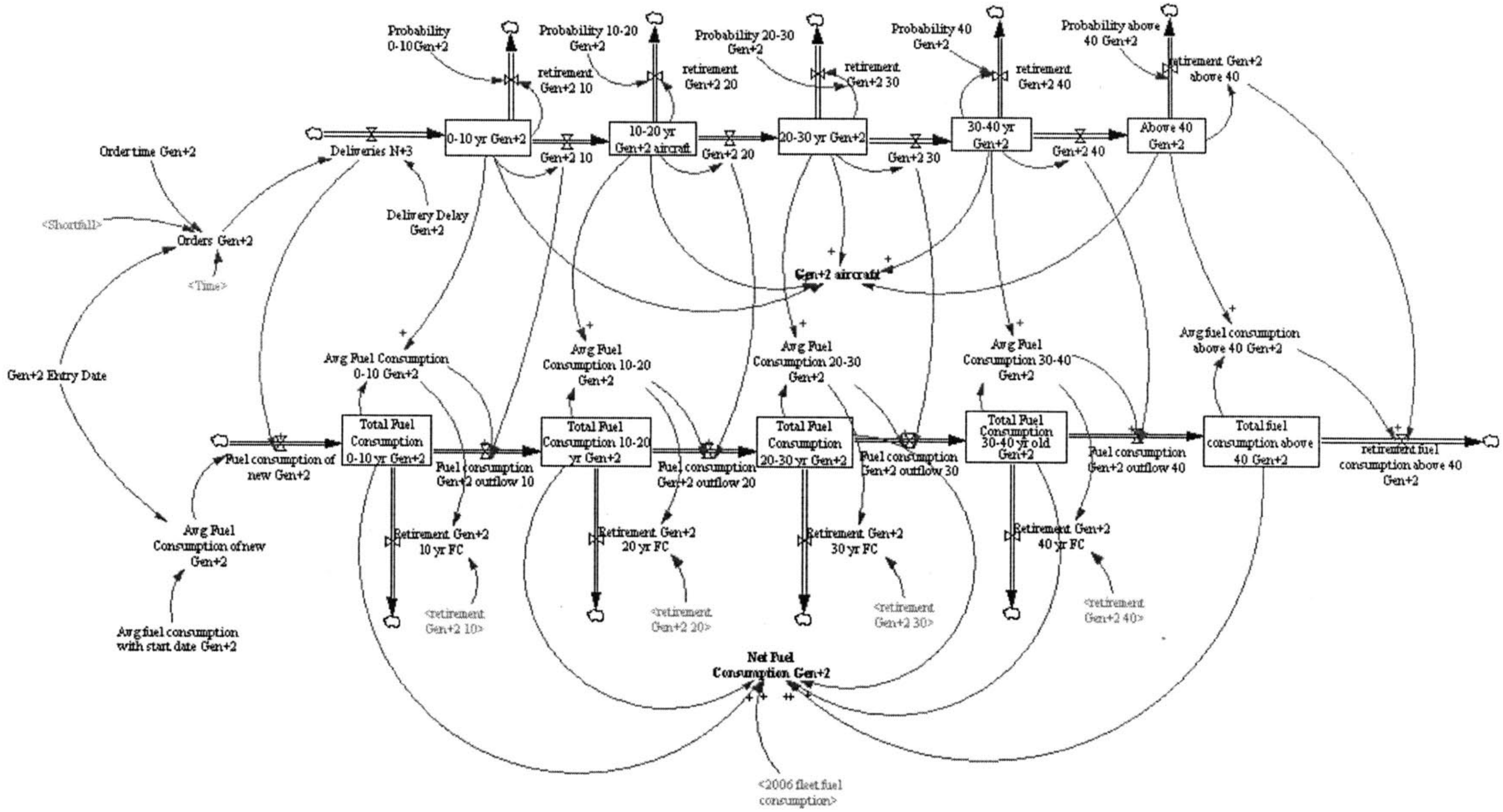
In Production Fleet Turnover Model:



Gen+1 Fleet Turnover Model:



Gen+2 Fleet Turnover Model:



Demand Module: