GAME THEORY ANALYSIS OF THE IMPACT OF SINGLE AISLE AIRCRAFT COMPETITION ON FLEET EMISSIONS

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Game Theory Analysis of the Impact of Single Aisle Aircraft Competition on Fleet Emissions

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To meet aviation's CO_2 emission reduction targets while maintaining mobility in the face of increasing effective fuel costs, technology innovation will be required. The single aisle commercial aircraft market segment is the largest by quantity and value, but has the longest running product lines. New aircraft programs offer the largest potential gains in fuel efficiency, but are risky and require large capital investments. Re-engining existing airframes reduces risk and capital requirements, but offers lower potential fuel burn improvements. Incremental improvements to existing aircraft lines may entail the lowest risk. It is hypothesized that competition has important effects on manufacturers' decisions to innovate and that these effects must be considered when designing policies to reduce CO_2 emissions from aviation. An aircraft program valuation model is developed to estimate expected payoffs to manufacturers under different competitive scenarios. A game theory analysis demonstrates how the incentives for manufacturers to innovate may be altered by subsidies, technology forcing regulations, increased effective fuel costs, the threat of new entrants, and long-term competitive strategies. It is shown that increased competition may result in incumbent manufacturers producing re-engined aircraft while increased effective fuel costs may result in new aircraft programs. Incumbents' optimal strategies may be to delay the entry into service of new single aisle aircraft until 2020-24, unless technology forcing regulations are implemented.

I. Introduction

To meet CO_2 emission reduction targets while maintaining mobility in the face of increasing effective fuel costs, technology innovation will be required. The International Civil Aviation Organization (ICAO) has resolved to achieve an annual average fuel efficiency improvement of 2% until 2050 (ICAO, 2010) while IATA's 2050 aspirational goal is to reduce CO_2 emissions from aviation by 50%. Effective fuel cost increase expected from tightening oil supply and market-based carbon constraint policies will provide economic incentives for airlines to reduce fuel burn, but Morrell and Dray (2009) argue that fuel cost increase may have a smaller than expected effect on CO_2 emission reductions. The mean fuel burn of aircraft deliveries is affected by the introduction of new aircraft models with improved fuel efficiency. Therefore, increasing the rate of technology development is a useful policy lever for reducing emissions through fleet turnover. To do so, manufacturers must have the incentives to innovate. The purpose of this paper is to perform a game theoretic analysis of competition between large commercial aircraft

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manufacturers to demonstrate how changes to a symmetric duopoly market may incentivize the introduction of new single aisle aircraft with fuel efficiency improvements.

A. Aircraft Fuel Efficiency Improvements

Historically, jet aircraft fuel intensity has improved 1.2-2.2% per year on a seat-km basis, which is not sufficient to counter projected annual increases in demand for air transport of 4-6% (Lee et. al., 2001). While the IPCC (1999) cited a 70% improvement in aircraft fuel efficiency since the 1960s, their analysis focused on the largest wide body aircraft that are generally more efficient due to economies of scale. The last piston-powered aircraft were as fuel efficient as the current average jet (Peeters and Hoolhorst, 2005). Single aisle aircraft currently make up 61% of the world's jet fleet and 68% of forecasted deliveries over the next 20 years (Boeing, 2010). Therefore, to reduce fleet wide fuel burn, single aisle aircraft efficiency improvements will be required.

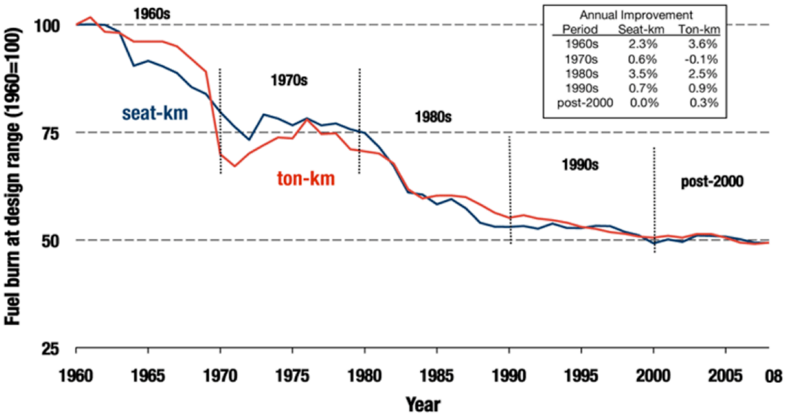

Figure 1: Sales-Weighted Average Jet Aircraft Fuel Burn, 1960-2008. Source: Rutherford and Zeinali, 2009

Using sales-weighted average aircraft fuel burn, Rutherford and Zeinali (2009) demonstrated efficiency improvements have stalled since 2000, as shown in Figure 1. The 1980s marked a period of fierce competition between Boeing, Airbus, Lockheed and McDonnell Douglas, resulting in more rapid efficiency improvements. Although as technology improves, reducing fuel burn becomes more technically challenging. It is hypothesized that competition between aircraft and engine manufacturers is a primary driver of innovation, including fuel efficiency improvements. Therefore, to understand what policies are likely to be effective at reducing aircraft fuel intensity, the effects of competition must be understood.

B. Single Aisle Aircraft Manufacturer Market Structure

As an industry with economies of scale, large capital requirements, high technical capabilities, and a worldwide service network, large commercial aircraft manufacturing is a naturally concentrated industry. Since Boeing's purchase of McDonnell Douglas in 1997, Airbus and Boeing have competed in a global duopoly. Large barriers to entry exist which protect the incumbents from new competition. The estimated cost of developing new aircraft ranges from $3 to $14 billion, depending on the aircraft size and technology level, and requires expertise only developed over long periods of time.

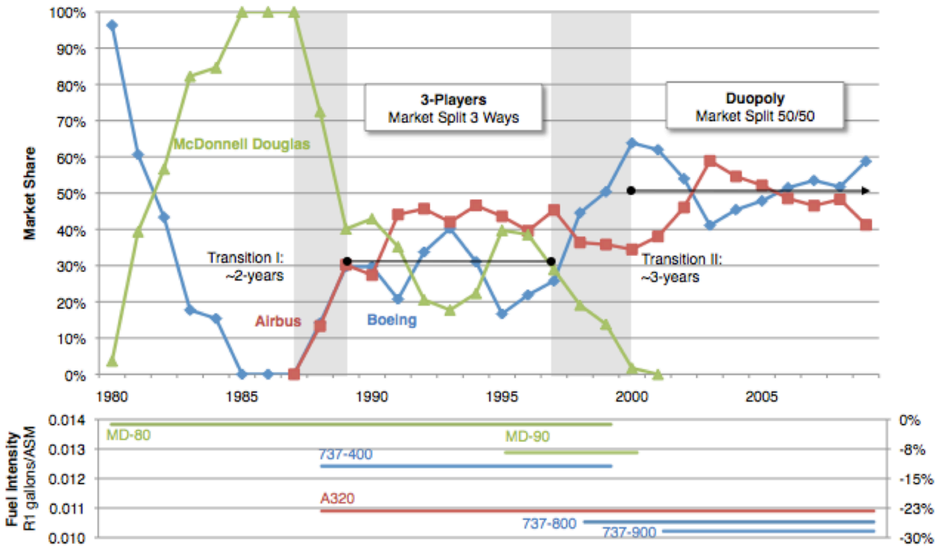

Figure 2: Single Aisle, 150-185 Seat Market Shares and Fuel burn Performance, 1980-2009 (MD-80 baseline). Data Source: Boeing (2010), Airbus (2010), Piano-X.

Airlines purchasing new aircraft demand low operating costs and competitive pricing. Fleet commonality reduces operating and maintenance costs, as well as spare part inventories, providing incentives for airlines to lock in to aircraft families. In order to maintain market share, manufacturers must produce aircraft that match or exceed the competition's performance. If one manufacturer develops a superior aircraft, it can gain significant market share, as shown in Figure 2. In the 150-185 seat single aisle short- to medium-range market segment, Boeing's 727-200 enjoyed a monopoly until the MD-80 entered service in 1980. Among other advancements, the MD-80 offered a 35-40% fuel efficiency improvement (not shown). Boeing's 737-400 and Airbus's A320 entered service in 1988, again offering significant performance improvements over the incumbent, capturing market share. McDonnell-Douglas exited the market in 1997, leaving the two remaining manufacturers to split the market. Since the late 1990s when Boeing introduced the derivative 737-800 and 737-900 models, the competitors have performed incremental improvements on their existing product lines.

New competitors in single aisle markets are on the horizon. Embraer's E195 encroaches on the 100+ seat market while Bombardier's CSeries is scheduled to enter service in 2013 with 110-145 seat variants. Commercial Aircraft Corporation of China (Comac) is planning to introduce its 168-190 seat C919 in 2016 while Russia's United Aircraft Corporation is developing the 150-210 seats MC-21 family for entry into service 2015-16. Engine manufacturers are developing geared turbofan and high by-pass ratio engines that will power the new entrants' aircrafts and will enable incumbent manufacturers to improve their existing aircraft performance. In November 2010, Airbus announced its decision to offer a new engine option on its A320 family of aircraft for entry into service in 2016. After Airbus logged over 1000 orders for re-engined aircraft, Boeing followed suit in July 2011. As new entrant aircraft models prove their value, Airbus and Boeing may again choose to update their single aisle offerings to gain performance advantages, creating opportunities to reduce the environmental impacts of aviation.

C. Paper Overview

The research focus and approach are discussed in Section II while Section III introduces the structure of the game analyzed. Estimates of the rank order of payoffs for manufacturers are presented to evaluate the impact of competition and other market factors on new aircraft performance. In Section IV, an aircraft program valuation model is developed based on publicly available data. The valuation model is then used in Section V to identify factors and policies that may shift the competitive equilibrium. Finally, conclusions are drawn in Section VI.

II. Research Approach and Assumptions

It is hypothesized that in a duopoly market where both manufacturers have existing single aisle aircraft families and fuel prices are low, neither competitor has an incentive to produce a clean sheet design aircraft. Although a new aircraft line can be designed to offer large performance improvements, it requires a significant research, development, testing and evaluation investment, is technically risky, and may cannibalize the sales of existing overlapping product lines. The existence of production learning curves with steady or increasing deliveries allows manufacturers to produce and sell initial aircraft at a net loss in order to gain the experience required to improve production processes and reduce unit costs to achieve profitability as volumes rise (Benkard, 2000). As the effects of the learning curve are negated with the introduction of a new line, the incentive to do so is reduced. Our research focuses on the factors or policies that may change the dynamics of aircraft manufacturer competition to incentivize the development of a new aircraft and to compare these factors on the basis of expected impact on fleet carbon emissions.

We chose a game theoretic framework as it accounts for the presence of multiple competitors, all of whom make rational decisions in accordance with their own best interests. Further, it is assumed that all players know that all other players make rational decisions. These assumptions enable the discovery of the Nash equilibrium of competing players' strategies. The Nash equilibrium is the predicted strategy for each player that is the best response to the predicted strategy of all other players (Gibbons, 1992). Game theory frameworks have previously been used successfully to analyze competition between aircraft manufacturers. Brander and Spencer (1985) showed how government subsidies could be used to change the initial conditions of games between non-cooperative international rivals. Krugman (1987) used hypothetical payoff matrices to show how government subsidies could enable domestic firms to increase profits in excess of the subsidy amounts by deterring foreign entry and allowing domestic firms to capture excess returns, increasing social welfare.

The research approach is three staged. First, we construct static and dynamic game structures for a two- and three-player market. Second, an aircraft program valuation model is developed to estimate payoffs to manufacturers under different market share, fuel price, and demand scenarios. Third, a game theory analysis is used to model competitive forces impacting manufacturer decisions. Understanding how competition impacts the decision to invest in new aircraft designs may assist policy makers in developing regulatory mechanisms to improve aviation's fuel efficiency and can inform expectations of the introduction of new aircraft for global aviation emission models. We test policy options to determine their outcomes in a competitive market, based on the assumptions in the valuation model.

The purpose of this analysis is *not* to determine aircraft manufacturers' profitability, but to estimate the rank ordering of payoffs to determine how changes in the market structure may change the equilibrium game outcome using a consistent framework for comparison. Unfortunately, such analysis is hindered by the proprietary nature of aircraft program economic data. We use reasonable assumptions based on publicly available data sources as proxies. A sensitivity analysis on those assumptions allows us to determine the extent to which they impact our findings.

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

The aircraft performance parameter of interest in this paper is fuel intensity - the energy consumed per unit of output. As a proxy, the fuel burn per seat mile is used. Efficiency improvements indicate reductions in fuel intensity.

III. Structure of the Single Aisle Aircraft Competitive Game

Boeing and Airbus have existing single aisle aircraft in production. As incumbent manufacturers, they have three generic strategies: (1) *maintain* their existing product lines, with incremental improvements over time, (2) *re-engine* their existing airframes, enabling superior performance improvements, or (3) develop *new*, clean sheet design aircraft that offer the greatest fuel burn improvements. For the static games (outlined in Figure 3) manufacturers make their decision to proceed at the beginning of the time period examined. It is assumed that there is a 5-year delay from when a decision is made to when the aircraft enters service. Therefore, a decision to develop a new aircraft includes the production and sale of the existing aircraft for 5-years until the new aircraft enters service. Although the development time for a re-engined aircraft may be less than for a new aircraft, it is assumed to be the same to simplify the structure of the game into four 5-year stages. A 20-year period of analysis was selected for the static games to correspond to market and fuel price forecasts.

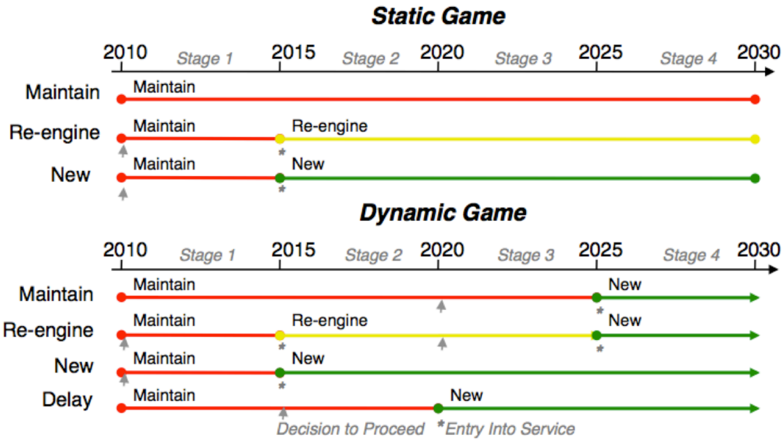

Figure 3: Structure of Static and Dynamic Games.

Static games enable an understanding of current factors impacting manufacturer decisions, but in reality players are engaged in a long-term game that extends beyond the 20-year horizon. Dynamic games were investigated in which manufacturers update their decisions at 5-year increments, based on the evolution of fuel prices and demand for single aisle aircraft. As shown in Figure 3, it was assumed that incumbent manufacturers would enter a new aircraft into service by the fourth stage (2025-29). Therefore, in the dynamic game, the *maintain* strategy includes deciding to proceed with a new aircraft in the third stage (2020-24) for entry into service in the fourth stage (2025-29). It is assumed that a manufacturer would produce a re-engined aircraft for at least 10-years to receive a sufficient payback on their investment. Therefore, in the dynamic game the re-engine strategy includes the decision to proceed with a re-engined aircraft and a new aircraft, 10-years later. The dynamic games lead to a new strategy in which manufacturers *delay* the entry into service of a new aircraft until the third stage (2020-24), deciding to continue to maintain their existing aircraft until that time. For each strategy, it is assumed that a player's game terminates when they decide to develop a new aircraft. A 30-year period is used for the dynamic games to allow for the new aircraft investment made in the later stages to be repaid.

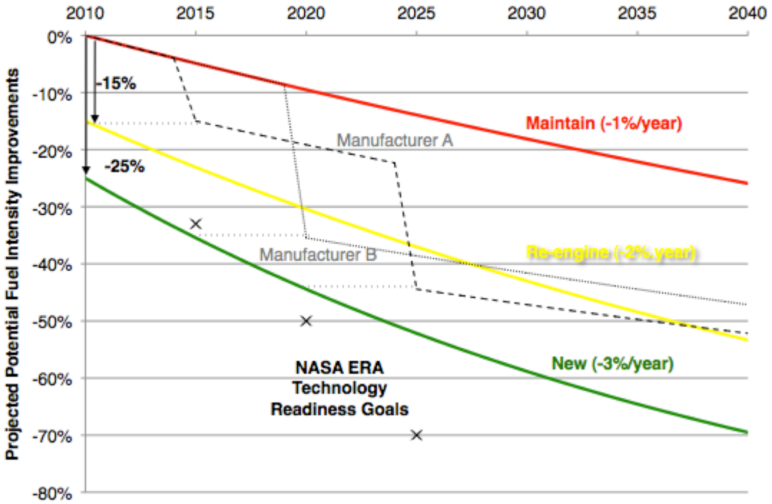

Figure 4: Conceptual Model of Future Potential Fuel Burn Improvements due to Technological Advancements. Hypothetical efficiency improvements over current single aisle aircraft.

Each strategy has a different impact on the fuel efficiency improvement of a new aircraft. Based on historical data, incremental improvements to an existing aircraft line generally amount to ~1% annual fuel intensity reductions. Re-engining is expected to offer a one-time step fuel efficiency improvement of up to 15% (Airbus, 2010). Finally, new aircraft with a clean sheet design could potentially offer a step fuel efficiency improvement on the order of 25% (ACARE, 2008; Morrell and Dray, 2009). These efficiency improvements are indicated in Figure 4. As technologies mature, clean sheet design aircraft in the future will offer greater efficiency improvements, expected to reach up to 70% over the current fleet average by 2040 (Kar, 2010). NASA's Environmentally Responsible Aviation (ERA) goals include developing technologies that will enable 70% or better fuel burn performance on clean sheet design aircraft by 2025. Therefore, in the long term there is a performance advantage to delay the release of a new aircraft. Due to payback periods on the order of 10-15 years for large commercial aircraft programs, when a manufacturer commits to a new aircraft, they lock-in to the technology level for the duration of the program, only enabling incremental improvements on the order of 1% per year. The strategy set generates an envelope that locks an aircraft program to a technology level.

Figure 4 shows illustrative fuel efficiency improvement pathways based on the sequence of *re-engine 2015 +new 2025* for Manufacturer A and *new 2020* for Manufacturer B. If Manufacturer A decides to re-engine in 2010, the aircraft would enter service around 2015, providing a performance advantage over Manufacturer B's product. But, if Manufacturer B decided to develop a new aircraft around 2015, they would gain the performance advantage around 2020 when it enters service. Locking into a technology level may leave a competitor vulnerable to their aircraft becoming obsolete before profitable, unable to benefit from reduced unit production costs through learning effects. Aircraft that have superior performance gain market share and yield higher sale prices. Although manufacturers can increase market share to an extent by dropping sale price, this strategy reduces profitability.

When designing an aircraft, the manufacturer must balance a variety of criteria of which fuel burn is just one. Aircraft are generally optimized for one speed, altitude, stage length, payload, and fuel price. Fuel prices are volatile, resulting in uncertainty about the dollar value of efficiency improvements. The Energy Information Administration (EIA) forecasts jet fuel prices to increase to \$2.93/gallon by 2020, with low and high scenarios of \$1.53 and \$4.72. Design compromises are inevitable, as in the A380's airport handling constraint of an 80m wingspan, resulting in an 11% increase in fuel burn over optimal (Peeters and Hoolhorst, 2005).

Moreover, the demand for new aircraft is volatile, impacted by GDP growth, macroeconomic cycles, and passenger preferences. Manufacturers must build production facilities and supply chains with the flexibility to meet expected demand, but decisions based on optimistic forecasts may result in severe financial consequences while overly pessimistic forecasts can limit the potential upside of an aircraft program. These sources of uncertainty are included in the dynamic games investigated. In the next section, the aircraft program valuation model used to estimate the payoffs of the competitive game is introduced.

IV. Methodology for Aircraft Program Valuation

To find the expected competitive equilibriums in the static and dynamic games, an estimation of the payoffs to the players is required. An aircraft program valuation model was developed, based on assumptions found in the literature and publicly available data. The purpose of the valuation model is not to determine the profits manufacturers can expect to receive, but rather to determine the rank ordering of expected payoffs under different competitive scenarios. To determine the Nash equilibrium of the game, the rank ordering of payoffs is required - not absolute values. A sensitivity analysis is performed in Section IV J to determine whether the rank ordering of payoffs remain constant for the expected range of input values, and to which parameters the model is most sensitive.

As in Irwin and Pavcnik (2004), we assume the objective function of each firm f is to maximize the net present value of expected profits π at time t:

$$\pi_{ft} = E_t\left[\sum_{t=0}^{20} \partial^t \left(q_t(p)\left(p_t - c_t\right)\right) + I_t\right] \tag{1}$$

where E_t is the expectation operator conditional on information at time t, δ is the discount factor, q_t is the quantity of aircraft sold (which is a product of firm market share and total market size), p_t is the unit sale price, c_t is the variable cost of production, and I_t is the nonrecurring investment. This objective function is expected for nongovernmental firms operating in market economies. Firms operating in other types of economies may choose different objective functions, but this complexity is not investigated in this paper. A symmetric duopoly is assumed in which firms have the same cost and revenue functions. The static analysis was limited to a 20-year period as manufacturers release 20-year demand forecasts and discounting reduces the present value of future cash flows, while the dynamic game was extended to a 30-year period to enable manufacturers to book revenues from aircraft that enter into service later in the game. The periods of analysis were broken into five-year stages to reduce the number of states considered, making the problem tractable. Forecasted demand and fuel prices represent average values over the course of a business cycle. The objective function in equation 1 is expanded in parts A through I and the model input parameters are summarized in Table 5.

A. Nonrecurring Investments

Aircraft program nonrecurring investments consist of the research, development, testing and evaluation (RDT&E) of the aircraft. This includes the design, prototypes, flight testing, production facility construction, and tooling that is required to produce the first plane that enters commercial service. While this analysis assumes symmetric firms, due to past design decisions, Boeing's 737 requires additional engineering work to re-engine. The 737 sits lower to the ground than the A320. New geared turbo fan high bypass ratio engines are heavier and the inlet diameter is larger than the traditional CFM56 that power the aircraft. To model this difference, it was assumed that Player B requires a greater investment to re-engine its aircraft than Player A. It was assumed that nonrecurring costs are distributed over one 5-year stage. Estimates of the investment required were taken from industry press, based on historical programs.

B. Recurring Costs of Production

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

$$c_{q_i} = c_1 q_i^{\ln\beta/\ln 2} \tag{2}$$

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

The learning curve slope has been estimated to be between 75-95%, with 80% generally accepted based on empirical analysis and expert opinion (Benkard, 2004; Irwin and Pavcnik, 2004). The theoretical first unit cost was estimated using the DAPCA IV model, developed by the RAND Corporation using a statistical analysis of past commercial and military aircraft programs (Raymer, 2006). The estimated unit cost of the 100th aircraft produced was used to estimate the theoretical unit cost of the first, based on the learning curve slope assumption, in the same manner as Markish (2002).

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

C. Demand Forecast

The global demand for single aisle aircraft was forecasted as yearly deliveries, for each 5-year stage, using a recombinant binomial lattice model. Although this method assumes a lognormal distribution, it limited the number of states in the model while recognizing the uncertainty inherent in forecasting future demand. For each stage of the lattice model, the average demand over the next 5-year stage could increase by amount *u* or decrease by amount *d* with probability *p* or *1-p*, respectively. The values for *u*, *d*, and *p* were estimated from historical delivery data using the formulas in equation 3 (Chance, 2007):

$$u = e^{\sigma\sqrt{\Delta t}} \qquad d = e^{-\sigma\sqrt{\Delta t}} \qquad p = \frac{e^{\nu\Delta t} - d}{u - d} \tag{3}$$

where σ is the delivery variance, ν is the expected mean growth rate of deliveries, and *Δt* is the number of periods. The variance was calculated from the 2000-09 deliveries of MD-80/90, Boeing 737-800/900 and Airbus A320. High and low estimates were calculated using the periods 1990-2009 and 2005-09. The mean growth rate was calculated so that the expected deliveries over the next 20-years equaled the average of the Airbus and Boeing 2010-29 single aisle market forecasts. High and low estimates were calculated using the two manufacturer's independent forecasts. Each state of the lattice model in Table 1 represents the average expected deliveries over the 5-year period, beginning in the year indicated. The initial state represents the average deliveries in the period 2005-09.

Table 1: Aircraft Demand Base Case Lattice Model
Data Source: Boeing, 2010; Airbus, 2010.

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

D. Fuel Price Forecast Model

The expected price of jet fuel influences airlines' willingness to invest in fuel burn reducing technology. It is assumed that if fuel prices are expected to escalate, airlines will be more willing to invest in new aircraft that reduce fuel burn. Therefore, the expected price of fuel influences the prices airlines and leasing companies are willing to pay for new aircraft and the amount of risk manufacturers are willing to take to implement fuel efficiency technologies. Fuel prices were modeled in the same manner as demand using a binomial lattice model. The mean growth rate was taken from the Energy Information Administration's (EIA) 2010 Annual Energy Outlook while the variance was determined from historical jet fuel data. High and low estimates were taken from the different EIA oil price scenarios.

Table 2: Jet Fuel Price Base Case Lattice Model
Data Source: ATA, 2010; EIA, 2010.

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

E. Aircraft Lifecycle Cost Analysis

Airline purchase decisions are modeled using an aircraft lifecycle cost analysis. The model was developed using assumptions based on Morrell and Dray (2009), updated with average BTS (2009) operational and cost data for A320s and 737-800s operated by US carriers, as shown in Table 3. The sale price of the aircraft represents ~20% of the present value of the lifecycle costs, as shown in Figure 5. Fuel can account for 33% of total aircraft related operating expenses (TAROC) using an 8% discount rate, the base fuel price scenario, and a 20-year operating lifetime. Although these calculations are approximate, they demonstrate that for a rational agent, sale price is one component of the decision to purchase an aircraft while lifecycle operating costs is a larger share. A manufacturer that can reduce operating costs will be able to increase sale price within a range that keeps TAROC constant, or reduces it.

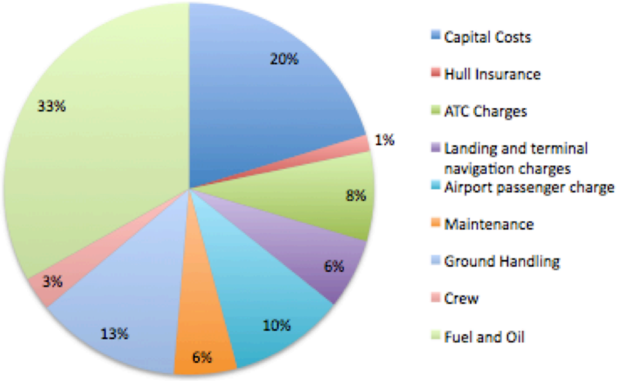

Figure 5: A320/737-800 Lifecycle Cost Estimates
Data Source: BTS (2010), Morrell and Dray (2009)

F. Aircraft Sale Price

There are strong anecdotal reports of significant discounting in large commercial aircraft pricing (Newhouse, 2007). An analysis of Boeing and Airbus annual reports demonstrates that revenue has never matched the aircraft list prices of the aircraft delivered in any one year. The Airline Monitor (2004) reported average A320 and 737-800 sale prices of \$53.3 and \$49.4 million (2008 \$), respectively. A 35% discount from list prices is assumed, yielding an estimated base sale price of \$50 million.

Table 3: Aircraft Lifecycle Cost Model Inputs

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

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

G. Market Share Model

Airlines are assumed to select the aircraft that gives them the highest utility. We assume manufacturers produce equivalent aircraft, with fuel burn the only differentiating factor. But, due to past fleet decisions, airlines have generally committed to one manufacturer's product. Airlines prefer a fleet composed of aircraft from the same family to reduce training, maintenance, and spare part inventory costs. Therefore, airlines select the aircraft with the lowest TAROC, as long as the reduction of TAROC of the aircraft is greater than the aircraft family switching cost the airline may incur.

The world's single aisle fleet is roughly split between the 737 and A320 families, with unfilled orders slightly favoring Airbus. It is expected that incremental improvements in the fuel efficiency of one manufacturer's aircraft are not enough to convince airlines operating the competitor's aircraft to switch. A substantial operating cost improvement is required relative to the competition to gain market share. Further, it is assumed that some airlines will never choose to switch manufacturers, leaving some minimum market share that a manufacturer will maintain as long as they choose to produce their aircraft.

Assuming airline's switching costs are evenly distributed between 10% of the aircraft price and the reduction in TAROC resulting from a new aircraft, a historical analysis of narrow body and wide body market segments was used to determine the market share rules shown in Table 4. The minimum market share values were taken from the wide body market segments where Boeing's 777 controls ~85% of the market vs. Airbus's A340, and Airbus's A330 takes ~85% of the market vs. Boeing's 767. The market share assumption for the three player games are shown in the Appendix. It is assumed that a new entrant would take market share away from the incumbent manufacturers with the same rules as in the two-player game.

Table 4: Two-Player Game Market Share Rules

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

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

H. Production Capacity Constraints and Fixed Costs

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

I. Expected Net Present Value Calculation

The values of the aircraft program valuation model input parameters as described in sections A-H are summarized in Table 5. The low and high values used in the sensitivity analysis performed in the next section are included to indicate the expected range of inputs.

Table 5: Aircraft Program Valuation Model Assumptions

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

To calculate the expected net present value E(NPV) of a manufacturer's strategy, the NPV and probability of each possible path through the demand lattice model shown in Table 1 was calculated. E(NPV) was the sum of the probability of each path times its NPV. This approach was necessary as the path through the lattice model impacted the unit production cost (as the cost of any unit produced was dependent on how many previous units had been produced) and the fixed costs (as the production capacity was assumed to not contract).

J. Sensitivity Analysis

A sensitivity analysis was performed to determine whether the aircraft program valuation model is robust, within the high and low range of input parameters listed in Table 5. Figure 6 shows that the model is most sensitive to the learning curve slope and theoretical first unit cost (TFUC) assumptions. In comparison, the development cost and discount rate assumptions have little impact on the expected net present value of the new aircraft program.

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

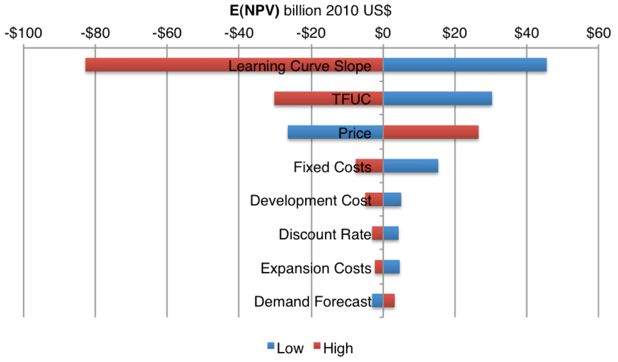

Figure 6: Sensitivity of New Aircraft Program E(NPV) to Change in Input Assumptions.

Next, each high and low input value was tested individually to determine if it would change the outcome of the game, given the market share assumption in Table 4. The only parameters to change the outcome of the game were the low inputs for the learning curve slope and the theoretical first unit cost. By decreasing these values, the new aircraft option had a higher E(NPV), resulting in both players choosing to develop a new aircraft. No other parameters within the range investigated changed the outcome of the two-player game. A learning curve slope of 75% is thought to be optimistic, so the sensitivity of the model to this parameter was considered to be acceptable.

The market share assumptions in Table 4 were tested to determine what magnitudes of changes were required to change the outcome of the game. Each superior performing aircraft market share assumption was varied between 50% and 100%. The outcome of the game was only sensitive to the re-engine vs. maintain market share assumption. Using the base case input parameters, the outcome of the game remained the same for the range 50% to 77% for the re-engine vs. maintain market share assumption.

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

V. Game Theory Analysis of Single Aisle Aircraft Competition

The aircraft program valuation model developed was used to estimate the payoffs in nine games summarized in Table 6:

Table 6: Overview of Games Played.
E(Fuel Price) indicates the low fuel price (-) or increasing fuel price (+) scenarios.

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

Game 1 is the base case against which the other games are compared to understand how the scenario examined impacts the outcome of the game. Complexity is built up with each game, providing an understanding of how different factors change the expected outcome of the game. Two- and three-player games were analyzed to understand the impact of new competition on the current duopoly market. Static and dynamic games were used to show how long-term product line strategies might impact decisions made in the present. The expectation of future fuel prices had important impacts on the outcome of the games investigated. The first three games were played under the expectation of low fuel prices, while the remaining games assumed increasing fuel prices. Under the expectation of low fuel prices it is assumed that manufacturers are not able to raise the sale price of aircraft with fuel efficiency improvements, while the expectation of increasing fuel prices enables sale price increases (as described in Section IV F).

This is a conceptual analysis in which players are assumed to be symmetric, except for the difference in re-engining investment required, as described in Section IV A. Labeled A, B, and C, the players in the games are not meant to reflect real world manufacturers. Players A and B are incumbent manufacturers that have existing single aisle aircraft product lines, while Player C is a new competitor with the strategy set [*Enter*, *Don't Enter*]. Normal form games are used to determine pure strategy Nash equilibriums. Underlined payoffs are the dominant pure strategies, given a competitor's strategy. A Nash equilibrium occurs when both players' payoffs dominate.

A. Two-Player Static Games

Game 1: Expectation of Low Fuel Prices

Under the expectation of low fuel prices, incumbent manufacturers are not able to increase the sale price of a new aircraft as fuel cost savings are negligible over the course of the aircraft's life. The incentive to develop a new aircraft is to gain market share from a competitor or to raise entrance barriers to protect against new entrants. Table 7 shows that the status quo

Table 7: Low Fuel Prices Game
billion 2010 US$ (Player <A>, <B>)

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

is the competitive equilibrium. Both incumbents maintain their current aircraft, reaping large profits while splitting the market. The development of a new aircraft is strictly dominated for both players. This scenario provides a baseline against which scenarios explored in the next sections can be compared to understand their impacts.

Game 2: Technology Forcing Regulations

If low fuel prices are expected, a technology forcing regulation could be implemented to obsolete existing aircraft product lines, forcing manufacturers to re-engine or develop a new aircraft. Rutherford and Zeinali (2009) point out that if the standard applied to new aircraft types, grandfathering in existing production lines, the introduction of new aircraft designs may be delayed to avoid triggering the standard. It is assumed here that the regulation would force manufacturers to either *exit* the market, *re-engine*, or develop a *new* aircraft within a 5-year time frame (i.e. one stage in the valuation model). Exiting the market would be preceded by a phase-in period in which incumbent manufacturers sell their current product lines while replacements are developed, resulting in a positive exit payoff, as shown in Table 8. The predicted equilibrium is for manufacturers to harvest their existing product lines while making the minimum investment to meet the regulation by re-engining. Incumbent manufacturers would not have an incentive to make the larger investment required to develop a new aircraft in the near-term.

Table 8: Technology Forcing Regulations Game

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

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

Game 3: Manufacturer Subsidies

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

Table 9: Manufacturer Subsidies Game

$15 billion subsidy provided for *new* aircraft

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

To incentivize the development of a new aircraft, the payoff for a *new-maintain* strategy must be greater than the payoff for a *maintain-maintain* strategy. Based on our model's assumptions and the expectation of low fuel prices, governments would need to provide new aircraft subsidies on the order of $15 billion to increase the *new-maintain* payoff to shift the competitive equilibrium, as shown by comparison of Table 9 and Table 7.

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

Game 4: Expectation of Increasing Fuel Prices

Under the expectation of high effective fuel prices (due to market forces and/or carbon pricing policies), it is assumed that manufacturers are able to increase the sale price of new aircraft that reduce fuel burn. The expected lifecycle fuel cost savings are split between the airline and manufacturer, as described in Section IV F. Therefore, a new aircraft program yields increased revenue for the manufacturer, but requires a large capital investment and significant demand to reduce unit costs by working down the production learning curve. If demand does not develop as expected, this can be a risky endeavor. Table 10 demonstrates that the increased revenue from increased sale price provides the incentive required to shift the equilibrium to a new aircraft for both players.

Table 10: Increasing Fuel Prices Game

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

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

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

For the remainder of the games examined in this paper, the expectation of increasing fuel costs using the base case values shown in Table 2 were used to calculate the expected aircraft sale price increase over the base price.

B. Three-Player Static Games

With a new entrant, the game changes from a single move to two moves, as shown in Figure 7. In the first move, Player C decides whether or not to enter the market. In the second move, the incumbent manufacturers simultaneously choose their best response to the new entrant's strategy. To deter Player C from entering the market, the incumbents could send credible threats of developing a new aircraft that is superior to the new entrant's. Further, the new entrant could send a threat forcing the incumbents to decide their optimal strategy given their perceived probability of a new competitor entering the market. For this analysis, it is assumed that Player A and B decide their optimal strategy given Player C's decision to enter the market. Given this outcome, Player C would decide whether or not to enter. Therefore, if Player C expected a negative E(NPV) given Player A and B's expected response to the new entrant, Player C would decide to not enter the market, making the game a two-player game, as discussed in Games 1 to 4. Games 5 and 6 demonstrate that the performance of the new entrant's aircraft impacts the outcome of the game. An aircraft with superior performance would capture a greater market share, reducing the incumbents' payoffs further.

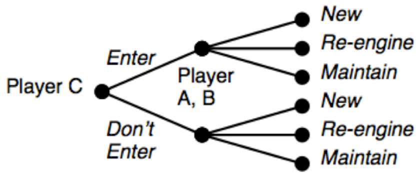

Figure 7: New Entrant Extended Form Game

Game 5: New Entrant, -25% Fuel Intensity

If the new entrant's aircraft has superior performance to the incumbents', the incumbents would expect to lose a significant number of sales, providing them with an incentive to develop a new aircraft. Assuming that sale prices are increased to reflect lifecycle fuel cost savings under the increasing effective fuel price scenario (as in Game 4) and that the new entrant produces a new aircraft that meets the performance of the incumbent's new aircraft option (i.e. a 25% fuel burn improvement), Table 11 shows that an equilibrium may exist in which one incumbent chooses to

Table 11: New Entrant, -25% Fuel Intensity
billion 2010 US$ (Player <A>, <B>, <C>)

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

maintain while the other decides to *re-engine*. Although this equilibrium is sensitive to the input parameters in the aircraft program valuation model, the greater investment required by Player B to re-engine results in an off-symmetric equilibrium. The superior performance of the new entrant's aircraft captures a significant market share while Player A attempts to maintain market share by re-engining. Player B's optimal strategy is to avoid the investment and maintain its current aircraft. Once the competitors' new and re-engined aircraft enter service in stage 2, Player B suffers from a greatly reduced market share, but continues to make small profits due to its unit production cost advantage while harvesting its existing product line. The new entrant has a positive expected net present value in each possible outcome, except if both of the incumbents develop a new aircraft. This result suggests that there may be rents available in the single aisle market, providing an incentive for increased competition if new entrants are able to overcome the significant entrance barriers to develop an aircraft that can compete with the incumbents' new aircraft option.

Game 6: New Entrant, -15% Fuel Intensity

Due to limited design and production experience, a new entrant may not be able to match the incumbents' new aircraft option performance. For this game, it is assumed that the new entrant is only able to develop an aircraft that matches the performance of the incumbents' re-engined aircraft (i.e. a 15% fuel burn improvement). A different off-symmetric equilibrium is shown in Table 12. Player B develops a new aircraft to maintain a 50% market share while Players A and C split the remaining market by offering an aircraft with an inferior performance to Player B's.

Table 12: New Entrant, -15% Fuel Intensity

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

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

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

C. Dynamic Games

If manufacturers consider how their decision in the present impact future product line decisions, the game can be modeled dynamically where the evolution of demand and fuel prices impacts the equilibrium strategy set. Committing to a re-engined or new aircraft locks into a technology level for 10 or more years, requires an investment, and can be risky. Delaying the decision provides more flexibility for future actions, but gives competitors an opportunity to develop a superior aircraft. If it is assumed that both incumbent manufacturers will decide to proceed with a new aircraft by the third stage (i.e. 2020-24), a dynamic game (as depicted in Figure 4) can be evaluated to understand the timing of the decision, given the competitive scenarios developed in this section.

Game 7: Two-Player Dynamic Game

Table 13: Two-Player Dynamic Game

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

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

The payoff for the new strategy was determined for the fourth stage, based on the expected demand and fuel prices. Increased fuel costs enabled manufacturers to increase the sale price of the new or re-engined aircraft while the existing aircraft sale price was assumed to hold constant in real dollar terms. Technology levels were assumed to improve at the rates shown in Figure 3. Therefore, delaying the decision enabled a superior aircraft to be developed that yielded a higher sale price, assuming the expectation of future fuel prices increased or remained constant. Backwards induction down each possible decision path, with each possible fuel and demand scenario, was used to determine the expected payoffs in present value terms in the normal form game shown in Table 13. The dynamic game demonstrates that delaying the development of a new aircraft to take advantage of improved technology levels and the increase in sale price may be the game equilibrium.

The two-player dynamic game was repeated for each combination of the high/low fuel price and demand scenarios in Table 5. Higher fuel prices raise the value of fuel burn reduction technologies, enabling manufacturers to increase the sale price of new and re-engined aircraft, while high demand enables manufacturers to work down the production learning curve more rapidly and spread the fixed costs of development across more aircraft. The low states have the opposite effects. It was found that varying demand did not alter the outcomes of the dynamic game, whereas the low fuel price scenarios resulted in both players selecting the maintain strategy. Therefore, as in the static game, the expectation of higher fuel costs drives manufacturers to develop a new aircraft. This is a result of the aircraft program valuation model's greater sensitivity to price than demand, as shown in Figure 6. All dynamic game results displayed were found using the expectation of increasing fuel costs.

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

The dynamic game was played with a new entrant to the market in the 2015-19 time frame. This analysis enabled the understanding of how new competition – or the credible threat of new competition – may change the dynamic game. As in the static games in Table 11 and Table 12, the level of performance of the new entrant's aircraft impacted the outcome of the game. A new entrant's aircraft with the same performance as the incumbents' new option would take significant market share unless the incumbents move, while a new entrant's aircraft that has the same performance as the incumbents' re-engined aircraft would capture less market share.

Table 14 shows that there are potentially two pure strategy equilibriums. While the incumbents may find it most profitable to harvest their existing product lines, there is an incentive for one incumbent to develop a new aircraft, but not both. The incumbents play a waiting game, with the first one to move taking the risk of developing a *new* aircraft along with a higher expected payoff, while the other stands pat with the less risky *maintain* strategy. To determine which manufacturer is likely to move first would require information regarding the incumbent manufacturer's assessment of the probability of a new entrant and the new entrant's aircraft performance. The manufacturer that believes it is more likely that a new competitor will enter the market with a competitive aircraft will be the first to move, resulting in the late mover delaying the introduction of their new aircraft until the fourth stage (2025-29). The payoffs for the first mover to select the *new* or *delay* strategy are very close, with payoffs that are sensitive to the assumptions of the aircraft program valuation model. Therefore, the timing of the first incumbent new aircraft may be either the second (2015-19) or third stage (2020-24).

Table 14: New Entrant 2015 Dynamic Game, -25% Fuel Intensity

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

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

If a new entrant is expected to develop an aircraft that has the same performance as the incumbents' re-engined aircraft, the incumbents have an incentive to develop a new aircraft, as shown in Table 15. The Nash equilibrium is predicted to be the case were either Player A or B enters a new aircraft into service in 2015-19 while the other delays until 2020-24. Player C gains less market share than required to have a positive E(NPV), suggesting an early move by one of the incumbents could prevent the new competitor from entering the market. The incumbent that delays entry into service of a new aircraft temporarily loses market share while it produces an aircraft inferior to the new entrant and the other incumbent, regaining market share in the third stage (2020-25) when it introduces a new, superior aircraft. If both incumbents delay the entry into service of a new aircraft, the new entrant is able to capture significant market share in the short term, increasing its payoff, and the likelihood of entry.

Table 15: New Entrant 2015 Dynamic Game, -15% Fuel Intensity

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

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

D. Discussion

The static Games 1 to 6 demonstrated the impact of different scenarios on the single-aisle aircraft manufacturer's competitive game. Dynamic decision-based analysis was introduced to combine multiple factors in Games 7 to 9, demonstrating how a game theory analysis of the single aisle aircraft market segment may be used to determine the optimal timing of manufacturer's strategies. Table 16 summarizes the games discussed, showing that while subsidies or expected increasing fuel prices may incentivize the development of new aircraft, consideration of longer-term strategies in the dynamic game may provide incentives for manufacturers to delay the entry of a new aircraft. This may result in superior performing aircraft that enter into service in the next decade, at the cost of increased carbon emissions in the near-term. Kar (2010) showed that early entry into service of available technology (as opposed to delaying entry for more advanced technologies) has greater potential to improve fleet fuel-burn performance due to the dynamics of fleet turnover. Therefore, public policies may be required to incentivize the development of new aircraft.

Table 16: Summary of Game Equilibriums

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

VI. Conclusions

Competition is an important factor to consider when designing policies to reduce aviation's CO_2 emissions. This paper has outlined a framework of analysis for the single-aisle aircraft market segment that uses an aircraft program valuation model and a game theoretic approach to understand the impacts of changes in the market on manufacturer decisions to *maintain*, *re-engine*, or develop a *new* aircraft. It was found that subsidies and higher fuel prices should provide sufficient incentives for incumbent manufacturers to develop a new aircraft. New competition in the market segment is also likely to trigger innovation as incumbent manufacturers attempt to produce more efficient aircraft that maintain sales in a more competitive market. Interestingly, it was found that a new entrant's aircraft that offers a fuel efficiency improvement on the order of 15% may incentivize the incumbents to develop a new aircraft while a new entrant with a 25% fuel burn improvement may cause incumbents to select a less risky strategy.

A number of further complexities could be explored using the framework developed in this paper. It was assumed that competitors act with perfect information. Imperfect information would cast doubt on the technical capabilities of competitor's aircraft as well as the financial payoffs. Incumbent manufacturers could collude either implicitly or explicitly to select the strategy that yields the highest total payoffs with least risk, avoiding Prisoner's Dilemmas. Further, it was assumed that all manufacturers are risk neutral and have the same objective function – to maximize expected net present value of a program. But aircraft manufactures have different corporate cultures and the aerospace industry has spill over effects that impact other sectors of a nations economy, providing incentives for governments to subsidize new aircraft programs that may otherwise not be profit maximizing.

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

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Appendix

A. Market Share Assumptions

The average market share assumptions for the three player games are shown in Table 17 and Table 18. The market share assumptions differ based on the assumed performance of the new entrant's aircraft. If the new entrant produces an aircraft of equivalent performance to the incumbent's new aircraft option, the market would be evenly split three ways if all manufacturers select the new strategy. If the new entrant produces an aircraft of equivalent performance to the incumbent's re-engined aircraft, the market is evenly split three ways if the incumbents select the re-engine strategy.

Table 17: Three Player Game Market Share Rules
New Entrant Performance = Incumbent New (-25%)

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

Table 18: Three Player Game Market Share Rules
New Entrant Performance = Incumbent Re-engined (-15%)

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

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