12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM
17 - 19 September 2012, Indianapolis, Indiana

AIAA 2012-5466

Airline Competition in Duopoly Market and its Impact on Environmental Emissions

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The Fleet-Level Environmental Evaluation Tool (FLEET) is a simulation tool developed to assess the impact of new aviation technologies and policies on fleet-level environmental metrics of CO_2 and NO_x emissions and noise. Previous work with FLEET simulated the operations of a 'benevolent monopoly' airline in the US domestic and US-originating international air transportation network. This paper presents a newly developed capability to capture the more realistic case of airline competition, though still in abstract form via modeling competition between two typical airlines: a legacy carrier and a low-cost carrier. The resulting duopoly model is described and the simulation results are first compared to the prior monopoly model and then explored under various scenarios on fuel price levels.

Nomenclature

$BH_{k,j}$	=	Block hours or aircraft type *k* on route *j*
$C_{k,j}$	=	Direct Operating Cost (DOC) of aircraft type *k* on route *j*
cap_k	=	Capacity of aircraft type *k*
dem_j	=	Passenger demand on route *j*
$fleet_k$	=	Number of aircraft type *k* in the fleet
LF_k	=	Load factor of aircraft type *k*
MH	=	Maintenance hours for each flight hour for all aircraft types
$P_{k,j}$	=	Ticket price on aircraft type *k* on route *j*
$pax_{k,j}$	=	Number of passengers that fly on aircraft type *k* on route *j*
$x_{k,j}$	=	Number of trips of aircraft type *k* on route *j*

I. Background and Motivation

AVIATION'S environmental impact has gathered increasing concern over the past few years, and several agencies such as NASA and ICAO have established emissions reduction targets in response. NASA, for example, has established goals for emissions reduction from consecutive generations of aircraft. As of 2005, they refer to current in-production aircraft as "N" generation. The next generation is referred to as the "N+1" generation aircraft, and these use technology predicted to be available by 2015. These are followed by the "N+2" generation with technology available by 2020 and the "N+3" generation with technology available by 2025. Focusing on individual aircraft, NASA aims to reduce fuel burn by 33% with respect to current generation aircraft, cumulative

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certification noise by 32 dB from Stage 4 levels, and landing and takeoff nitrogen oxide (LTO NO_x) emissions by 60% from CAEP/6 levels for the N+1 generation. The N+2 generation aircraft will reduce fuel burn by 50% from current aircraft, cumulative noise by 42 dB from Stage 4 levels and LTO NO_x by 75% from CAEP/6 levels. The goals for N+3 generation aircraft are to reduce fuel burn by more than 70%, cumulative noise by 71 dB, and LTO NO_x by more than 75%.[1]

While technologies that promise such benefits appear feasible,[2] the realization of the above goals depends not only on the application of technology in individual aircraft but also on the utilization of these aircraft by airlines. Even with improving aircraft technology, future emission and noise levels can exceed current levels if the demand for air transportation continues to grow and outpaces the effect of improved aircraft technologies. Several organizations, again including NASA, have stated goals for reducing the carbon emissions of air transportation. Most of these goals share two important points: 1) to achieve “carbon neutral growth” by 2020, meaning that the carbon emissions of air transportation is the same level as it was in 2005, and 2) that the carbon emissions level of air transportation in 2050 is half the level it was in 2005, both while serving increasing demand.[1]

The Fleet-level Environmental Evaluation Tool (FLEET) is a NASA-sponsored simulation tool developed at Purdue to simulate aircraft operations in the US air transportation network and to assess the corresponding environmental impact. This tool, which solves a resource allocation problem to simulate airline operations, can be used to study the effect of different technologies, economic conditions and policy initiatives on the airlines' performance, their emissions in form of CO_2 and NO_x emissions and their noise footprint.

Previous work (Refs. 3-7) described the development of FLEET and the accompanying studies. FLEET was based on the modeling of a benevolent monopoly airline to estimate aviation demand and operations, and this model of FLEET is referred to as the monopoly model. The presence of competition between airlines in the model, however, would better represent the real world situation. Therefore, the work presented here is based on the implementation of a duopoly model, wherein two airline types, one based on the low-cost model and the other based on the legacy network model, are considered. As the simulation progresses, these two airlines compete for market share and reshape their fleets and fleet utilization in attempt to maximize profit. We hypothesize that the competition between airlines with different aircraft fleet composition would create distinct dynamics that ultimately produce different trajectories of emissions over time.

The following section describes the duopoly model starting with the simplifying assumptions followed by the various functions used and problem formulation. The paper closes with a section on studies and results along with concluding comments.

II. Scope and Methods of Approach

A. Route Network, Demand and Aircraft Fleet Setup

The modeled air transportation network uses a subset of the WWLMINET 257 airports,[8] and the routes that connected these airports based upon 2005 reported operations. The subset of airports includes all of those in the United States and international airports that had direct service to or from an airport in the US. In 2005, approximately 65% of all passenger air traffic – 80% of international passengers traveling to and from the US and domestic passengers – had as origin or destination one of these airports. The 2005 passenger demand between these 257 airports is obtained from data provided by the Bureau of Transportation Statistics DB1B database.[9] This demand data is used to filter only those airport-pair connections which have non-zero demand resulting in a total 2134 routes being simulated. The total demand is segregated into two datasets – one for each airline type – and is used to decide their respective operational routes. The legacy airline provides service to demand on both domestic and international routes while the low-cost carrier only operates domestic routes with some of these coinciding with the legacy carrier resulting in competition for market share.

The aircraft in operation are represented by a set of 18 aircraft divided into 6 classes based loosely on seat capacity. To represent technology groups (or technology “ages”) within the aircraft classes, each class is further segregated into a representative-in-class, a best-in-class, and a new-in-class aircraft. Representative-in-class aircraft are those that had the highest number of operations in 2005 within each seat class and are typically older aircraft. The best-in-class aircraft are those that had the most recent service-entry date within each seat class and are generally equipped with the more recent technological advances. The new-in-class aircraft are either aircraft currently under development that will enter service in the future or concept aircraft that incorporate technology improvements expected in the future. Table 1 presents the representative-, best- and new-in-class aircraft used in FLEET.

The new-in-class aircraft modeled here are the Canadair CS100 (a class 2 aircraft), expected to enter service in 2013,[10] the Boeing 787 (a class 5 aircraft) that entered service in 2011.[11] Note that the entry-into-service (EIS) date

Table 1. Aircraft types modeled in the study

Class	Seats	Representative-in-Class	Best-in-Class	New-in-Class
Class 1	20 – 50	Canadair RJ200/RJ440	Embraer ERJ145	Aircraft X1
Class 2	51 – 99	Canadair RJ700	Embraer 170	CS100
Class 3	100 – 149	Boeing 737-300	Boeing 737-700	Boeing 737-700 Re-engined
Class 4	150 – 199	Boeing 757-200	Boeing 737-800	Boeing 737-800 Re-engined
Class 5	200 – 299	Boeing 767-300	Airbus A330-200	Boeing 787
Class 6	300+	Boeing 747-400	Boeing 777-200ER	Aircraft X6

of these aircraft makes them N+1 type aircraft. The re-engined version of Boeing 737-700 is used as new-in-class aircraft for class 3 while the reengined version of 737-800 is used for class 4, reflecting the decision made by both Boeing and Airbus in introducing the 737 Max and A320 Neo respectively. The remaining new-in-class aircraft for class-1 and class-6 – labeled Aircraft X1 and X6 respectively – are concept aircraft models that incorporate technology advancements that enable them to achieve the NASA SFW N+2 emissions and noise goals. Each of these aircraft was sized using the Flight Optimization System (FLOPS).[12] FLOPS was used to simulate various missions to generate look-up tables for direct operating costs (DOC), fuel burn and LTO NO_x over all ranges and load factors for the aircraft, which are then used to estimate the operating costs and emissions due to aircraft operations. However, because no models for the conceptual aircraft for class-1 and class-6 exist, these aircraft are assumed to be equal in dimensions and performance to the corresponding best-in-class aircraft, but with fuel burn rate, NO_X emissions, and noise levels that meet the NASA SFW goals. In other words, these aircraft have not been re-sized to account for the technology improvements.

The size of aircraft fleet in 2005 is determined from the the Bureau of Transportation Statistics DB1B database.[9] While this database is used to calculate the size of the total fleet, the division of aircraft between the legacy and low-cost airlines is based on the data from the BTS Schedule B-43 Aircraft Inventory database[13] for the years from 2006 to 2009. Table 2 gives the starting fleet composition for both legacy and low cost airlines. The low-cost airline operates only class 3 and class 4 aircraft. This is justifiable due to the fact that the existing low-cost airlines use a more homogeneous mix of aircraft; for example, Southwest airlines operates only Boeing 737 in its fleet.

Table 2. Starting (2005) fleet composition

Class	Legacy	Low-Cost
1	942	0
2	230	0
3	1236	632
4	874	185
5	339	0
6	162	0

B. Description of the Duopoly Model

As compared to the monopoly model, the duopoly model needs additional details due to the existence of two airlines and their competition for market share on common routes. While the legacy airline in the duopoly model is similar to the lone airline used in the monopoly model, the low-cost airline has certain differences in its characteristics. For example, the ratio of weighted average direct operating cost (DOC) between low-cost and legacy airlines is 0.73 based on 2007 data obtained from the Air Transport Association (ATA).[14] This unit DOC for each airline is a weighted average with the number of aircraft acting as the weight. Since low-cost airlines usually have faster turn-around times between consecutive flights of a given aircraft, this value is set at 0.5 hours as opposed to 1 hour for the legacy airline. The seat capacity for class 3 aircraft is set at a higher value of 137 for low-cost carriers as compared to 126 for legacy carriers to account for an almost 9% higher load factor in class for low-cost carriers (see Table 3); this loosely represents no first-class cabin in the low-cost airline's aircraft.

Table 3. Parameter Setup in Duopoly Model

	Legacy	Low-Cost
Turn-around Time	1 hour	0.5 hour
Seat Capacity (Class 3)	126	137
Direct Operating Costs	Derived from FLOPS	0.73*(DOC for Legacy)

Further, passenger sensitivity to ticket price changes is different for the two airlines and both airlines calculate their ticket prices independent of each other; the ticket price calculation and passenger sensitivity are described in the following sub-section. New market shares (i.e., the ratio of demand served by each airline) on common routes are calculated every year. Following an econometric model of passenger choice, the predicted market shares depend on the frequency of service, the average aircraft size on the route (i.e., the average number of seats on each flight) and the average ticket price per trip. The function that gives the new market share is given by Eq. 1.[15]

$$\frac{S_{leg,m}}{S_{low,m}}=\left(\frac{Freq_{leg,m}}{Freq_{low,m}}\right)^{1.08}\left(\frac{Seat_{leg,m}}{Seat_{low,m}}\right)^{-0.94}\frac{e^{-0.0061\times\left(Fare_{leg,m}-BLF\right)}}{e^{-0.0061\times\left(Fare_{low,m}\right)}} \tag{1}$$

In the above equation, S represents the market share on route m, *Freq* represents frequency of operations, *Seat* gives the average aircraft size in number of seats onboard, *Fare* is the average ticket price on a route and *'BLF'* represents the brand loyalty factor which is set constant at $110 based on 2005-08 market share data. Subscript *leg* represents legacy airlines, subscript *low* represents low-cost airlines and *m* represents the particular route.

Figure 1 shows the flowchart of the duopoly model indicating that computations for each year include calculation of route-wise demand, available fleet and solution of the resource allocation problem. Only the estimation of demand each year is done jointly for both airlines in the model. Eq. (1) above is used when splitting demand between the two carrier types. As noted earlier, the estimation of ticket prices, as well as the retirement and acquisition of aircraft and the allocation problem are all done independently for both the airlines.

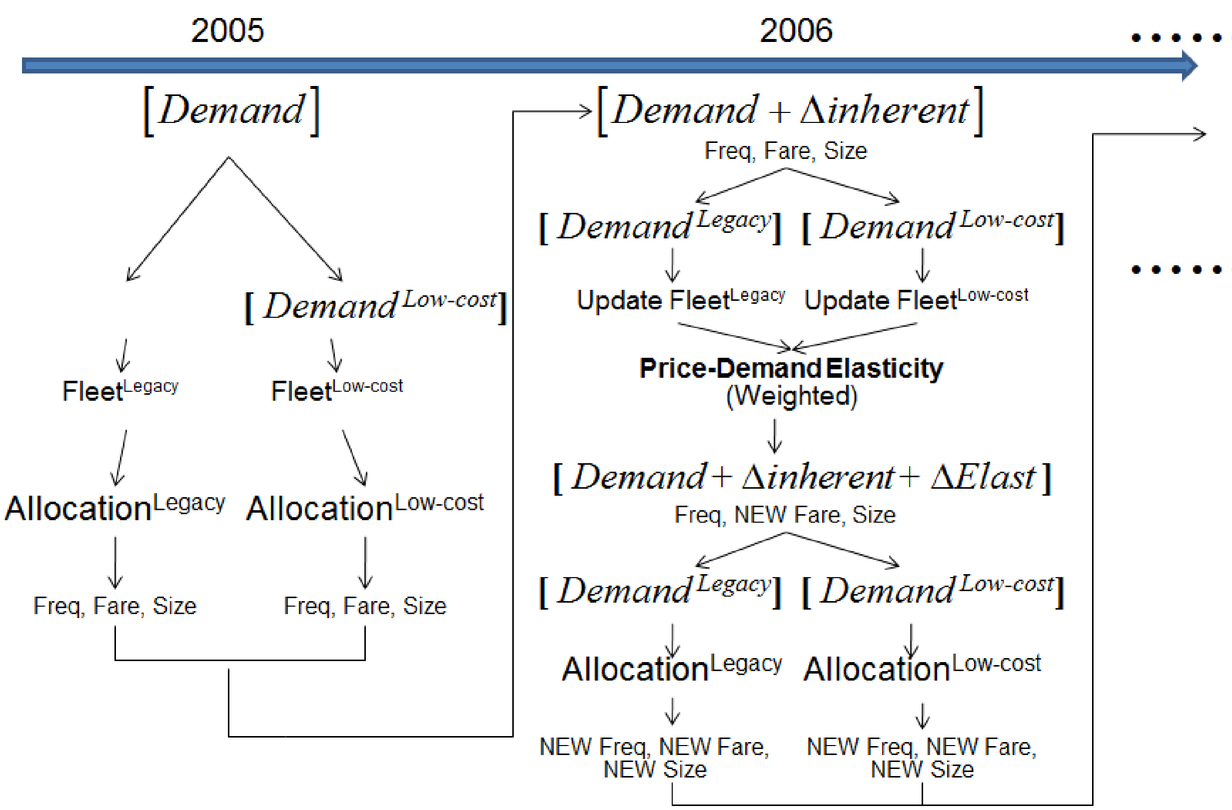

Figure 1. Duopoly Market Demand and Fleet Allocation Flowchart

C. Ticket Price Calculation and Passenger Demand Calculation

1. Ticket Price Calculation

To represent the decision-making of airlines, but not model their scheduling problems, the revenue model assumes that the passenger ticket price is a function of the aircraft type and the route. An earlier revenue model which accounted only for the direct operating costs is described in Refs. 6 and 7. In the new model, the total operating cost of the aircraft now includes Indirect Operating Costs (IOC) along with Direct Operating Costs (DOC). The DOC in turn includes the maintenance and servicing expenses, crew salaries, insurance charges, and fuel cost. Furthermore, the new model implements a financing scheme for the airlines which assumes that they pay off the acquisition cost of the aircraft over a period of 15 years at in interest rate of 10% per annum. Therefore, the total aircraft acquisition cost (principal + interest) is split into 15 equal installments. Thus, the cost components of the revenue model include the DOC, the IOC and the financed acquisition cost. The total daily cost, calculated for each aircraft on each route, is a product of their direct operating costs and the number of trips flown in a day.

The revenue model utilizes historical data from BTS T100 database[16] and Bureau of Transportation Statistics DB1B database[9] to get the aircraft types in use and the median ticket prices for all routes included in the network model. It uses this data to generate the yield predictors. A nonlinear least squares regression approach then generates yield coefficient values as a function of route distance and the aircraft type. The regression utilized actual data on airfares and aircraft type flown, obtained from the above databases for the years 2005- 2010, to generate yield vs. route distance curves for each aircraft class operated in FLEET.

The total operating cost and yield are added together to calculate the ticket prices. Both the legacy and low-cost airlines calculate their ticket prices independent of each other by the same method. The difference in ticket prices offered by the two airlines is primarily due to the use of different aircraft on a particular route.

2. Passenger Demand Calculation

While passengers might generally choose to use the airline offering a lower fare for a specific trip, a brand loyalty facor, as mentioned above, is imposed. The brand loyalty factor helps represent behavior associated with frequent flyer programs and helps match Eq. (1) to reported data. This means that the market share changes only in response to passenger sensitivity to change in ticket price. For instance, increase in ticket prices will cause a general decrease in demand, along with migration of passengers towards cheaper travel alternatives. This price elasticity of demand, applicable to both domestic and international routes is shown graphically in Fig. 2.[17] In the figure, the curve showing elasticity with availability of alternate modes of transport is used for routes within the US while the one without alternate modes is used on international routes. This is not a perfect representation (e.g., JFK-YYZ, New York to Toronto is an international flight of short distance with alternate modes, while LAX-HNL, Los Angeles to Honolulu is a domestic flight without alternate modes). On routes that are common to both airlines, a weighted elasticity based on independent elasticity of the two airlines is used to calculate change in demand, as shown by Eq. (2). In the equation, *ΔFare* gives the change in ticket price, while *MS* represents the market share of the airline, indicated by the subscript *'leg'* for legacy or *'low'* for low-cost; β is the elasticity of demand on each route.

$$\beta_{weighted} = (\Delta Fare_{leg} \cdot MS_{leg} + \Delta Fare_{low} \cdot MS_{low}) \bullet \beta \qquad (2)$$

As seen in Figure 1, the demand calculation for the succeeding year is done jointly for the two carriers. This calculation comprises of two modes of demand change, viz. the inherent demand change which is a function of economy, and the elastic demand change which is a function of change in ticket prices. Passenger response to ticket price changes has already been mentioned; the response of demand to economy is implemented using the income-demand elasticity. Based on a study by MIT/PARTNER, FLEET uses a value of 1.4 for income-demand elasticity, meaning that a 1% growth in GDP results in 1.4% growth in inherent demand for air transportation.[18] This value is assumed to be applicable to both domestic and international routes. Once the new total demand for a route shared by the two carriers is calculated, it is split between the two carriers using the market share function Eq. (1).

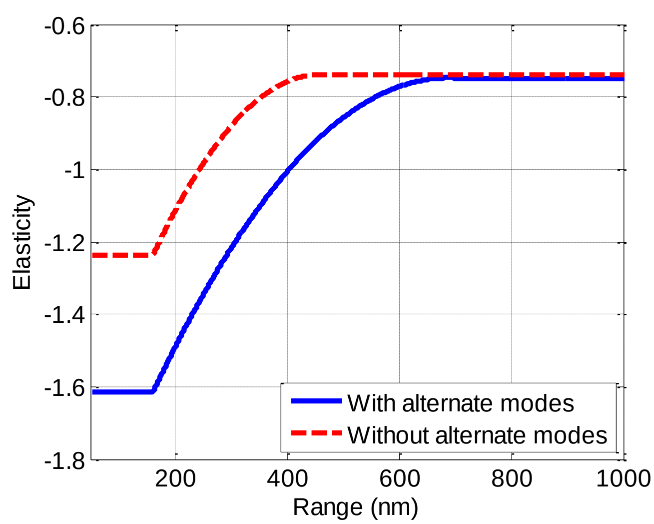

Figure 2. Demand Elasticity as a Function of Range

D. Aircraft Retirement and Acquisition

Considerable effort was expended to develop aircraft retirement and delivery models. These models make possible the consideration of several aircraft delivery approaches which can lead to the analysis and identification of technology penetration schemes that can help to achieve the NASA SFW goals. These models are now described in detail.

1. Aircraft Retirement

Previous work in FLEET assumed a fixed retirement age of 25 years for all aircraft based on literature which considered this reasonable.[19] However, an unpredictable change in fuel price, availability of new technology or an increase in maintenance cost with aircraft age may lead the airlines to consider an earlier or delayed retirement age. For example, under a scenario with rapidly increasing fuel prices, it may not be economical for the airline to continue to operate an older aircraft, while introducing a new aircraft in the fleet would add to the acquisition cost. Bearing this in mind, the team developed a net present value based model to decide on a retirement age of aircraft, similar to those in Ref. 20 and 21.

To model aircraft retirement, the BTS Schedule B-43 Aircraft Inventory database[13] is used to determine entry-in-service date of the aircraft modeled here. This database contains detailed information regarding the entry in operation of passenger transport aircraft by tail number. By keeping track of the entry in service dates and availability of the new aircraft in the market, the model seeks to find an optimal retirement age of the aircraft in the fleet.

The new retirement model evaluates the economic feasibility of retaining an aircraft for an additional year versus its immediate retirement in the current year. In other words, it works by comparing the net present values (NPV) of two options: that of operating the currently owned aircraft for one more year, replacing it with a new aircraft in the following year, and that of replacing the current aircraft for a new one immediately. In the calculation of NPV, all future cash flows are discounted with respect to the base year 2005 using a discount factor as prescribed by the Office of Management and Budget.[22]

The model requires a detailed cost and revenue structure for both the currently owned and the replacement aircraft. The components of cash flow for an aircraft include the fuel costs, its initial acquisition cost, and its direct and indirect operating costs. All these values are obtained from FLOPS. The revenues in form of ticket prices are obtained from the ticket price function in FLEET as described above. To simulate the increase in maintenance cost as the aircraft ages, the model uses an airframe maturity curve presented in Refs. 23 and 24. However, the maximum airframe life of an aircraft is assumed to be 40 years. This means once an aircraft is over 40 years old, it is automatically retired from service.

As was noted earlier, the acquisition cost of an aircraft is paid off over a period of 15 years. Early retirement of an aircraft leads to a penalty being applied. Also, at the time of its retirement, the aircraft is sold off by the airline. The resale value of an aircraft depreciates according to a bi-linear curve wherein its value falls to 10% of original in the first 15 years and then reduces to 1% of original by the end of 40 years. Finally, since the number of deliveries is limited, as described in the following subsection, a cap is set on the number of aircraft that can be retired and this cap equals the total number of possible deliveries per class.

2. Aircraft Acquisition

The aircraft acquisition process has two main steps:

1. The calculation of maximum number of deliveries possible based on aircraft production capacity, and
2. The calculation of number of aircraft to be acquired to meet projected demand for the following year.

The total number of deliveries possible each year is constrained by the production capacity of the various airframe manufacturers as approximated by Eq. (3).

$$production = 1309 + 30.83 \times time \tag{3}$$

This equation is based on regression of the historical data of actual deliveries of the six classes aircraft used in FLEET. Here, *production* gives the total number aircraft that are produced in the current year and *time* indicates the number of years since start of simulation, i.e. 2005. This production capacity is then split amongst the six classes based on the market share of each of these classes, which is the fraction of total passengers that were carried in that class of aircraft.

The aircraft delivery model calculates the number of aircraft to be acquired in the following year as a function of estimated future demand growth and current capacity; Eq. (4) gives this number for each class in each year.

$$acquisitions_i = fleet\_need_i + retirements_i \tag{4}$$

Here, *fleet_need* reflects the increased capacity required due to an increase in demand while *retirements* accounts for the number of aircraft retired this year and the subscript i indicates that these values are calculated for each class. The calculation of *fleet_need* is shown in Eqs. (5) to (8).

$$fleet\_need_i = \frac{cap\_needed_i}{average\_trips_i \times seat\_cap_i} \tag{5}$$

$$\begin{aligned} cap\_needed_i = {} & (\Delta demand \times acquisition\_factor_i) - \\ & (unused\_ac_i \times average\_trips_i \times seat\_cap_i) \end{aligned} \tag{6}$$

$$acquisition\_factor_i = \frac{\sum_j weighted\_factor_{i,j}}{\sum_i \sum_j weighted\_factor_{i,j}} \tag{7}$$

$$weighted\_factor_{i,j} = \alpha \frac{pax_{i,j}}{\sum_j pax_{i,j}} + \beta \frac{1/unitDOC_{i,j}}{\sum_j 1/unitDOC_{i,j}} \tag{8}$$

First, the additional capacity required in terms of number of seats is calculated as the increase in passenger demand from previous year. This capacity is distributed to the six classes of aircraft based on a *weighted_factor* for each class which is calculated as explained below. Also, from the calculated capacity, excess capacity in form of unused aircraft is subtracted. This reflects the extra aircraft available to the airline in the previous year that were not required to solve the allocation problem.

The *weighted_factor* determines the distribution of new capacity between the six classes of aircraft on each route. This factor assigns weights to aircraft based on their market share as measured by the fraction of passengers carried by that class on each route, and their predicted operating cost per seat mile. The rationale for this is that a higher utilization in one year would mean that the airline would seek to buy more of similar aircraft in following years, while a lower operating DOC would mean that these aircraft would be more economically efficient and thus desirable for inclusion into the fleet. In the calculation of *weighted_factor*, the parameters α and β can be used to assign different weights to each of the two contributing factors. Here, both were given a value of 0.5 to indicate the airline giving equal importance to them. Finally, the *acquisition_factor*, calculated as in eq. (7), assigns weights to acquisition of a particular class of aircraft based on its *weighted_factor*.

E. Solution Methodology

The backbone of FLEET is an aircraft allocation problem, which is formulated and solved as a mixed integer programming problem using the GAMS software package.[25] This problem uses the performance characteristics of aircraft to maximize profit while meeting demand and operational constraints as a model of airline operations and decision-making. The mathematical form of the resource allocation problem is given by Eqs. (9) – (12):

Minimize

$$\sum_{k=1}^{K}\sum_{j=1}^{N}\left(pax_{k,j} \cdot P_{k,j}\right) - \sum_{k=1}^{K}\sum_{j=1}^{N}\left(x_{k,j} \cdot C_{k,j}\right) \tag{9}$$

Such that

$$\sum_{k=1}^{K} pax_{k,j} \le dem_j \tag{10}$$

$$pax_{k,j} \le x_{k,j} \cdot \left(cap_k \cdot LF_k\right) \tag{11}$$

$$\sum_{k=1}^{K}\left(x_{k,j} \cdot \left(BH_{k,j} + MH\right) + x_{k,j} \cdot t\right) \le \left(24/2\right) \cdot fleet_k \tag{12}$$

where $x_{k,j}$ and $pax_{k,j}$ are integer variables.

The integer decision variable $x_{k,j}$ is the number of trips that aircraft type k flies on route j while the integer variable $pax_{k,j}$ is the number of passengers carried by aircraft type k on route j. Routes use a single subscript, because of a round trip assumption described below. Eq. (9) is the objective funtion to be maximized by the optimization program. It gives the profit of the airline, defined as the difference between revenue and cost. Revenue is a function of ticket price, $P_{k,j}$, and the number of passengers on each aircraft type and route, $pax_{k,j}$. Ticket price is a function of the aircraft type and route on which a passenger flies. Profit is, therefore, the sum of profit from each of the routes and for each of the aircraft types.

Constraints in Eq. (10) ensure that the airline does not transport more passengers than the market demand on each route while constraints in Eq. (11) ensure that the airline flies a sufficient number of trips to meet passenger demand while considering the seat capacity of each aircraft type, cap_k, and its load factor, LF_k. The constraints in Eq. (12) count the number of aircraft necessary to satisfy demand and limit the number of hours available for aircraft "use" in a given day. The problem assumes that passenger demand is symmetric and the aircraft always fly round-trips (e.g., an aircraft operating from ORD to ATL would then fly a return from ATL to ORD); therefore, the number of available hours is limited to 12 hours (24/2). This appears to be a reasonable assumption, because the fleet allocation problem estimates the cost and profit of average daily operations, and the BTS data shows that average daily demand is nearly symmetric although a given passenger may not fly a return trip on the same day. Further, many – but not all – aircraft, particularly those operated in hub-and-spoke networks, often fly from a hub to a spoke and back to the hub. Bounds on the decision variable $x_{k,j}$ ensure that an aircraft type does not operate in and out of an airport that does not have a long enough runway and that an aircraft does not operate on routes that exceed its design range. The round-trip simplification removes the need for flow-balance constraints in the allocation problem.

Integer Programming methods can solve the allocation problem presented in Eqs. (9) – (12). The software package GAMS (General Algebraic Modeling System)[25] facilitates formulation and solution of this IP problem. GAMS provides an algebraically-based, high-level language for the compact representation of large and complex models and uses the CPLEX[26] solver to solve the IP problem.

The solution of the allocation problem allows calculation of the daily profit and cost, CO_2 production, total NO_x production, and total noise area of the airline as it seeks to maximize profit while satisfying demand. Of these, total noise area is not a commonly used metric; generally, aviation noise deals with noise associated with a local airport. However, to provide a single metric to describe the broad fleet impact, "total noise area" is the sum of the predicted area inside the 65 dB DNL contour at all 257 domestic airports in the LMINET. This metric does not include international airports, because the airline model does not attempt to represent all operations at those airports; the current airline model more nearly represents all operations at US airports.

III. Studies and Results

FLEET has the ability to simulate different scenarios and study the effects on the airline's performance and emissions. However, before initiating any studies, it is worthwhile to understand the difference between the results of the duopoly model from the monopoly model.

The baseline scenario in FLEET, wherein the simulation starts in 2005 and continues until 2030, is used to understand these differences. This scenario is defined as one in which the new-in-class aircraft come into service at the best guess entry in service dates given earlier. The gross domestic product growth is assumed to be a constant 2% per annum throughout the period of simulation, and the fuel prices increase as per the reference fuel price scenario. The fuel price scenarios simulated are based on the prediction of future fuel prices as given by the Energy Information Administration (EIA);[27] all these scenarios are shown graphically in Fig. 3. EIA uses historical values of fuel prices for years until 2009, after which, the low-and the high-price cases give the best and worst case scenarios of fuel price increase. The difference between the two scenarios is significant – by 2030, fuel prices under the

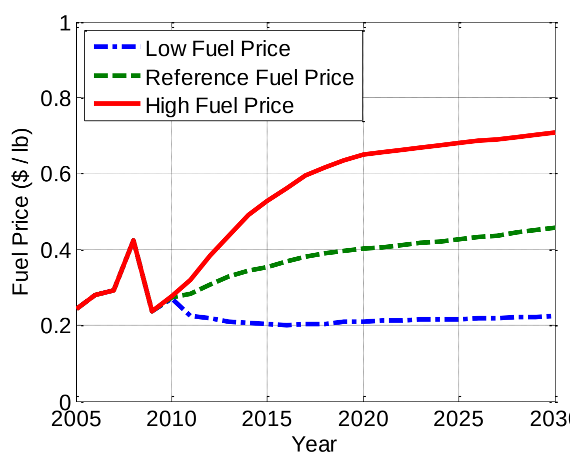

Figure 3. Fuel Cost Scenarios based on Energy Information Administration data (2005 $)

high-price case are more than 68% higher than in the low-price case.

However, initial runs using the baseline scenario showed that the two airlines in duopoly model could not serve market demand. For example, the legacy airline could only serve 75% of the total demand by 2030. This problem was found to be a result of a small size of initial fleet, and doubling the fleet size solved the problem. While such doubling of the starting fleet means that both the legacy and low cost airlines have access to near unlimited number of aircraft, no significant difference was found in the allocation decisions of the two airlines even after this increase. The increased number of initial aircraft required is a current limitation of the model and would be addressed during future development of the tool. The results presented below are under the case of double the starting fleet size only for the duopoly model.

Figures 4 and 5 show the results obtained by the duopoly model as compared to the monopoly model. The demand and CO_2 emissions data for legacy and low-cost carriers is calculated and stored separately, and their sum gives the network level values shown in the figures. Clearly, the total market demand served in the duopoly model is lower than the demand served in the monopoly model. Together, the two airlines in duopoly model serve 4.96% lower demand in 2030 than that served by the monopoly airline. In the same year, the difference in total emissions is even more pronounced, and the two airlines in duopoly model together emit 6.77% lower CO_2 than the monopoly airline. This difference is attributed to the higher efficiency, here with regards to the number of daily trips needed to meet market demand, with which the two airlines can serve their respective markets. As seen from Fig. 5, the difference in total CO_2 emissions between the two duopoly airlines and the monopoly airline grows gradually. Over time, as the two airlines in the duopoly model tailor their respective fleet sizes to better match their needs, they need fewer trips to serve demand; the total number of trips in 2030 differs by 9.68% with the two duopoly airlines making fewer trips.

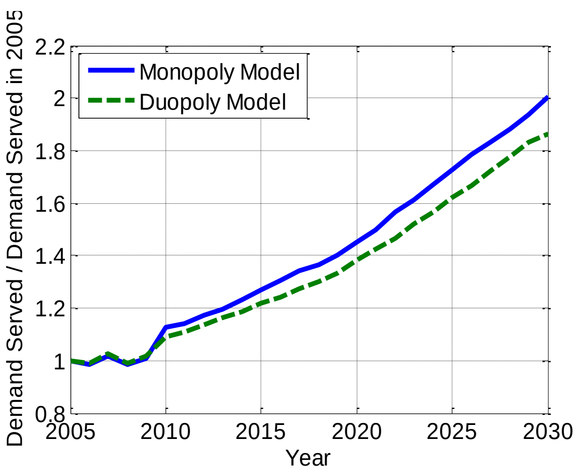

Figure 4. Demand Served

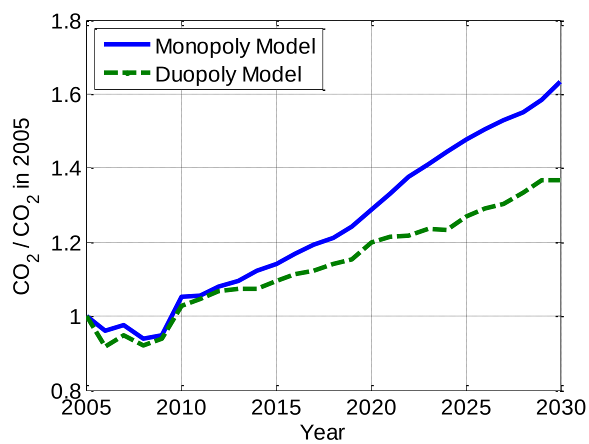

Figure 5. CO_2 Emissions

Finally, the fleet composition of the monopoly airline and the two duopoly airlines taken together also differs. By 2030, the monopoly airline used a total of 9814 aircraft across all classes combined, while the duopoly airlines use 11021 aircraft, a difference of 1207 aircraft, with the biggest difference being in class 3. This is, perhaps, not surprising, given that the monopoly model and the duopoly model seek to serve nearly similar levels of demand. Without competition, the monopoly airline increases profit when it can use fewer aircraft to serve demand at the likely sacrifice in service frequency.

Having seen the difference in results between the monopoly and duopoly models of FLEET under the baseline scenario, the effect of fuel prices on performance of legacy and low cost carriers can now be compared. Fuel prices have a significant effect on airline DOC and can result in changes in ticket prices, which in turn would affect the demand for air travel. Additionally, in the duopoly model, since both the legacy and low cost airlines have different fleet compositions as well as market share, the increase in fuel prices would impact them differently.

Figure 6 shows the evolution of market share under the reference fuel price case. The market share of the legacy carrier increases from 77.42% in 2005 to 80.66% in 2030, while that of the low cost carrier decreases from 22.58% to 19.34%. Other scenarios of fuel price change did not have a significant effect on the model results, with the market share division in 2030 being very close in all three scenarios. However, fuel prices did affect airline profits noticeably. Since profit depends on the demand for air travel and demand in the three scenarios differs significantly due to the presence of price-demand elasticity, a direct comparison of profit would not yield any meaningful results. Hence the estimated airline profit per passenger nautical mile is used as the metric for comparison of the three scenarios.

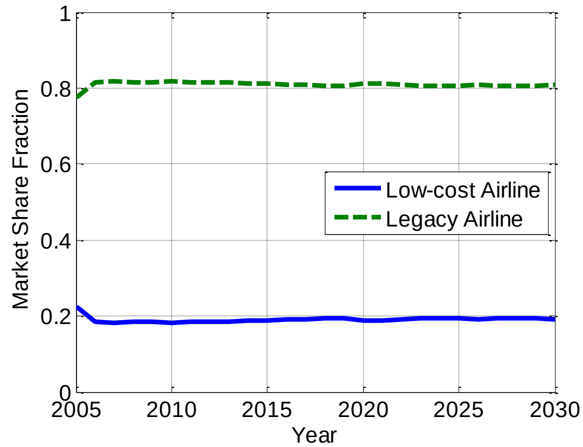

Figure 6. Market Share Evolution under Reference Fuel Price Scenario

By 2030, the legacy airline's profit per passenger nautical mile grows by 83.12% under the low fuel price scenario, by 62.74% under the reference fuel price scenario and by 70.34% under the high fuel price scenario. The low fuel price scenario is most favorable for the legacy airline, which is to be expected since under this scenario, there is there is higher growth in the demand for air travel. On the other hand, between the reference and the high fuel price scenarios, the high fuel price scenario is more favorable for the legacy airline. This is justifiable since regardless of the increase in fuel prices, the long distance passengers, and especially international passengers who do not have an alternative mode of transport, would continue to fly. This is why even with increasing fuel prices, the legacy airline's profit would have only a limited impact.

On the other hand, for the low cost airline, only an increase in market demand for air travel translates to an increase in its profit. This is why the low fuel price case, which results in the maximum increase in market demand, is highly beneficial to this airline. Furthermore, the profit per passenger nautical mile value for this airline shows different behavior to the same value for legacy airline. From 2005 to 2025, it drops to 50% of its 2005 value in the high fuel price scenario, to 57.74% in reference fuel price scenario and to 63.62% in the low fuel price scenario, but later recovers to close to its 2005 value by 2030 and all three scenarios.

Finally, for both airlines, the class-wise distribution of aircraft utilization remained the same regardless of the fuel price scenario. The availability of excess aircraft in fleet and the resultant flexibility of choice when making allocation decisions could be a possible reason for this uniformity of aircraft choice. Future efforts towards development of the tool would address this issue of excess aircraft and thereby providing a more realistic assessment of fleet utilization decisions made by these airlines.

IV. Conclusion

FLEET now has the capability to model airline competition, between two different airline models, viz. the legacy and low cost models. In addition to the research previously conducted using FLEET, this capability would allow for examining the effects of economy, aviation policy and aircraft technology on the performance of these two airlines. This paper compared the effects of fuel price increase on the two airlines. Results indicate that it would work to the low cost airline's favor if fuel prices continue to remain lower, or grow slowly, since under this case they would continue to see an increase in profits. However, in case of a large increase in fuel prices, the legacy airlines would be at an advantage since the long-haul passengers, especially those on international routes who are less sensitive to increase in flying cost, would continue to travel, contributing to sustained profits for these airlines.

Though the results obtained make intuitive some sense, they have been obtained by increasing the starting airline fleet size to twice the number of aircraft suggested by reported data. This limitation would be addressed in future development of the tool so that more realistic results can be obtained and analyzed. Additionally, future studies using FLEET would include the capability, currently being integrated, to model the effects of capacity constraints at the airports. The effect of availability of technology and imposition of environmental policy are also worth investigating and would be considered during future studies.

Acknowledgments

The authors would like to thank program technical monitors Bill Haller of NASA Glenn Research Center and Craig Nickol of NASA Langley Research Center. NASA Cooperative Agreement NNX07AO13 supported the work presented in this paper. The authors would also like to thank Purdue graduate students Parithi Govindaraju and Satadru Roy for their support in completing this work.

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