51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
07 - 10 January 2013, Grapevine (Dallas/Ft. Worth Region), Texas

AIAA 2013-0652

Assessment of the Effect of Aircraft Technological Advancement on Aviation Environmental Impacts

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This paper studies the evolution of fleet-level emissions from aviation under different scenarios of aircraft technology availability and fuel price variation. The aim is to assess the efficacy of introducing advanced technology aircraft as a means to reduce total emissions while still serving increasing passenger travel demand. Particularly, this paper explores the potential existence of an effect in the aviation industry similar to the so-called the Jevons' Paradox, in which the profit-seeking airline modeled here uses a larger number of more fuel-efficient aircraft so that the increasing number of flights overwhelms the fuel efficiency gains of the individual aircraft. Simulation results confirm that, while advanced technology aircraft would improve the emissions efficiency of the airline fleet, the advance technology alone would not be sufficient to reduce total fleet-wide CO_2 emissions. This finding implies the need for other initiatives (e.g., operations changes, alternate fuels, and carbon policies) to provide incentives to airlines to reduce CO_2 emissions.

Nomenclature

BH_{kj}	=	Block hours for aircraft *k* on route *j*
MH	=	Maintenance hours
$x_{k,j}$	=	Number of trips of aircraft *k* on route *j*
$pax_{k,j}$	=	Number of passengers that fly on aircraft *k* on route *j*
$C_{k,j}$	=	Cost of flying aircraft *k* on route *j*
cap_k	=	Seating capacity of aircraft *k*
dem_j	=	Demand on route *j*
LF_k	=	Load factor on aircraft *k*
$fleet_k$	=	Number of aircraft type *k* in fleet

I. Introduction

THE development and use of advanced technology aircraft is intended to reduce both costs (thus making airlines more profitable and, possibly, making fares lower for passengers) and the environmental impact of aviation (lower fuel burn leads directly to lower CO_2, for example). Further improvements in aircraft technology may also decrease travel times and provide other benefits to the traveler such as higher frequency of service. These benefits could make air travel more attractive both leading to and enabling higher air transportation demand that would

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intensify the environmental impacts and possibly nullify the benefits of new technology. This effect, where a more energy efficient technology leads to higher use of energy, is known as the Jevons' Paradox;[1] the studies in this paper help identify scenarios under which the unintended consequences of improved aircraft efficiency leading to increased fleet-level environmental impact may occur. If such an effect exists, the introduction of new technology alone may do little to reduce aviation's environmental impact; other initiatives such as implementation of appropriate policies and changes to operational procedures would be required to reduce environmental impact. Hence an awareness of the existence of this effect would help both policymakers and business stakeholders make informed decisions regarding the future of the aviation industry.

II. Background and Motivation

The growth of the air transportation industry follows the world GDP growth closely, and has seen an average growth of 5% per annum in total revenue passenger kilometers since 1980.[2] At the same time, increasing competition among airlines and advances in aircraft technology have made air travel cheaper, faster and more convenient for all people. This, too, has led to an increase in demand for air travel. However, of late, the environmental impact of aviation has come under increasing focus; as a result, reduction of this impact has become very important to ensure the sustained future growth of aviation and commercial airline service.

To address this challenge, agencies such as NASA and ICAO, among others, have set forth goals for reduced CO_2 and NO_x emissions from aviation. For example, NASA aims to develop technology that could reduce aircraft fuel burn by 33% with respect to current aircraft, cumulative 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 N+1 generation aircraft that use technology with predicted availability by 2015. With technology available by 2020, NASA's 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, with technology available by 2025, aim to reduce fuel burn by more than 70%, cumulative noise by 71 dB, and LTO NO_x by more than 75%.[3]

In response to the above targets, several technology options, operational procedures and policies that promise such benefits have been proposed. For example, development of new technologies to reduce drag, aircraft and engine weight, and engine specific fuel consumption would provide expected ability to reduce fuel burn. Improved aerodynamic shaping, including landing gear fairings and improved high-lift devices, along with engine technologies and engine placement for acoustic shielding will contribute to noise reductions. Development of alternative combustor concepts, active combustor control, alternative combustor liners, and alternative fuels can contribute to the achievement of the LTO NO_x emissions goals.[3] Furthermore, aircraft concepts such as the blended wing body, airspace operations concepts like NextGen and SESAR and policies like the European carbon emissions taxes have all been proposed to help meet goals to reduce aviation emissions. However, the first step in implementation of all such measures, and upon which the success of such targets depends most, is the availability of next generation advanced aircraft.

While technologies that promise such benefits appear feasible,[4] the realization of the aviation-wide emissions goals depends not only on the application of technology in individual aircraft but also on the utilization of 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. 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) "carbon neutral growth" by 2020, here meaning that the carbon emissions of air transportation is at the same level as it was in 2005, while serving increased demand, and 2) the carbon emissions level of air transportation in 2050 is half the level it was in 2005, again while still serving increasing demand.[3] In context of such challenges, it is worthwhile to evaluate how the introduction of new technology and its use by airlines would impact future market demand and the environment. A tool that simultaneously assesses market demand, airline economics, aircraft technology introduction into airline fleet, and the emissions resulting from their operation would help accomplish this evaluation.

Previous work (Refs. 5-11) described the development of and some studies conducted with the Fleet-Level Environmental Evaluation Tool (FLEET). The Fleet-Level Environmental Evaluation Tool (FLEET) is a computational simulation tool developed to assess how aviation's fleet-level environmental impacts – in the form of CO_2, NO_x emissions and noise – evolve over time. Central to FLEET is an aircraft allocation model that represents airline operations and decision-making. Additionally, the tool has a system dynamics-inspired approach that mimics the economics of airline operations, models the airlines' decisions regarding retirement and acquisition of aircraft, and represents passenger demand growth in response to economic conditions. The overarching objective of FLEET is to enable an understanding of how variation in external factors such as market conditions, policy implementation, and technology availability will affect aviation environmental impacts into the future.

FLEET is based on the modeling of a single airline, wherein all the airlines in US are represented by one large airline to estimate how a profit-seeking airline would conduct operations to meet passenger demand. A system dynamics model represents all the interactions between various components of the air transportation network; this model is graphically represented by the stack and flow influence diagram shown in Fig. 1. An example of a study conducted using this tool is a study done to analyze the effect of different entry-into-service (EIS) dates of advanced aircraft on fleet-wide emissions; results obtained showed that the level of carbon emissions are sensitive to EIS dates only for a short period after introduction and that a late introduction of new technology leads the airlines to increase the use of larger aircraft.[9] Another study assessed the effect of competition between a low-cost and a legacy carrier under different scenarios of fuel price variation; this study showed that a large increase in fuel prices would favor legacy carriers allowing them to remain competitive and would be detrimental to the low-cost airlines.[10]

Though the primary aim of FLEET is to study the environmental impacts of aviation, the use of system dynamics approach means that FLEET enables an assessment of the many different interdependencies in the commercial airline industry. This warrants a study of the potential for Jevons' Paradox in aviation, because the environmental impacts of aviation are directly proportional to its energy use and because this study can only be undertaken with an integrated modeling approach such as FLEET. The Jevons' Paradox suggests that, contrary to common intuition, the improvement in efficiency of energy usage would lead to an increase in the overall consumption of energy rather than a decrease. This has important implications because, if true, it would imply that development of new technology aircraft alone would not be sufficient to meet the industry goals of emissions reduction and meeting these goals would require more efforts on the fronts of operations changes and policy implementation.

Motivated by this paradox, different scenarios of aircraft technology development and fuel price variation are modeled and their respective impacts on aviation studied. The combination of new aircraft technologies with the airlines' decision-making provides insight to policymakers and technologists in the aviation industry leading, it is hoped, to more informed polices and the avoidance of unintended consequences. The studies presented herein only seek to suggest scenarios in which Jevons' Paradox might exist in the aviation industry, without trying to propose solutions to overcome its existence. The assessment of operational changes or policies that could help avoid this paradox is the subject of ongoing research.

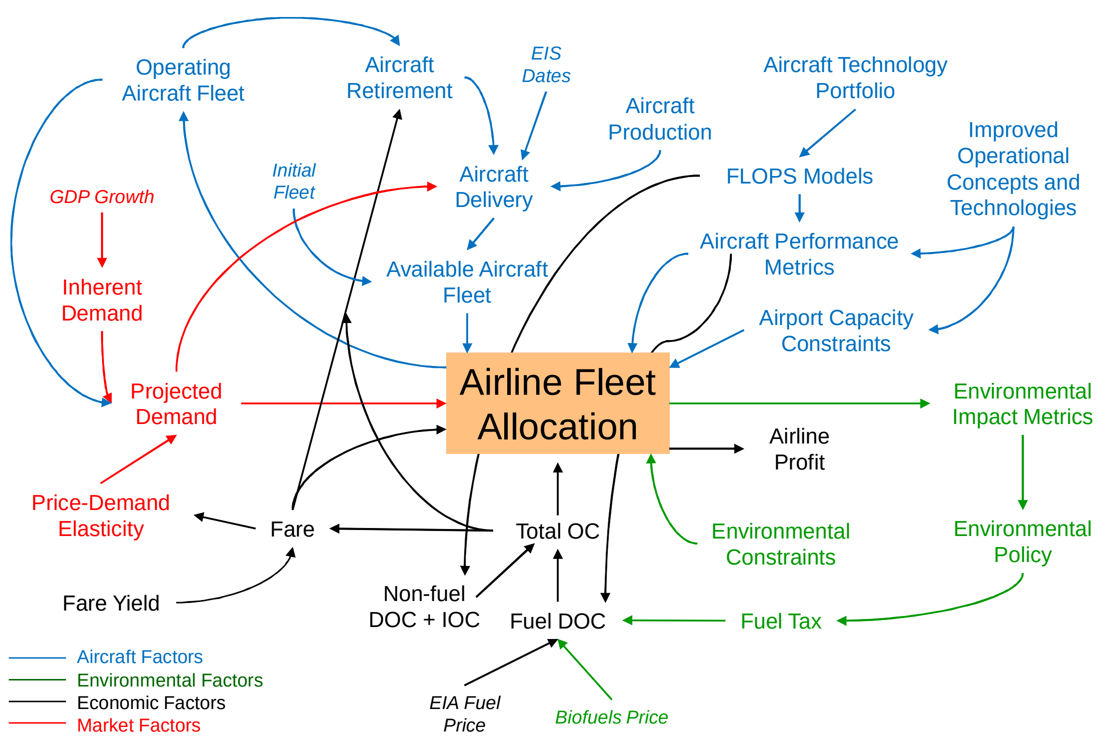

Figure 1. FLEET System Dynamics Stock and Flow Diagram

III. Technical Approach: Initialization and Use of FLEET

A. Route Network, Initial Demand and Aircraft Setup

The number of routes and operations in the US air transportation network is very large. Hence, the simulation in this work only uses those routes that represent passenger demand amongst a subset of the WWLMINET 257 airports* that includes international routes with either the origin or destination at a US airport. In 2005, these airports accounted for approximately 65% of all passenger air traffic operations, and 80% of all passengers transported, including both domestic and international passengers traveling to and from the US.[12] The 2005 passenger demand between the resulting 169 airports uses data available from the Bureau of Transportation Statistics DB1B database.[12]

To manage the number of aircraft types used by the airline, current (and potential future) aircraft are aggregated into six classes based on seat capacity. To represent technology groups (or technology "ages") within the aircraft classes, each class is further segregated into categories of representative-in-class, best-in-class, new-in-class, and future-in-class. 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 as of 2005 and, thus, incorporate 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. Likewise, the future-in-class aircraft are those aircraft expected to include another generation of technology improvements and therefore expected to enter in service a date further in the future. Table 1 presents the representative-, best- and new- and future-in-class aircraft used in FLEET. The airline operates only these aircraft; this provides a representative fleet mix that would match that of the broad set of aircraft that most airlines would have.

All existing aircraft were sized (and calibrated to actual performance and economic data, where possible) using the technological factors provided by NASA using the Flight Optimization System (FLOPS).[13] New-in-class and future-in-class aircraft also relied upon FLOPS estimations of size, performance and cost, but with the impact of new technologies modeled via "technology factors" in a way that is consistent with other NASA models of advanced technology aircraft. For new-in-class aircraft with no reasonable conceptual models available, adjusting the fuel burn, NO_x and noise of existing aircraft to meet the NASA goals provided the aircraft models; hence the "magic wand" label in Table 1. FLOPS was used to simulate various missions with different ranges and aircraft load factors

Table 1. Aircraft Types Modeled in Study

Class	Seats	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
Class 1	20 – 50	Canadair RJ200/RJ440	Embraer ERJ145	Small Regional Jet	"Magic Wand" CRJ 200
Class 2	51 – 99	Canadair RJ700	Embraer 170	CS100	"Magic Wand" CRJ 700
Class 3	100 – 149	Boeing 737-300	Boeing 737-700	Boeing 737-700 Reengined	Small Purdue ASAT
Class 4	150 – 199	Boeing 757-200	Boeing 737-800	Boeing 737-800 Reengined	D-8 Double-Bubble
Class 5	200 – 299	Boeing 767-300	Airbus A330-200	Boeing 787	"Magic Wand" Boeing 767
Class 6	300+	Boeing 747-400	Boeing 777-200ER	Large Twin Aisle	"Magic Wand" Boeing 777

to create tables for Direct Operating Costs (DOC), fuel burn and LTO NO_x for these aircraft, which are then used to estimate aircraft emissions.

B. Future Demand Calculation

Demand change modeled is a function of two factors: the demand change due to broad economic factors, referred to here as the "inherent demand growth", and the demand change due to passenger response to changes in ticket prices charged by the airlines, called the "elastic growth". In the inherent demand growth model, the demand growth is a function of GDP growth, while the elastic growth model incorporates the effects of range and availability of alternative modes of transport into its calculation.

* "List of WWLMINET 257 airports," Personal communications with Dou Long of LMI, 4 May 2009.

1. Inherent Demand Growth

Growth in a nation's economy, which is best represented as the growth in its gross domestic product (GDP), inevitably leads to a proportional increase in demand for air travel. This response of demand to the economy is referred to as inherent demand growth and is implemented in FLEET using the income-demand elasticity. Based on Ref. 14, 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 travel. This value is applied to both the domestic and international routes in the airline network.

2. Elastic Demand Growth

Demand for air travel also changes as passengers respond to changes in air fare; this change is represented using price-demand elasticity. In modeling price-demand elasticity, two factors affect passenger choice to fly. The first is the distance of travel – over short distances, the passengers may choose not to fly and opt for alternative modes of travel. The second factor is whether the route is domestic or international, since over many international routes, alternative modes of travel are not feasible. The elasticity values used for price-demand elasticity are based on a study by AERO,[15] and appear in Fig. 2. In the figure, elasticity values for the 'without alternative modes' case are used on international routes, while those for 'with alternative routes' case are used for domestic routes. For very short distances (less than 280 nm) or distances where ground-based transportation becomes too time consuming (more than 450 nm for international routes and more than 650 nm for domestic routes), the elasticity is assumed constant and is represented by the flat portion of the figure.

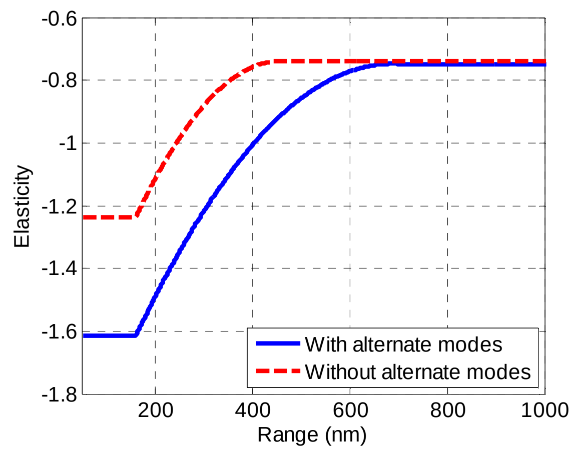

Figure 2. Demand Elasticity as a function of Range

C. Ticket Price Calculation

To approximate the decision-making of airlines, but not model their scheduling problems, the ticket price model assumes that the passenger ticket price is a function of the aircraft type and route. This model is driven by the 'yield per ticket' values for each class of aircraft on a particular route, which is the profit making potential of each of the 24 aircraft on each route. To calculate the ticket prices, the model identifies the aircraft that have been utilized in the network in the previous year and the costs associated for operating those aircraft. Using the previous year's allocation to set ticket price ensures that the ticket price for each route calculated will be based on the aircraft type capable of flying those routes.

The 'yield per ticket' values are obtained by the regression of historical data obtained from BTS of the years from 2005 to 2010. These values, calculated for each of the 24 aircraft for each route, allow for the generation of Yield vs. Range curves; these curves generally have an exponential trend and the form shown in Eq. (1) represents these acceptably. The cost per trip data for various routes is obtained from FLOPS. Finally, the ticket prices for each aircraft on each route are calculated as shown in Eq. (2). In the equation, the coefficients *A* and *B* result from a regression of the data from the Yield vs. Range curves for each aircraft.

$$Yield_i = A \times Range_i^B \tag{1}$$

$$Ticket\_Price_i = Cost_{A,i} + Yield_i \times Range_i \tag{2}$$

A result of this yield model is that smaller sized aircraft have higher yield on shorter routes, where passengers would be likely to pay a higher fare for the additional frequency of service available from smaller aircraft. Similarly, larger aircraft have higher yield on longer routes, where passengers would be uncomfortable in a small aircraft for trips of several hours. This approach does not perfectly represent any specific route, because it does not account for the "attraction" between two airports in setting the fare.

D. Aircraft Retirement and Acquisition

Considerable effort was expended to develop an aircraft retirement and acquisition module that makes possible the consideration of several aircraft delivery approaches. This allows an analysis and identification of technology penetration schemes that can help to achieve the emissions reduction goals given above; these models are briefly described here.

1. Aircraft Retirement

The retirement model evaluates, annually, economic feasibility of retaining an aircraft for an additional year versus its immediate retirement. It works by comparing the Net Present Values (NPVs) of the following two options:

- Option 1: Operate the existing aircraft for one more year and the replacement aircraft enters service in the following year.
- Option 2: The replacement aircraft enters in service in the current year.

In calculation of the 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.[16] The retirement model requires a detailed cost and revenue structure for both the existing and replacement aircraft. The components of cash flows for an aircraft include the fuel costs, initial acquisition cost, maintenance costs, other direct operating costs such as insurance, crew salaries and servicing and its indirect operating costs. FLOPS provides all these values. The revenues in form of ticket prices are obtained from the ticket price model described above. To simulate the increase in maintenance cost as the aircraft ages, the model uses a maturity curve based upon work done at the RAND Pardee Graduate School.[17, 18] Finally, since the number of deliveries are limited, a cap is set on the number of aircraft that can be retired which equals the total number of possible deliveries per class.

The calculation of the NPV for a given, existing aircraft requires the age of that aircraft. The BTS Schedule B-43 Aircraft Inventory database[19] contains detailed information regarding the age of each registered passenger transport aircraft; this provides a distribution of aircraft ages that FLEET uses to describe the ages of the representative- and best-in-class aircraft owned by the aircraft at the start of the simulation.

Finally, the retirement function makes some assumptions in its calculations, including:

a. The aircraft maximum airframe life is assumed to be 40 years. This means once an aircraft is over 40 years old, it is automatically retired from service.

b. The acquisition cost is paid off over a period of 15 years with an annual interest rate of 5%. Early retirement of an aircraft leads to a cost penalty.

c. 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.

2. Aircraft Acquisition

The aircraft acquisition approach consists of delivering new aircraft to the airlines based on estimated future demand and current aircraft capacity. After estimating future demand based on inherent demand growth rate and demand price elasticity and retiring aircraft as described above, the fleet available for operations in the following year is computed. Calculation of fleet available for next year is based on projected capacity required, capacity currently available, and unused capacity. This approach does not account for delay between order and delivery of the aircraft, this is as though the airline had properly placed orders in advance of the delivery. Also, because the total number of deliveries possible each year is constrained by the production capacity of the various airframe manufacturers, an upper limit on aircraft acquisitions per annum is implemented; this is shown in Eq. (3). This equation, based on regression of data on actual deliveries of the aircraft used in FLEET, gives the total number aircraft that are produced in the current year (denoted as 'production') as a function of time since start of simulation (denoted as 'time'). This production capacity is then split amongst the six classes based on the market share of each of these classes.

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

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.[20] 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. (4) – (8):

$$\text{maximize} \quad \sum_{k=1}^{K}\sum_{j=1}^{N}(pax_{k,j} \times P_{k,j}) - \sum_{k=1}^{K}\sum_{j=1}^{N}(C_{k,j} \times x_{k,j}) \tag{4}$$

$$\text{subject to} \quad \sum_{k=1}^{K} pax_{k,j} \le dem_j \tag{5}$$

$$\sum_{k=1}^{K} pax_{k,j} \ge 0.2 \times dem_j \tag{6}$$

$$\sum_{j=1}^{N} 2(x_{k,j} \times (BH_{k,j} + MH_{k,j}) + x_{k,j} \times t) \le 24 \times fleet_k \tag{7}$$

$$pax_{k,j} - x_{k,j} \times cap_k \le 0 \tag{8}$$

The integer decision variable $x_{k,j}$ is the number of trips that aircraft type k flies on route j while the variable $pax_{k,j}$ is the number of passengers that fly on aircraft type k on route j. Routes use a single subscript, because of a round trip assumption described below. Eq. (4) is the objective function; is 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.

The constraint in Eq. (5) ensures that the airline does not transport more passengers than the market demand on each route, while the constraint in Eq. (6) ensure that the airline meets at least 20% of the demand on each route. This bounded inequality facilitates faster solution times than imposing an equality constraint on demand.

The constraints in Eq. (7) 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 can fly round-trips; therefore, the number of available hours is limited to 12 hours (24/2). This is 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. Constraints in Eq. (8) 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. 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 and also reduces the number of variables.

Time contributors to the aircraft utilization are block time ($BH_{k,j}$), which accounts for the taxi-out time, flight time on route j, and taxi-in time. The turnaround time, t, is assumed to be one hour per trip for all aircraft. In this constraint, an aggregate approach accounts for the unavailability of aircraft due to maintenance. By accounting for elapsed maintenance hours for each flight hour for all the aircraft, MH_k, the total number of aircraft the airline needs to serve the daily demand cannot exceed the available number of aircraft in the fleet, including those available for flight and those in maintenance. By analyzing the aircraft utilization and traffic data of the BTS database, the Airline Data Project[21] presents a breakdown of the average daily departures and daily block hour utilization of the aircraft utilized by main and regional domestic carriers. Using this data and assuming a turnaround time of one hour per departure it is possible to account for the aircraft activity during an average day by computing the sum of the time the aircraft spent in flight, in maintenance, and preparing for departures:

$$BH_a \times \left(1 + \frac{EMH_a}{BH_a}\right) + t \times departures_a = 24 \tag{9}$$

where BH_a is the average daily block hour utilization for each aircraft type a (Ref. 22 classifies aircraft into three types: small narrow-body, large narrow-body, and wide-body), EMH_a is the Elapsed Maintenance Hours, which captures the clock time that the aircraft is unavailable and $departures_a$ is the average daily departures of aircraft type a.

Solving Eq. (9) for the ratio of Elapsed Maintenance Hours per block hour, *EMH/BH*, estimates the unavailability of aircraft due to maintenance as a function of the aircraft utilization. Because FLEET uses six classes of aircraft based on their seating capacity, we apply the *EMH/BH* ratio of the small narrow-body aircraft to the class-1, class-2 aircraft, and class-3 aircraft, the ratio of the large narrow-body aircraft to class-4 aircraft, and the ratio of the wide-body aircraft to class-5 and class-6 aircraft. Table 2 presents *EMH/BH* for the aircraft modeled in the study. With finer data resolution, each of the aircraft types modeled here – representative-, best-, and new-in-class – and each aircraft class could have a different ratio of maintenance hours per block hour because newer designs explicitly address maintainability and an aircraft's physical size impacts the inspection and repair time.

Integer Programming methods can solve the allocation problem presented in Eqs. (4) – (8). The software package GAMS[20] (General Algebraic Modeling System) facilitates formulation and solution of this MIP problem. GAMS provides an algebraically-based, high-level language for the compact representation of large and complex models and uses the CPLEX[23] solver to solve the IP problem.

Table 2. Equivalent Maintenance hours per block hour (EMH/BH) of modeled aircraft

Aircraft Type	EMH/BH
Class 1	0.936
Class 2	0.936
Class 3	0.936
Class 4	0.948
Class 5	0.866
Class 6	0.866

After obtaining a solution to the allocation problem, the results allow calculation of the daily profit and cost, fuel consumed (which directly relates to CO_2 produced), landing and takeoff cycle as well as total mission NO_X produces, and a "total airport noise area" metric for the entire fleet operated by the airline (see Fig. 1). 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.

IV. Studies and Results

Two studies, the first concerning the effect of use of new technology aircraft on system-level emissions, and the second study concerning the effect of variation in fuel prices on air travel demand and consequently the system-level emissions are carried out. These studies would shed light on the ability of advanced technology aircraft to help achieve the emissions reduction goals based on when the aircraft are introduced and how the airline uses them. In doing so, these studies would also show if the effect called Jevons' Paradox might exist in the aviation industry, or, in other words, would the improvement in aircraft efficiency have the counter-intuitive and undesirable result of increasing the total emissions. A related study done by Pfaender and Mavris also explored this effect; they concluded that it is unlikely that this paradox exists. [24]

In both these studies, the effects of different scenarios are compared against a standard scenario setup in FLEET; this standard scenario is defined as follows:

a. The gross domestic product (GDP) grows at a constant value of 2% per annum which results in demand growth of 2.8% per annum
b. Jet fuel prices grow according to the Energy Information Administration (EIA) reference fuel price case[25]
c. The first new- and future-in-class aircraft enter into service at the years shown in Table 3

The EIA has given three scenarios of fuel price evolution over time called the low-, reference- and high-fuel price scenarios. FLEET sets the reference-fuel price scenario as the default, with the other two scenarios available as options to study the effect of their evolution on aviation. These alternate fuel price scenarios are used in the second study described later.

A. Effect of Technology Introduction

Conducting a study with two scenarios similar in all respects, expect for the technology level of available aircraft, assesses the effect of introduction new technology aircraft on fleet-level emissions. In one scenario, all four generations of aircraft technology are available for the airline to buy and use. The best-in-class aircraft are available from the start of the simulation, and new- and future-in-class aircraft become available for the airline at the years as shown in Table 3. The airline in FLEET never buys representative-in-class aircraft. For both the new- and future-in-

Table 3. Aircraft Types Modeled in Study

Class	New-in-Class		Future-in-Class	
	Aircraft	**EIS Date**	**Aircraft**	**EIS Date**
Class 1	Small Regional Jet	2021	“Magic Wand” CRJ 200	2030
Class 2	CS100	2013	“Magic Wand” CRJ 700	2025
Class 3	Boeing 737-700 Reengined	2018	Small Purdue ASAT	2027
Class 4	Boeing 737-800 Reengined	2018	D-8 Double-Bubble	2035
Class 5	Boeing 787	2011	“Magic Wand” Boeing 767	2030
Class 6	Large Twin Aisle	2020	“Magic Wand” Boeing 777	2030

class aircraft, production limits described above ensure that the entire fleet is not upgraded immediately. Furthermore, since the airline makes its decisions on acquisition based on its estimated need in the following year and retirement of current aircraft includes the costs of acquisition and financing, the penetration of these aircraft into its fleet is gradual. Hence, the benefits of these new aircraft are not immediately apparent and only become significant several years after their initial introduction.

In the other scenario, the future-in-class aircraft are not available to the airline. This means that there is no advancement of aircraft technology once the last of the new-in-class aircraft, the small regional jet, becomes available in 2021. In this case, the absence of new technology should lead to higher level of emissions in the later years.

Indeed, as Fig. 3 demonstrates, the total emissions in the scenario with future-in-class aircraft available is lower than in the scenario in which they are not available. The total emissions begin to differ only after 2025 when the future-in-class aircraft start being available; thereafter, the difference grows significantly towards the later years of the simulation. Also, for the years between 2025 and 2035, the emissions in the scenario without future-in-class aircraft are lower than the scenario with future-in-class aircraft. This is because during these years, in the scenario without future-in-class aircraft, the airline served lesser market demand. The problem formulation described earlier allows the airline to sacrifice some part of the market demand if, in doing so, it can achieve greater profits. In this case, the difference in market demand served in the years 2025 to 2035 was approximately equal to the difference in CO_2 emissions in the two scenarios.

Though the introduction of new technology aircraft reduced the emissions, the growth in market demand overwhelmed the advancement of technology, and as a result, the system-level emissions continued to grow illustrating a potential analogy to Jevons' Paradox. That the introduction of another generation of advanced technology aircraft had an effect on emissions appears in Fig. 4. This figure shows the fleet-level emissions efficiency as the CO_2 emissions in pounds per revenue passenger nautical miles. In both scenarios, the acquisition and use of new aircraft led to gradual decrease in unit emissions. However, in the case where future-in-class aircraft were not available, the improvement in efficiency stopped after 2025, seen from the flat part of the curve. Evidently, the development of new technology is necessary but not sufficient in an effort to reduce aviation emissions.

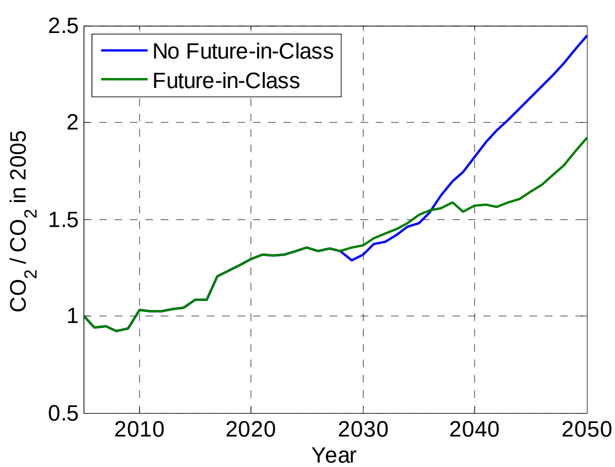

Figure 3. Normalized CO_2 evolution

B. Effect of Fuel Prices

The previous subsection showed that despite increasing aircraft efficiency, the total system-level emissions may continue to grow. The amount of emissions, however, also depends on the level of market demand. The market demand in turn, depends on several different factors. If total demand declines for any reason, then the emissions will also decline, and vice versa. This subsection describes a study set up to see the effect of demand variation in response to fuel price variation on the total emissions; price-demand elasticity calculates the change in demand. Simulations in this study assume that the airline can acquire future-in-class aircraft, representing continuing technology advancement.

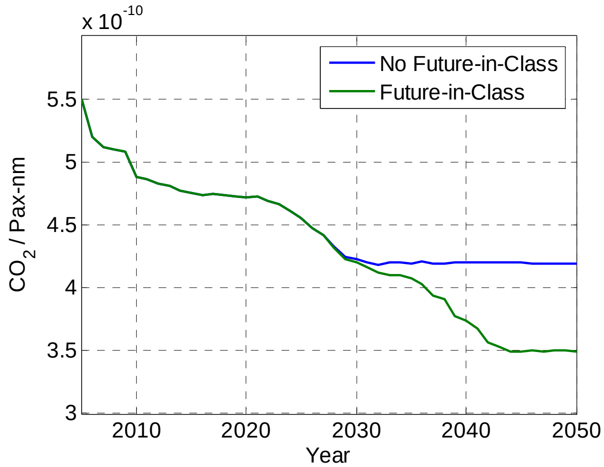

Figure 4. Emissions Efficiency Evolution

In this study, the economy growth rate is held constant at the FLEET default of 2% increase in GDP per year leading to similar inherent demand growth across scenarios. This means that the difference in demand is only due to its elastic response to changes in ticket prices. The rationale is that the state of the economy is an external factor not directly under the control of the airlines; however, airlines set ticket prices, but these type of aircraft and manner in which they are used affects the ticket price. New technology aircraft with higher fuel efficiencies may be more economical to operate, so the airline would have higher incentive to buy and use them, especially in cases of high fuel prices. Thus, to investigate the effect of demand, three scenarios of different fuel price growth rates were simulated. Here, the three fuel price scenarios were the low, reference, and high fuel price scenarios given by EIA; all three scenarios are similar in all other respects, including introduction of advanced technology aircraft.

Figure 5 shows the evolution of CO_2 emissions for the three fuel price cases. The total system-level emissions match closely for the reference and high fuel price cases. However, for the low fuel price case, there is a rapid increase, because lower fuel prices lead to lower ticket prices in the FLEET model, which results in higher demand for air travel. When fuel and, consequently, the ticket prices increase, air travel becomes less affordable, resulting in lesser demand on the short distance routes due to higher elasticity. As compared to the reference fuel price scenario, the airline serves a higher percentage of demand on the shorter routes under the high fuel price scenario. Hence, the similar levels of demand and emissions in the reference and high fuel price cases.

The evolution of emissions efficiency (Fig. 6) is similar across all three scenarios of fuel price variation. This can be explained by comparing at the manner of aircraft utilization by the airline in these scenarios. In all three scenarios, the distribution of utilized aircraft was similar both with respect to aircraft class and technology type. In other words, the airline met the higher demand in the low fuel price scenario by increasing the total number of aircraft in operation, but continued to maintain the same distribution of aircraft classes and types. Since the airline in FLEET has a profit seeking nature, it allocates aircraft similarly in all cases, and does not try to reduce emissions. Arguably, the emissions efficiency of the fleet can be improved if the airline bought and used a higher fraction of future-in-class aircraft. But, without an economic incentive to do so, the airline continued to operate in a manner that afforded it maximum profit. This observation is the basis for saying that policies that provide incentives to airlines to

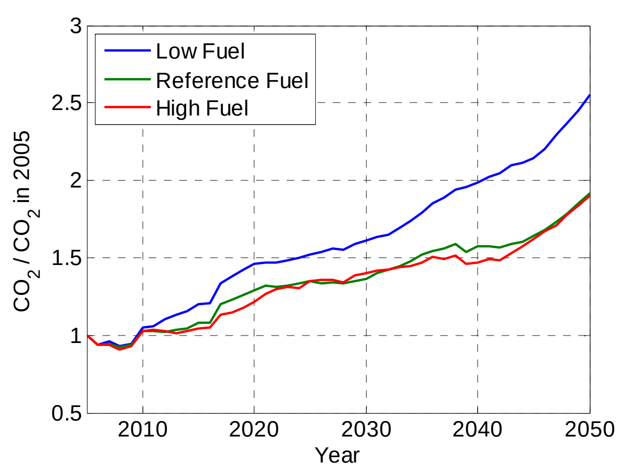

Figure 5. Normalized CO_2 evolution

reduce emissions are required in addition to technology development.

C. Discussion on Measurement of Aviation's Impact

The results obtained from the studies conducted for this paper indicate that if the demand in future continues to grow, development and use of advanced technology alone may not be sufficient to reduce emissions. Although these results are indicative of aviation's growing impact, they are based on the measurement of only those emissions that are a direct result of aircraft operations. Technological advancement, however, does not only imply aircraft technology, but also other technologies such as biofuels, which may have lower life-cycle CO_2 equivalent emissions, and airspace technologies, which improve operations to avoid fuel-consuming delays and potentially allow more direct routine of flights. Biofuels as drop-in replacements for current Jet-A provide no advantage when only the emissions resulting from aircraft operations are considered; they are better than conventional jet fuels only when their emissions are considered on a life-cycle basis. Hence, once they are introduced into service, other metrics that compare the environmental impact on a life-cycle basis will have to be used. Likewise, other technological advancements may require similar definition and use of metrics other than just the total emissions from aircraft operations.

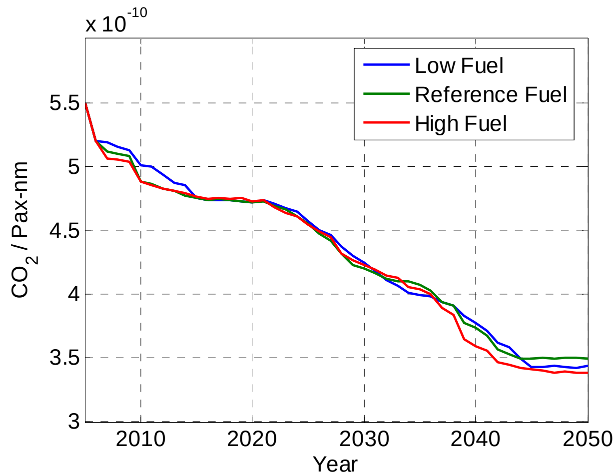

Figure 6. Emissions Efficiency Evolution

Finally, technological development focusses not just on reduction of emissions, but also factors such as increased safety and convenience of flying. Given the importance of aviation to the economy, all of these factors will have to be balanced with one another, so that future growth is sustained while at the same time reducing aviation's environmental impact.

V. Conclusion

This paper studied the effects of introduction of advanced technology aircraft and fuel price variation on total system-level emissions. The first of the two studies showed that the development and use of new class of aircraft technology in the 2025 timeframe is worthwhile, because it improves the emissions efficiency of the airline fleet. Though the total system-level emissions continued to grow, the emissions per revenue passenger nautical mile declined, which resulted in lower aggregate emissions at the end of the simulation period. The second study showed that though aircraft technology can provide some improvement, it alone is not sufficient to meet the emissions reduction goals. Further improvements required depend on operations changes, which the airlines would only undertake in the presence an economic incentive.

The results obtained also showed that Jevons' Paradox is a possible effect in the aviation industry. While considering this conclusion, however, the limitations of this study must be kept in mind. For example, in these studies, the demand growth in response to economic growth was large enough to overwhelm any technological advances; in reality, demand growth depends on many factors and the same level of increase may not happen. In addition, the airline in FLEET passes the entire burden of fuel price increase to the passengers in the form of increased ticket prices. In a competitive environment, however, the airline may be motivated to reduce their fares for a short duration to capture market share from other airlines.

Despite these limitations, the likelihood of increased emissions is an important conclusion that supports implementation of additional efforts like operations changes. Some of these efforts would be part of continuing research using FLEET.

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.

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