11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, including the AIA
20 - 22 September 2011, Virginia Beach, VA

AIAA 2011-6843

Impact of Development Rates of Future Aircraft Technologies on Fleet-Wide Environmental Emissions

Kushal A. Moolchandani[1], Datu B. Agusdinata[2], Muharrem Mane[3], William A. Crossley[4] and Daniel A. DeLaurentis[5]
Purdue University, West Lafayette, IN 47907

To mitigate the environmental impact of aviation while still allowing for growth in air transportations, various organizations – such as NASA – have set goals for advancing technologies that reduce the impact of aircraft on the environment. Meeting these goals would improve the environmental performance of an individual aircraft; however, the environmental impact of air transportation is a fleet-level effect that depends on the combined operation of all aircraft with their associated technologies. Economic factors, like fuel price, also impact aviation emissions, because economic factors drive air transportation demand and drive airline fleet composition. This paper analyzes the sensitivity of environmental metrics to the entry-into-service (EIS) dates of various potential new aircraft and to the penetration rate of these new aircraft into the fleet. The studies also incorporate three potential fuel price change scenarios. The results suggest insights in two areas. First, the level of (carbon) emissions is sensitive to EIS dates of new technology aircraft only during a short period after the introduction; later EIS dates lead to airlines upgauging their fleet to maximize profit. Second, high fuel price reduces demand, which reduces emissions, especially on short routes where alternative modes of ground transport likely exist.

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. Statement of Problem

THE environmental impact of transportation is an ever-growing area of interest. The NASA Subsonic Fixed Wing (SFW) Project key research areas and goals emphasize the importance of reducing both noise and emissions in future generations of aircraft. As presented in March 2011, NASA aims to reduce 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) 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

[1] Graduate Student, School of Aeronautics and Astronautics, 701 W Stadium Avenue, Student Member AIAA
[2] Post-Doctoral Fellow, School of Aeronautics and Astronautics, 701 W Stadium Avenue, Member AIAA
[3] Associate Research Scientist, School of Aeronautics and Astronautics, 701 W Stadium Avenue, Member AIAA
[4] Professor, School of Aeronautics and Astronautics, 701 W Stadium Ave, Associate Fellow AIAA
[5] Associate Professor, School of Aeronautics and Astronautics, 701 W Stadium Ave, Associate Fellow AIAA

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%.[1] Development of new technologies to reduce drag, aircraft and engine weight, and engine specific fuel consumption provide expected contributions 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.[1]

While better technologies can improve an individual aircraft's performance, the environmental impact of air transportation is a function of both the aircraft technologies and how the airlines operate all the aircraft in their fleet. While studies indicate that future aircraft designs can meet the NASA SFW goals,[2] the fleet-wide environmental impact of air transportation likely depends on the utilization levels of new aircraft by the airlines and on the rates at which new aircraft enter the fleet and at which older aircraft retire. 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 also stated goals for reducing the carbon emissions of air transportation. Most of these goals share two important points: 1) "carbon neutral growth" by 2020, meaning that the carbon emissions of air transportation is the same level as it was in 2005, while serving increased demand, and 2) that the carbon emissions of air transportation in 2050 is half the level it was in 2005, again while serving still increasing demand.[1]

References 3-6 describe the development of the Fleet-Level Environmental Evaluation Tool (FLEET) that assesses the fleet-wide environmental impact of aircraft operation. FLEET assesses fleet-level values of CO_2 emissions, NO_x emissions, and the airport noise levels associated with meeting demand on a model of US-related passenger air transportation. The modeling approach incorporates future aircraft and their technologies along with the economic environment and the operational decisions of airlines. Preliminary results indicate that, while the development of more fuel efficient aircraft technologies can reduce future fleet-wide emission levels, the rate at which the new technologies become available to airlines and the rate at which older aircraft retire from the fleet has a large impact on the potential achievement of the future goals for air transportation carbon emissions. The studies described here build upon the previous work and investigate the impact of entry-into-service date of new aircraft and their penetration rate in the airline fleets on emissions, and they attempt to identify the combination of aircraft entry-into-service date and penetration rate that are necessary to achieve fleet-wide carbon emissions goals. The studies also use three different future fuel price scenarios to incorporate this driver of air transportation demand. Exploring alternate scenarios in aviation transportation and translating these into likely changes in the composition of the fleet (and, thus, to emissions) will contribute to a better understanding of the air transportation system and the achievable environmental goals.

II. Scope and Methods of Approach

The goal of this work is to assess the fleet-wide impact of future aircraft technology improvements on aviation emissions. As such, modeling of aircraft technologies must be augmented by modeling of airline operations. A representation of airline decision-making and daily operations can provide the necessary detail to conduct such analysis. However, the details needed to model all aspects of airline operations (aircraft, aircraft fleets, crew scheduling, aircraft scheduling, etc.) would result in the development of numerous complex models that would make what-if scenario analyses difficult. FLEET focuses on a simplified resource allocation model that uses several levels of abstraction that reduce the complexity of representing airline operations but still enable meaningful assessments of the fleet-level environmental impact of future technologies.

The approach uses a single benevolent monopolistic airline to represent airline behavior. Without competition, "benevolent" implies that the single airline will not exploit scarcity rents and will meet all travel demand.[7] The optimization problem then allocates aircraft to maximize profit of this single entity. To reduce the number of routes in the allocation problem, the network includes only routes amongst a subset of the WWLMINET 257 airports[8] that had passenger demand in 2005; this includes domestic routes between US airports and international routes with either an origin or destination at a US airport. Data provided by the Bureau of Transportation Statistics DB1B database[9] for 2005 passenger travel describes the demand between these 257 airports.

To manage the large number of aircraft models used by airlines, the aircraft are aggregated into six classes based on seat capacity. To represent technology groups (or technology "ages") within the aircraft classes, each class has 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 class and are typically older aircraft. The best-in-class aircraft are those that had the most recent service-entry date within each class, so they are 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 some technology improvements expected in the future. Table 1 presents the representative-, best- and new-in-class aircraft used here.

Table 1: Aircraft types modeled in 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	Aircraft X2
Class 3	100 – 149	Boeing 737-300	Boeing 737-700	CS100
Class 4	150 – 199	Boeing 757-200	Boeing 737-800	Purdue ASAT
Class 5	200 – 299	Boeing 767-300	Airbus A330-200	Boeing 787
Class 6	300+	Boeing 747-400	Boeing 777-200ER	Aircraft X6

The new-in-class aircraft modeled here are the Canadair CS100 (a class-3 aircraft), expected to enter service in 2013,[10] the Boeing 787 (a class-5 aircraft) expected to enter service in late 2011,[11] and an Advanced Single Aisle Transport (ASAT), a class-4 aircraft. While the CS100 and the Boeing 787 are actual aircraft under development, the ASAT is a notional concept as a Boeing 737 / Airbus A320 replacement; the model used here is similar to an ASAT model developed by NASA engineers.[12] Note that the entry-into-service (EIS) date of these aircraft makes them N+1 type aircraft. The remaining new-in-class aircraft for class-1, class-2, and class-6 – labeled Aircraft X1, X2, and X6, respectively – are concept aircraft models that incorporate technology advancements that enable them to achieve the NASA SFW N+2 emission and noise goals. These aircraft were sized using the technological factors provided by NASA using the Flight Optimization System (FLOPS).[13] FLOPS was used to simulate various missions with different ranges and aircraft load factors to create tables for DOC, fuel burn and LTO NO_x for these aircraft which are then used to estimate aircraft emissions.

The resource allocation problem uses the performance characteristics of these aircraft to maximize profit while meeting demand and other constraints as a model of airline operations and decision-making. The results of the allocation can then estimate the expected future emission levels for different EIS dates and introduction rates of the new aircraft. Similarly, the results of the allocation problem can estimate future emissions when using different future fuel prices, demand evolution, and / or with better aircraft technologies than those currently modeled. A detailed description of the modeling of the new-in-class aircraft and their performance and environmental characteristics appears in Ref. 3 and 4.

1. *Fleet Resource Allocation*

The engine behind FLEET is the aircraft allocation model that represents airlines operations and decision-making. Aircraft allocation problems are not new, and the operations research community is quite active in posing and solving these types of problems. Refs. 14-19 provide some examples of this. However, to the authors' best knowledge, these allocation problems do not normally incorporate environmental impacts at the airline fleet level.

The fleet resource allocation problem seeks to determine the optimal allocation of a finite number of aircraft to satisfy passenger demand while maximizing profit. Mathematically, the resource allocation problem takes the form of an integer programming (IP) problem presented as Eqs. (1)-(5).

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

Such that
$$\sum_{k=1}^{K} pax_{k,j} = dem_j \tag{2}$$

$$pax_{k,j} \le x_{k,j}\cdot\left(cap_k \cdot LF_k\right) \tag{3}$$

$$\sum_{k=1}^{K}\left(x_{k,j}\cdot\left(BH_{k,j}+MH\right)+x_{k,j}\cdot t\right)\le (24/2)\cdot fleet_k \tag{4}$$

$$x_{k,j},\ pax_{k,j} = \text{integer} \tag{5}$$

The integer decision variable $x_{k,j}$ indicates the number of trips that aircraft type k fly on route j while the integer variable $pax_{k,j}$ indicates 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. The model seeks to assign passengers to aircraft types and demanded routes, $pax_{k,j}$, and trips to aircraft types and demanded routes, $x_{k,j}$ while maximizing profit. The objective

Eq. (1) is the difference between revenue and cost. Revenue is a function of ticket price, $P_{k,j}$, that each passenger pays according to the aircraft type and route on which he/she flies, the number of passengers on each aircraft type and route, $pax_{k,j}$. Profit is, therefore, the sum of profit from each of the routes (here, N = 2128, which includes 1791 domestic routes and 337 international routes with origin or destination in the US) and for each of the aircraft types (here, K = 18 for the six representative-in-class, six best-in-class, and six new-in-class aircraft types).

To approximate 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 demanded route. A description of the revenue model appears in Refs. 3 and 4. Cost is a function of the number of trips flown on each aircraft type and on each route and the direct operating cost of the aircraft on each route, $C_{k,j}$. This model does not consider indirect operating costs. Because no models for the conceptual aircraft for class-1, class-2, 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.

Constraints in Eq. 2 ensure that the airline meets all passenger demand while constraints in Eq. 3 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. 4 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[9] data shows that average daily demand is nearly symmetric although any given passenger may not fly a return trip on the same day. 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.

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, assumed to be one hour per trip.[20] In this constraint, an aggregate approach accounts for the unavailability of aircraft due to maintenance. By accounting for maintenance hours for each flight hour for all the aircraft, MH, 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:

$$BH_a\left(1+\frac{EMH_a}{BH_a}\right)+t\cdot departures_a = 24 \tag{6}$$

where

- BH_a is the average daily block hour utilization for each aircraft type a (Ref. 20 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. 6 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

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

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. 1-5. The software package GAMS[22] (General Algebraic Modeling System) 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[23] solver to solve the IP problem. The IP problem presented here has over 50,000 integer variables and over 1,800 constraints. GAMS provides a typical solution (allocation of aircraft for a representative day) in about 20 minutes on a server with two Dual Core Opteron 275 processors.

As an example, solving the fleet allocation problem for a representative day based on CY 2005, with 1.8 million passengers on the US-related subset of the WWLMINET 257 network, the benevolent monopoly airline will spend \$230 million in Direct Operating Costs while generating 990 metric-tons of CO_2, 2,000 metric-tons of LTO NO_X, and a total noise area inside the 65dB DNL contour of 209 nmi.[2] Total noise area here 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 102 domestic airports in the LMINET.[24] 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. The daily cost, CO_2 production, total NO_X and total noise area values reflect the allocated fleet to optimize profit while meeting demand, with the aircraft class abstractions and round trip assumptions described above.

2. Aircraft Retirement and Acquisition

The research team has developed an aircraft retirement and delivery model that can consider several delivery approaches that can lead to the identification of technology penetration schemes that can help to achieve fleet-wide carbon emissions goals. The BTS Schedule B-43 Aircraft Inventory database[25] allows determination of entry-into-service date of the aircraft modeled here. The Schedule B-43 database contains detailed information regarding the entry in operation of passenger transport aircraft by tail number. This gives the flexibility to change the retirement age of aircraft that had entered service through 2009.

The aircraft delivery approach consists of delivering new aircraft to the benevolent monopolistic airline based on estimated future demand and current aircraft capacity. Figure 1 presents a diagram of this approach.

After estimating future demand based on the inherent demand growth rate and demand price elasticity and retiring aircraft that have reached 25 years of service, the available fleet for the following year is computed based on projected capacity, available capacity, and unused capacity. The airline capacity of a given class-*k* aircraft is defined as the number of passengers that the airline can transport in a given day of operations given the average number of trips flown by class-*k* aircraft (*average_trips*$_k$), the passenger capacity of class-*k* aircraft (*seats*$_k$), the average load factor of the class-*k* aircraft (*LF*$_k$), and the number of class-k aircraft (*fleet_****$_k$), where ** refers to aircraft retired, available, or aircraft actually deployed to serve demand, depending on the type of capacity being computed:

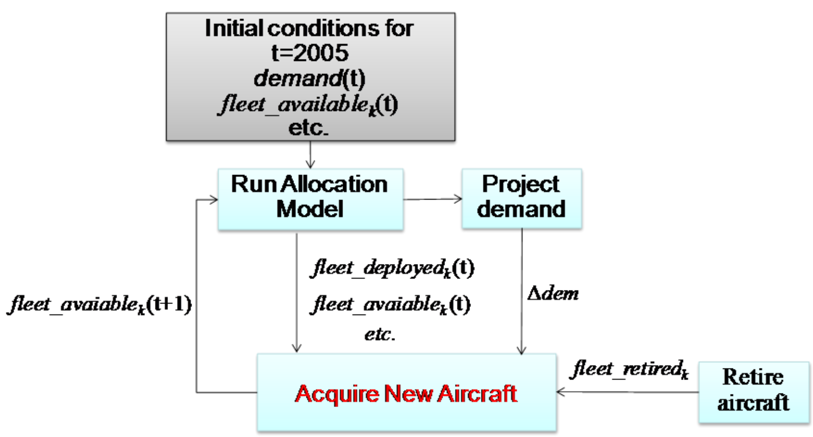


Figure 1. Airline fleet retirement and acquisition approach

$$capacity_k = (average\_trips_k)\cdot(seats_k)\cdot(LF_k)\cdot(fleet\_{**}_k) \quad (7)$$

Using this definition of capacity allows computation of the needed capacity for a given year of analysis by considering the number of available aircraft in the fleet after retirement of old aircraft and estimating demand growth:

$$capacity\_needed_k = \Delta demand_k - capacity\_unused_k - capacity\_retired_k \tag{8}$$

where the unused capacity is defined as the difference between deployed capacity and the available capacity for a given year. Deployed capacity is the capacity computed by using Eq. (7) and the number of aircraft allocated to serve demand ($fleet\_deployed_k$) – output of the allocation model (Figure 1) – while available capacity is computed by, again, using Eq. (7) and the number available for allocation ($fleet\_available_k$) – output of the aircraft delivery computation of the previous year (Figure 1). Similarly, the $capacity\_retired_k$ computation uses Eq. (7) and the number of retired aircraft ($fleet\_retired_k$). Demand growth ($\Delta demand$) is defined as:

$$\Delta demand_k = \left(demand(t+1) - demand(t)\right) \cdot fleet\_mix_k \tag{9}$$

where $demand(t+1)$ is the total projected demand while $demand(t)$ is the total demand of the previous year, and $fleet\_mix_k$ is defined as:

$$fleet\_mix_k = \frac{pax_k}{\sum_k \left(pax_k\right)} \tag{10}$$

The $fleet\_mix_k$ value estimates the fraction of passengers carried by each aircraft class, pax_k. This serves as an estimation of the fraction of the new demand served by each class of aircraft to-be-added to the fleet. With these definitions, solving Eq. (7) yields $fleet\_**_k$ (here $fleet\_available_k$), then the estimate of the number of additional aircraft needed for each year of operation is:

$$fleet\_available_k = \frac{capacity\_needed_k}{\left(average\_trips_k\right) \cdot \left(seats_k\right) \cdot \left(LF_k\right)} \tag{11}$$

Airlines typically place orders several years ahead of their projected need based on their knowledge of the prospective market; however, the model used in FLEET simplifies the order / delivery process by assuming immediate delivery. This is equivalent to assuming airlines make accurate predictions on future market and place orders accordingly in advance. Airframe manufacturers are, however, constrained with regards to number of aircraft they can manufacture each year, which means that airlines cannot obtained an unlimited number of aircraft each year. In the current work, the upper limit on number of aircraft available for delivery each year relies upon on the market forecast by Boeing,[26] which predicts that the world market will require 33,500 new aircraft between 2010 and 2029. Simply dividing 33,500 by 20 years leads to 1,675 aircraft per year, which this study uses as an upper bound on the number of aircraft available in any year. In addition, manufacturing facilities for new aircraft do not reach their maximum capability immediately; this gradually increases as man-hours required per aircraft reduces due to the learning curve effect and the manufacturer can deliver more aircraft in a given time. Here, the study assumes airframers provide a linearly increasing number of new-in-class aircraft per year from entry-into-service until reaching maximum production capacity as presented by Fig. 2. At the same time, the production of best-in-class aircraft decreases by the same amount to enforce the maximum production capacity rate. After a few years, best-in-class aircraft stop being available when the new-in-class aircraft attain their maximum production capacity. Varying this introduction rate for new-in-class aircraft can investigate how this factor impacts airline operations and the corresponding fleet-level emissions.

The limit of 1,675 new aircraft available per year is the cumulative limit for all six aircraft classes; however, the division between the six classes uses a moving average of current fleet utilization. In the years from 2005 to 2007, the fleet composition obtained from historical data sets the fraction of new deliveries that would belong to a particular class. For example, this model dictates that 26% of the total deliveries in 2006 would be for class 1 aircraft, because the existing fleet in 2005 had class 1 aircraft in the same proportion. From 2008 onwards, the production for the succeeding year is based on the moving average of past three years utilization of aircraft by airlines – in other words, if a certain percentage of total fleet deployed by airlines belongs to a particular class, the new aircraft

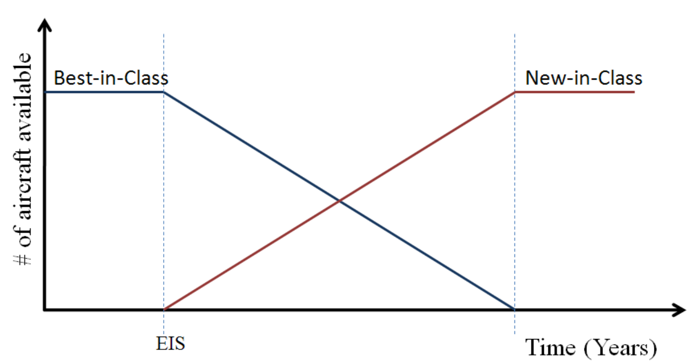


Figure 2. Production ramp-up and phase-out

produced in the following year would have the same concentration of aircraft of that class. This formulation reflects the idea that airframers prefer to produce aircraft that have the highest demand.

III. Studies Conducted

FLEET examined a number of different studies of how air transportation and the concomitant emissions will evolve from 2005 through 2050; each study differed in fuel cost scenario, the availability of new-in-class aircraft, and the dates of new-in-class aircraft introduction. Changes in the economy and passenger choice with regards to the mode of travel also impact air travel demand and, consequently, the environment. For instance, changes in GDP correlate with air travel demand; economic downturns result in less air travel. Less air travel means fewer aircraft flights, which in turn results in lower CO_2 and NO_X emissions. The effect that economic growth has on passenger demand can be said to lead to an inherent demand growth for demand for air travel. In one study, the GDP growth rate and the demand growth rate were correlated by a factor of 1.4, implying that for a unit change in GDP the demand changes by 1.4.[27] The FLEET model uses this factor to represent the response of demand to GDP growth rate. While this FLEET could use various scenarios of economic growth, the studies here assumed a constant GDP growth rate of 2% every year.

Passenger sensitivity to ticket prices varies as a function of distance of travel and availability of alternate modes of travel. Over short distances, passengers may choose to use alternate modes of transport while over longer distances air travel may be the only option. FLEET's model elasticity of passenger travel demand to change in ticket prices also incorporates this concept. Price elasticity here is a function of the stage length and availability of alternate modes of transport. This variation in elasticity (Fig. 3) relies on data obtained from Ref. 28. Here, domestic routes use the "with alternate modes" model, while international routes use the "without alternate modes" model. Data does not exist for very short routes; so the elasticity relationship uses a constant value for routes below 180 nmi, rather than decreasing asymptotically below this value.

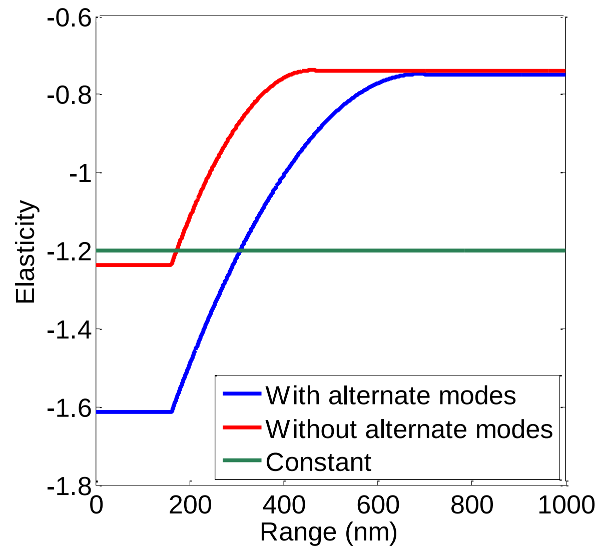


Figure 3. Demand Elasticity as a function of Range

There are two primary study cases described here. Case 1 studied the impact of different entry-into-service dates of new-in-class 1, 2, 4 and 6 aircraft.

Case 2 studied fuel price impact on the air travel demand and the resulting fleet-level emissions. Fuel cost forms a substantial portion of the airline's DOC. Thus, a change in fuel costs translates directly to a change in ticket prices. These studies considered three fuel cost scenarios based on data obtained from the Energy Information Administration (EIA);[29] these scenarios referred to as low-, reference- and high-fuel cost scenarios and appear in Fig. 4.

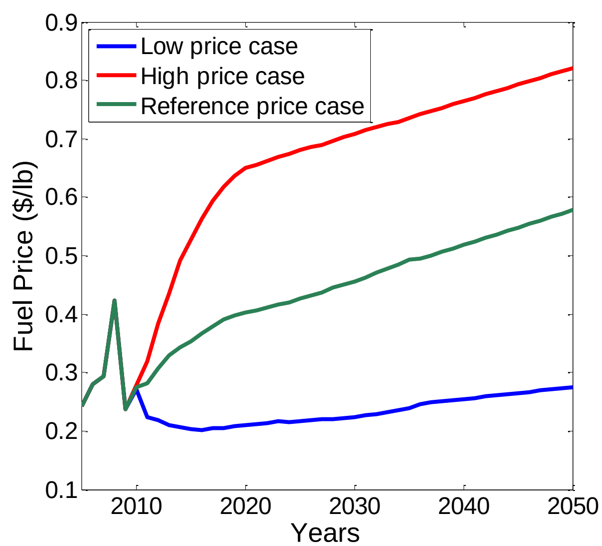


Figure 4. Fuel Cost Scenarios based on Energy Information Administration data (2005 $)

Finally, an analysis is conducted on the production capacities for new aircraft required to meet projected demand. The results of these analyses appear along with the results obtained by simulating the above scenarios in the following section. These results are primarily meant to be both explanatory of the current FLEET model logic. Additional features are envisioned in the FLEET model (some discussed later in Future Work section) to enable decision-quality findings.

IV. Results and Analysis

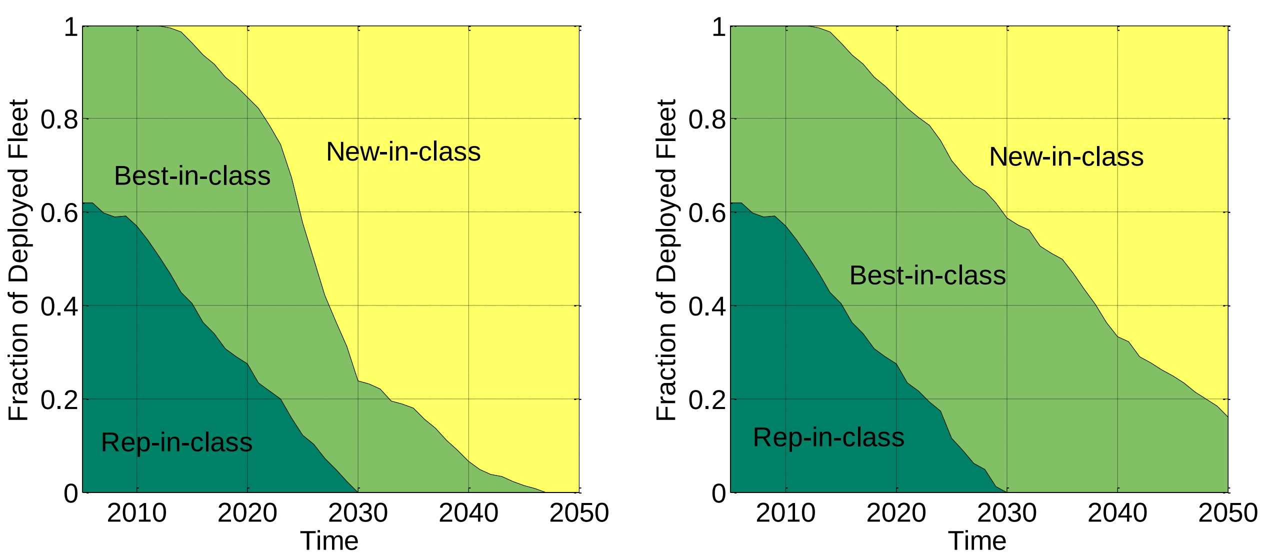
Case 1: Impact of different entry-into-service (EIS) dates on CO_2 emissions

In the spirit of the NASA technology descriptions, aircraft using N+2 technology would have likely EIS dates post 2020. The EIS dates for the Boeing 787 (class 5) and Bombardier CS100 (class 3) remained 2011 and 2013, respectively, while those of the other four new-in-class aircraft were 2020, 2025 and 2029. For simplicity, all of the new-in-class 1, 2, 4 and 6 become available in the same year, which may not be practical. The new aircraft would be environmentally cleaner, so the entry of new-in-class aircraft into active service is expected to reduce emissions or at least slow down their growth relative to passenger demand growth. Furthermore, earlier EIS might provide faster rate of emissions reduction.

Different EIS dates have impact on the fleet composition. Figure 5 shows the composition of deployed fleet as an area chart comparison of the two extreme scenarios simulated – one with and EIS of classes 1, 2, 4 and 6 of 2020, and the other with EIS of 2029 for these classes. For the EIS of 2020, the entire fleet will be new-in-class aircraft by 2050. In contrast, the later EIS of 2029 means that some best-in-class aircraft produced after 2020 operate until 2050. As a result, only about 85% of the 2050 fleet constitutes new-in-class aircraft.

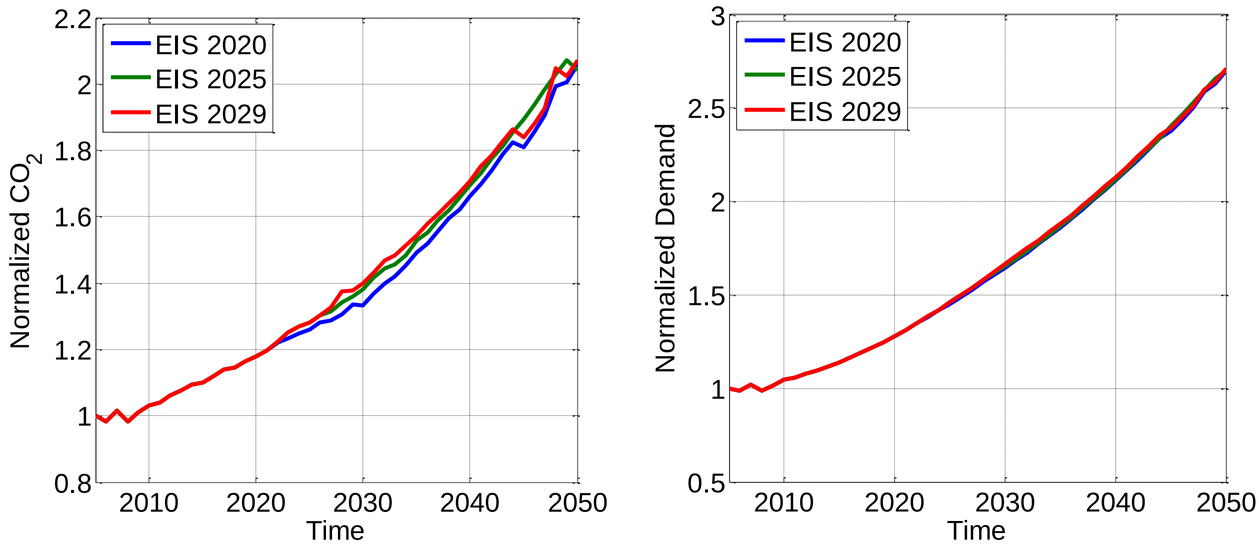
In all the three EIS scenarios, the prevailing economic condition driving the demand (i.e. GDP growth) is the same and the difference in change of ticket price across scenarios is not very significant, resulting in near identical demand evolution. In terms of CO_2 emissions, early or late introduction of new aircraft only showed different impact in the period when new aircraft entered into service. Figure 6 presents the normalized CO_2 emissions between 2005 and 2050 from the airline for all three EIS scenarios; the normalized CO_2 emissions use the 2005 level as the reference value. The CO_2 emissions are indeed lower during the periods that see rapid change in fleet composition with the retirement of best-in-class and introduction of new-in-class. However, once the fleet consists mainly of new-in-class aircraft, the total emissions gradually attain the same level, converging into more or less the same level of emissions at 2050. One might expect that with the earlier EIS dates, the 2050 emissions would be notably lower, given that the fleet turns over to 100% new-in-class aircraft by 2050.

Examining the evolution of class-wise fleet composition helps to explain this trend (Fig. 7). FLEET predicts that the later introduction of new-in-class aircraft, EIS of 2029, results in a higher proportion of bigger aircraft (especially best-in-class, class 4). It seems that when new-in-class are introduced in later dates, airlines are upgauging to maximize profit. On a passenger-mile basis, this aircraft class has a better fuel performance than new-in-class class 1 and 2 that dominate the fleet with EIS date of 2020. Thus, even though the fleet with EIS dates of



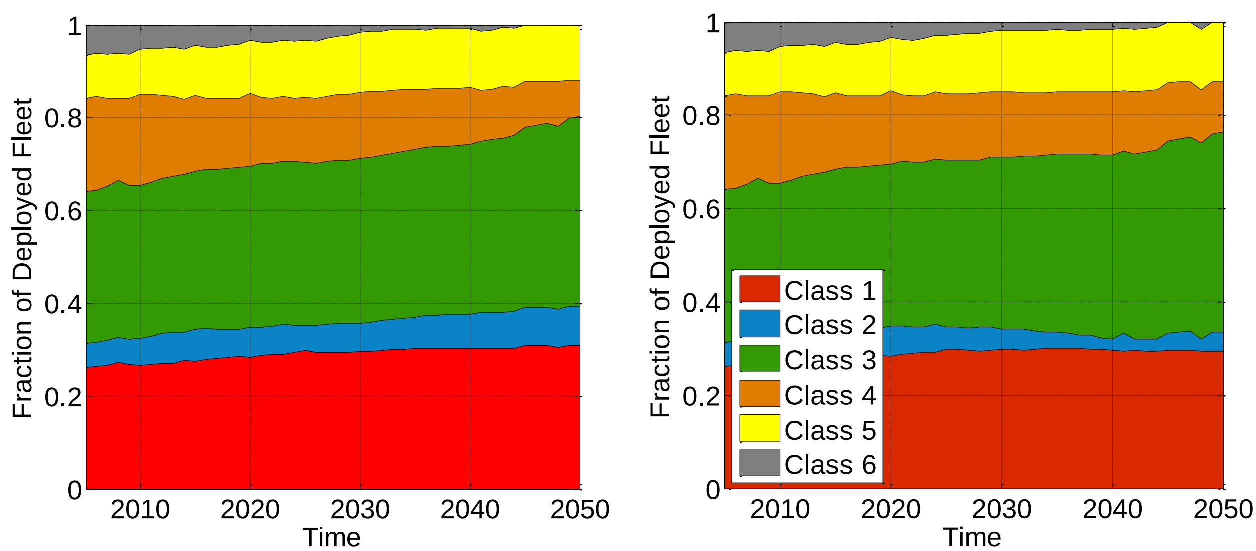
(a) EIS 2020 **(b) EIS 2029**

Figure 5. Deployed fleet composition under two different entry-into-service (EIS) dates



(a) Normalized CO_2 **(b) Normalized Demand**

Figure 6. Effect of different EIS dates on normalized CO_2 emissions and demand



(a) EIS 2020 **(b) EIS 2029**

Figure 7. Deployed fleet composition under different EIS dates

2029 has a lower proportion of new-in-class by 2050, its higher share of bigger size aircraft will lead to almost similar impact in emissions in 2050.

A continued decrease in emissions as desired can only be achieved with constant improvement of aircraft technology to counter act increasing demand. This confirms the need for introduction of N+3 technology aircraft to see continued decrease of emissions. Currently, the N+3 generation aircraft are envisioned to enter into service in the 2030-2035 time-frame succeeding the introduction of N+2 generation aircraft leading to a reduction in emissions.

Case 2: Impact of different fuel price scenarios on CO_2 emissions

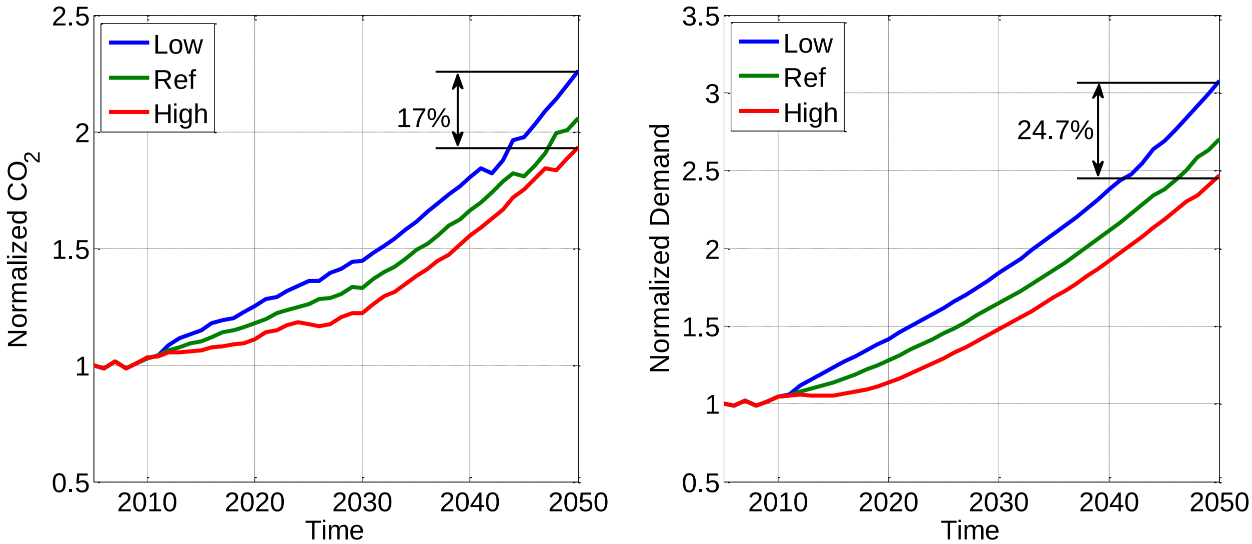
Fuel price affects air travel demand through demand price elasticity. The effect on demand and CO_2 emissions are simulated using the three fuel price scenarios based on the data obtained from Energy Information Administration (EIA) referred to as the low-, ref- and high-fuel price (Fig.4).

As expected, the scenario with higher fuel prices has higher ticket prices leading to lower demand and emissions. Between the low and high fuel price scenarios, we observed a 17% difference in CO_2 emissions (Fig. 8a). This difference corresponds to a 24.7% difference in passenger demand (Fig. 8b) and 17.3% difference in passenger nautical miles flown (Fig. 8c).

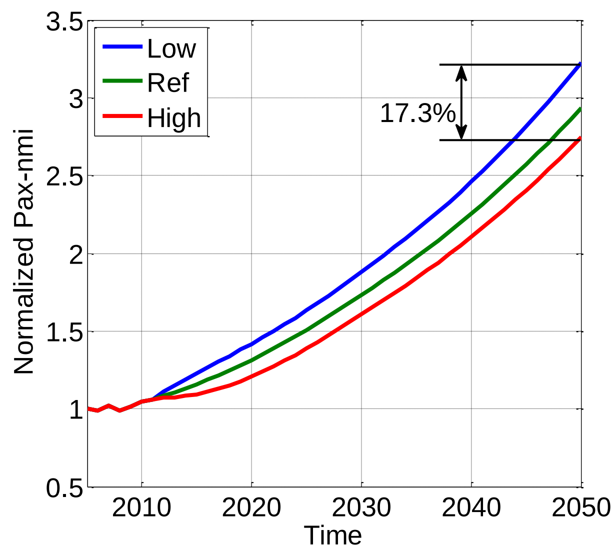
Because the drop in the number of passengers is larger than the drop in total passenger nautical miles flown, the increase in ticket prices affected passengers on short routes more than on long routes. Given that the price elasticity model incorporates trip distance (Fig. 3), this outcome is not unexpected.

Analysis of required aircraft production capacity

As mentioned, the fleet-level environmental metrics (here, CO_2 emissions) are functions of not only the new-in-class aircraft technology, but also the availability of the aircraft and how the airline allocates it for use. Without limiting the number of deliveries possible, the number of annual deliveries demanded by FLEET showed an increasing trend. Using a linear trend to fit the values from this FLEET study, the airline in FLEET needs



(a) Normalized CO_2 **(b) Normalized Demand**



(c) Normalized Passenger Nautical Miles

Figure 8. Effect of different fuel prices on (a) Normalized CO_2 emissions, (b) Normalized demand and (c) Normalized Passenger Nautical Miles

approximately 20 new aircraft each year, starting from 85 aircraft per year in 2005 (Fig. 9). This production rate entails ramping up of aircraft manufacturers' production capacity, which if not met, will require delayed retirement from the existing fleet.

Furthermore, the cumulative deliveries over the 2005 to 2050 period were observed to be 27,722, of which 11,014 are in the period from 2011 to 2030. By contrast Boeing, using a 2% per year demand growth rate, predicts a requirement for 7,530 aircraft in the period from 2011-2030 for the North American market.[26] The difference between the FLEET and Boeing forecast can be attributed to two major factors. First, FLEET assumes a GDP growth of 2% per year as a baseline case, which when combined with an income-demand elasticity of 1.4 leads to effectively 2.8% per year demand growth rate. Second, the proportion of regional jets (i.e. class 1 and 2 aircraft) in FLEET grows from 30% in 2005 to as high as 40% in 2050. In contrast, in Boeing's forecasts, the share will actually decline from 29% in 2010 to 8% in 2030 due to more attractiveness of single aisle aircraft such as B787 and ASAT type aircraft.

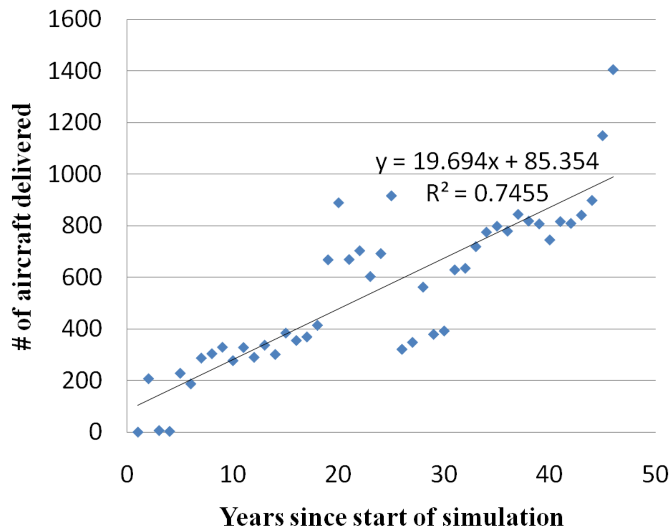


Figure 9. Annual aircraft deliveries across all six classes

V. Conclusions and Future Work

The studies presented here contribute to an understanding of how aircraft entry-into-service dates and future fuel price scenarios affect the environmental impact of air transportation. Thus these studies and other similar ones that can be done using this tool can potentially help understand the level of impetus to technology development that is needed to achieve the fleet-level goals.

The different entry-into-service scenarios for N+2 generation aircraft showed impact on network level emissions during the period of induction of new aircraft into fleet. This means that as new aircraft become available and airlines begin to operate them, the fleet shows improved performance with regard to emissions, but a late introduction means a delay in achieving the desired goals. Also, under the assumptions held here, the emissions continue to grow despite introduction of new aircraft since the total market demand for air travel increases continuously. To counter the impact of increased demand, we would need further improvements in aircraft technology which is envisioned in N+3 generation aircraft.

While the study in aircraft entry-into-service takes into account the aircraft technology level, the study of different fuel prices considers the impact of economic conditions on air travel. Higher fuel prices lead the airlines to pass the burden to passengers who in turn may choose to travel by alternate modes of transport in place of airlines. This was illustrated in the differences in total demand and consequently CO_2 emissions that were observed in this study. Eventually, growing fuel prices could be as important a reason as that of lowering emissions that would drive airlines to buy new aircraft.

FLEET enables the study of various scenarios with respect to the economy, policy and the state of technology to assess the environmental impact of aviation. However, the several layers of abstraction employed for purpose of simplification imply the there are a number of shortcomings that can be improved.

A major capability currently under development is that of modeling the decision that airlines make about the retirement of aircrafts in their fleet. FLEET hitherto assumed a constant retirement age of 25 years for all aircraft. However an unpredictable change in the fuel price, growth in the maintenance cost with the aircraft age may lead the airlines to consider an early or late retirement age. For example, under an economic scenario wherein fuel prices are very high, it may not economical for the airline to operate the existing aircraft and replacing them with newer, more fuel-efficient ones would be beneficial. Introducing a new aircraft in the fleet will, however, cost the airline its acquisition cost which may not be a favorable option either. Thus, different economic scenarios could lead to different decisions with regards to retirement of aircraft. A model for decision on aircraft retirement that airlines make based on their net present value is a logical next step under development.

It is assumed in the current version of FLEET that new aircraft are available immediately when required by the airlines. Since many commercial aircraft development projects are initiated in response to market requirement there is a gap of few years between market requirements for a certain technology level and its availability. This means that airlines have to foresee their future requirements and place their demand accordingly. The airlines have an incentive to buy new aircraft whenever their acquisition would help reduce costs, meet external constraints, increase capacity, etc. Thus, the ability to model the airlines decision making process for buying new aircraft in order to maintain economic and technical viability is being developed.

Furthermore, constraints on airport capacity could be one reason airlines choose to update their fleet. Future capacity limits either in the airspace or at the airports would require the airlines to change either their operation strategies and fly from nearby smaller airports or introduce new, possibly large, aircraft that can handle the increase in demand. In case the airline decides to buy new aircraft, they could choose to order one available in the market, or as it happens often, ask the airframe manufacturer to develop an entirely new aircraft. This would mean a certain development time during which the airline would have to contend with its existing fleet. This modeling of the airlines' forecasting of their requirements and subsequent decision making on aircraft acquisition would complement the modeling of their decision to retire aircraft.

Eventually, we expect to develop a capability to suggest a fleet composition that is optimal from the operational, economic and environmental standpoint. This capability could then be employed to different markets under different scenarios to derive similar results.

Acknowledgments

The authors would like to thank program technical monitors Bill Haller of NASA Glenn Research Center and Phil Acara of NASA Langley Research Center. NASA Cooperative Agreement NNX07AO13 supported the work presented in this paper.

References

[1]Del Rosario, R., Wahls, R., Follen, G., and Madavan, N., "Subsonic Fixed Wing Project," NASA Fundamental Aeronautics Program 2011 Technical Conference, Cleveland, OH, Mar. 15-17, 2011.

[2]Nickol, C., "Assessing Progress Toward Simultaneous Reductions in Noise, Fuel Burn and NOx", Environmentally Responsible Aviation (ERA) Project, *49th AIAA Aerospace Sciences Meeting*, Orlando, Florida, Jan. 4-7, 2011.

[3]Tetzloff, I. and Crossley, W., "An Allocation Approach to Investigate New Aircraft Concepts and Technologies on Fleet-Level Metrics," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, Hilton Head, SC, 22 September 2009.

[4]Zhao, J., Agusdinata, D.A., DeLaurentis, D., "System Dynamics Fleet Forecasting with Technology, Emission, and Noise Goals," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, Hilton Head, SC, 22 September 2009.

[5]Zhao, J., Tetzloff, I.J., Tyagi, A., Dikshit, P., Mane, M., Agusdinata, D.A., Crossley W.A., DeLaurentis, D., "Assessing New Aircraft and Technology Impacts on Fleet-Wide Environmental Metrics Including Future Scenarios", AIAA 48th Aerospace Sciences Meeting, Orlando, Florida, Jan. 4-7, 2010.

[6]Mane, M., Agusdinata, D.A., Crossley, W.A., and DeLaurentis, D.A., "Fleet-Wide Environmental Impacts of Future Aircraft Technologies ," *10h AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, Fort Worth, TX, 18 September 2010.

[7]Le, L.T., "Demand Management at Congested Airports: How Far are We from Utopia?," Systems Engineering and Operations Research, George Mason University, 2006.

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

9Bureau of Transportation Statistics (BTS), US Department of Transportation, online database, http://www.bts. gov, [accessed May 2010].

[10]Bombardier Aerospace, Company website: http://bombardier.com, [accessed May 2010].

[11]Boeing, Commercial Airplanes, Company website: http://boeing.com, [accessed May 2010].

[12]Guynn, M., Subsonic Fixed Wing Project Fundamental Aeronautics Program, 2nd Annual Meeting, Atlanta, GA October 7-9, 2008.

[13]FLOPS, Flight Optimization System, Software Package, Release 7.01, NASA Langley Research Center, Hampton, VA, June 2006.

[14]Clarke, M. and Smith, B., "Impact of Operations Research on the Evolution of the Airline Industry," *Journal of Aircraft*, Vol. 41, No. 1, 2004, pp. 62-72.

[15]Barnhart, C., and Lohatepanont, M., "Airline Schedule Planning: Integrated Models and Algorithms for Schedule Design and Fleet Assignment", *Transportation Science*, Vol. 38, No 1, 2004, pp. 19-32.

[16]Clarke, L. W., Hane, C. A., Johnson, E. L., and Nemhauser, G.L., "Maintenance and crew considerations in fleet assignment", *Transportation Science*, Vol. 30, No. 3, 1996, pp. 249-260.

[17]Hane, C. A., Barnhart, C., Johnson, E. L., Marsten, R., Nemhauser, G. L., and Sigismondi, G., "The Fleet Assignment Problem: Solving a Large-Scale Integer Program", *Mathematical Programming*, Vol. 70, Nos. 1-3, 1995, pp. 211-232.

[18]Rexing, B., Barnhart, C., Kniker, T., Jarrah, A., Krishnamurthy, N., "Airline Fleet Assignment with Time Windows", *Transportation Science*, Vol. 34, No. 1, 2000, pp. 1-20.

[19]Subramanian, R., Scheff, R. P., Quillinan, J. D., Wiper, D. S., and Marsten, R. E., “Coldstart: Fleet Assignment at Delta Airlines”, *Interfaces*, Vol. 24, No 1, 1994, pp. 104-120.

[20]Henkle, A., Lindsey, C., Michelle Bernson, ”A review of the operational and cultural aspects of Southwest Airlines”, online source: http://ocw.mit.edu/NR/rdonlyres/Sloan-School-of-Management/15-761Operations-ManagementSummer2002/7370C22B-1762-4B76-BE28-775A0987C8AC/0/lec25swa.pdf, [accessed May 12, 2009].

[21]MIT Global Airline Industry Program, The Airline Data Project, online database: http://web.mit.edu/airlinedata/www/default.html, [accessed August, 2010].

[22]GAMS, General Algebraic Modeling System, Software Package, Distribution 21.2, GAMS Development Corporation, Washington, DC.

[23]McCarl, B.A., “GAMS User Guide: 2004, Version 21.3”, GAMS Development Corporation, Washington, DC.

[24]Dou, L. *et al.*, "Modeling Air Traffic Management Technologies with a Queuing Network Model of the National Airspace System," the Logistics Management Institute (LMI), 1999.

[25]Bureau of Transportation Statistics (BTS), Schedule B-43 Aircraft Inventory, US Department of Transportation online database: http://www.bts.gov/programs/airline_information/schedule_b43/, [accessed April 2010].

[26]Boeing, *Current Market Outlook 2011*.

[27]Winchester, N., Wollersheim, C., Clewlow, R., Jost, N., Paltsev, S., Reilly, J., Waitz, I., “The Impact of Climate Policy on US Aviation,” *Partnership for Air Transportation Noise and Emissions Reduction*, PARTNER-COE-2011-001, 2011.

[28]Aviation Emissions and Evaluation of Reduction Options, 2000.

[29]Energy Information Administration, *Annual Energy Outlook 2011*, 2011.