JOURNAL OF AIRCRAFT
Vol. 54, No. 3, May–June 2017

# Assessing Effects of Aircraft and Fuel Technology Advancement on Select Aviation Environmental Impacts

Kushal Moolchandani,* Parithi Govindaraju,* Satadru Roy,* William A. Crossley,† and Daniel A. DeLaurentis‡
*Purdue University, West Lafayette, Indiana 47907*

DOI: 10.2514/1.C033861

**The ability to simultaneously assess airline operations, economics, and emissions would help evaluate the progress toward reduction of aviation's environmental impact as outlined in the NASA Environmentally Responsible Aviation program. Furthermore, assessment of aircraft utilization by airlines would guide future policies and investment decisions on technologies most urgently required. This paper describes the development of the Fleet-Level Environmental Evaluation Tool, which is a computational simulation tool developed to assess the impact of new aircraft concepts and technologies on aviation's impact on environmental emissions and noise. This tool uses an aircraft allocation model that represents the airlines' profit-seeking operational decisions as a mixed-integer programming problem. The allocation model is embedded in a system-dynamics framework that mimics the economics of airline operations, models their decisions regarding retirement and acquisition of aircraft, and estimates market demand growth. This paper describes the development of Fleet-Level Environmental Evaluation Tool to use a single large airline to represent operations of all airlines in the United States aviation market. The paper also demonstrates Fleet-Level Environmental Evaluation Tool's capabilities using scenarios on the assessment of effects of new technology aircraft and biofuels on aviation's emissions.**



## Nomenclature

| | | |
|---|---|---|
| $BH_{k,j}$ | = | block hours of aircraft type $k$ on route $j$, h |
| $C_{k,j}$ | = | direct operating cost of aircraft type $k$ on route $j$ |
| $cap_k$ | = | passenger capacity of aircraft type $k$ |
| $dem_j$ | = | passenger demand on route $j$ |
| $(EMH/BH)_k$ | = | equivalent maintenance hours for each block hour of aircraft type $k$, h |
| $fleet_k$ | = | number of aircraft type $k$ in the fleet |
| $P_{k,j}$ | = | 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. Introduction

AVIATION, along with other modes of transportation, is a key source of emissions and noise. In 2007, for example, aviation accounted for 5.6% of the U.S. gross domestic product (GDP) [1] and 4% of total carbon dioxide ($CO_2$) emissions [2] within the United States; with predictions of increasing passenger (pax) and cargo air travel, both of these figures are likely to grow. Unlike other modes of transport, however, aviation emissions are mostly created at higher altitudes; thus, their impact is not clearly understood, although it is possible that this impact is higher [3].

This expected increase in aviation emissions motivates a need to address aviation's environmental impact, and it has prompted agencies such as NASA and the International Air Transport Association to propose several noise and emissions reduction targets [4,5]. For example, as a means to drive development of new aircraft technologies and concepts, NASA has established emissions reduction targets for each future generation of aircraft after those in current production in 2005, which they refer to as the "N" generation. For the next generation, referred to as "N + 1," with predicted availability by 2015, NASA aims to reduce fuel burn by 33% with respect to current-generation aircraft, cumulative certification noise by 32 dB from stage 4 levels, and landing and takeoff oxides of nitrogen (LTO $NO_x$) emissions by 60% from Committee on Aviation Environmental Protection (CAEP)/6 levels. Following the N + 1 aircraft, the "N + 2" generation employs technology available by 2020 with the aim to reduce fuel burn by 50% relative to current aircraft, cumulative noise by 42 dB from stage 4 levels, and LTO $NO_x$ by 75% from CAEP/6 levels. The "N + 3" generation of aircraft, available by 2025, has goals to reduce fuel burn by more than 70%, cumulative noise by 71 dB, and LTO $NO_x$ by more than 80% [4]. Since the initial establishment of these goals, NASA has revised the target values, but the focus remains to mitigate the environmental footprint of individual aircraft.

Meeting these future aviation emissions targets will require the development and introduction of not just advanced technologies but also new operational concepts and alternative fuels with lower emissions impacts. Moreover, it is likely that several new technologies and policies will be implemented simultaneously because none of them will be independently able to achieve the goals. This means that the effect of these technologies and policies will also be cumulative; Fig. 1 shows a reproduction of a notional illustration prepared by NASA showing such cumulative effects. All of this means that the environmental impact of aviation depends not only on individual aircraft performance but also on how airlines use these aircraft to provide transportation while pursuing business objectives.

It is likely that future air transportation demand could increase at a rate such that the increased number of flights leads to an increase in total fleet-level emissions and airport noise, even though the individual aircraft have improved environmental characteristics over the current aircraft. The need to reflect airlines' use of aircraft and simultaneously predict the future fleet-level environmental impact of aviation provides the motivation for the development of the Fleet-Level Environmental Evaluation Tool (FLEET). In brief, FLEET is a computational simulation tool developed to assess the impact of new aircraft concepts and technologies on aviation's impact on environmental emissions and noise. The following section reviews a

Presented as Paper 2013-0652 at the AIAA 51st Aerospace Sciences Meeting, Grapevine, TX, 7–10 January 2013; received 14 January 2016; revision received 8 July 2016; accepted for publication 11 September 2016; published online 28 December 2016. 

*Graduate Research Assistant, School of Aeronautics and Astronautics. Member AIAA.

†Professor, School of Aeronautics and Astronautics. Associate Fellow AIAA.

‡Professor, School of Aeronautics and Astronautics. Associate Fellow AIAA (Corresponding Author).

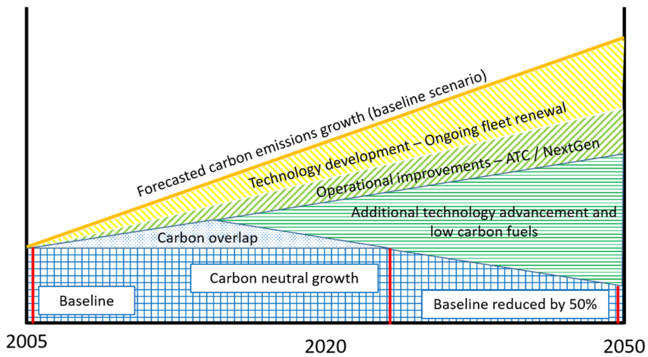



**Fig. 1 Reproduction of NASA-generated illustration of carbon emissions from aviation (from the 2010 Aeronautics Research Mission Directorate Green Aviation Summit). ATC, air traffic control; NextGen, next generation operational concepts.**

portion of the literature on environmental impact of aviation, especially those studies that relate to FLEET's capabilities, including airline fleet assignment, the environmental impact of aviation and aviation policy, and future aircraft technology advancement and airline fleet composition. It highlights the commonalities between these studies and FLEET, and where FLEET's capabilities are in addition to those already addressed.

## II. Related Work

One of FLEET's key capabilities is aircraft assignment to routes, modeled as a resource allocation problem. Numerous other studies, many of them in the operations research community, have tackled aircraft assignment problems. Frequently, these studies model aircraft assignment as linear programming problems using an objective function such as that of cost minimization. For example, Hane et al. [6] tackled a problem of fleet assignment as a multicommodity flow problem using the interior point and simplex methods. They modeled their optimization problem as a cost minimization problem and used different methods like interior point algorithm, dual steepest-edge simplex, etc. to find optimal integer solutions. Barnhart et al. [7] solved a similar problem but by using a subnetwork fleet assignment model instead of using the entire network. They operated under the hypothesis that some real-life airline networks were weakly coupled with respect to revenue and may operate independently of other subnetworks. Others (for example, Rexing et al. [8] and Lohatepanont and Barnhart [9]) incorporated scheduling within the problem of fleet assignment. In contrast, Huang and Schleicher [10] developed the "AvDemand" program to predict future demand and assign aircraft to meet that demand. Their model used the MITRE aircraft forecast as a baseline to determine which aircraft would be available in future years. This kind of model showed how aircraft were used based on passenger demand, but it did not capture economic factors from the airline's viewpoint. Whether or not such studies incorporate features such as predictions of future market demand growth, scheduling, etc., all of them attempt to address the question of where the airlines should operate their existing fleets of aircraft to meet their objectives. FLEET addresses this same question by taking a model-based approach of forecasting demand and assigning aircraft to meet future demand while meeting the objective of airline's profit maximization; FLEET does not currently account for scheduling in its problem formulation, relying instead on certain simplifying assumptions. In fact, using models for different aspects of the system is a key distinguishing feature of FLEET; a later section will return to this aspect of FLEET and explain the details of some key models (see Sec. IV).

Some other studies analyzed aviation's environmental impact together with economic and policy effects. Reynolds et al. [11] and Vera-Morales and Hall [12] introduced the Aviation Integrated Modelling project (AIM) that provided this capability at both local and global levels. They used publicly available data to model aircraft trajectories and could model multiple policy scenarios to estimate aviation emissions. Dray et al. [13] used the tools developed under AIM to examine the effects of global emissions trading on aviation emissions and technology uptake. Their results showed that aviation emissions grew, regardless of the scenarios they studied, and that any significant reduction in emissions resulted only through a combination of technological improvements and demand reduction. Similarly, Winchester et al. [14] studied the effect of the cap-and-trade policy on U.S. aviation, especially the emissions generated by the industry, and the change in demand for air travel over time. Pfaender et al. [15] proposed a system-dynamics model to explore the environmental impact of the decisions aircraft operators made in response to policy changes. Their system-dynamics model included feedback effects for limiting fuel supply, enforcing cap and trade policies, and evolving passenger demand. FLEET's constituent models fit into a system-dynamics-type framework, and the tool's modular structure allows for easy replacement of any of the models as desired. Additionally, different scenarios of economic growth and policy implementation can be set up in a FLEET simulation by making changes to one or more of its models.

Studies on the impact of introduction of new aircraft technology on the aviation industry include those such as Kernstine et al. [16], who suggested methods to select the right set of technologies for aircraft based on their environmental impact. Hollingsworth et al. [17] developed a parametric approach to model and study the impact of new technologies on the environment. Others such as Sherry et al. [18] and Christensen et al. [19] looked at the sizes of aircraft that would be most beneficial to invest in for future development efforts. FLEET models emissions based on aircraft technology level and their operations, complementing the capabilities of the previously cited studies. Furthermore, the airline modeled in FLEET not only makes decisions on fleet assignment but also the replacement of existing aircraft with newer technology aircraft based on past years' utilization by aircraft size and predicted future need. FLEET is not the only tool offering such capabilities, however, with the following being some of other examples.

The System for Assessing Aviation's Global Emissions (SAGE) project [20,21] developed a tool that estimates the global fuel burn and emissions using publicly available databases and methodologies without accounting for airline operations while still using flight mission profiles to measure emissions. The SAGE tool estimates emissions of various pollutants like oxides of nitrogen ($NO_x$), carbon monoxide (CO), carbon dioxide, etc., that serve as a basis to develop scenarios for other studies. This tool, however, has now been superseded by newer tools, an example of which is the Aviation Environmental Tool Suite.

The Aviation Environmental Tool Suite serves to study the environmental impact of aviation and is composed of three main components: the aviation environmental design tool (AEDT), the environmental design space (EDS), and the aviation environmental portfolio management tool (APMT). The AEDT integrates existing models for aviation noise and emissions, and it studies interdependencies among them. The EDS is used for the analysis of aircraft and engines, whereas the APMT is used for economic analysis. The latter has an economics module (APMT-economics) [22] that models airline and aviation market responses to environmental policy options. Starting from a baseline year, APMT-economics projects the future aviation operating costs, demand and fleet development projections, and fleet assignment to an aggregate set of operations. APMT-economics can model global operations and considers both passenger and cargo air carriers.

Other studies have tackled similar problems, though with different implementations. Pfaender and Mavris [23] studied a net present value-based approach for decision making on aircraft technology upgrades and showed how this model could, in turn, be used to study aviation's environmental impact. The same authors looked at the effect of fuel prices on future technology and environmental outcomes of aviation using a system-dynamics-type approach [24]. Finally, [25,26] were yet more examples of work that was similar in nature to the work presented in this paper. Despite these tools, there was a need to continue investing in effective tools for assessing aviation's environmental impacts. This viewpoint was also supported by Waitz et al. [27], who recommended investing in the development of both tools and metrics for this purpose. They, in fact, referred to the

**Table 1 Levels of abstraction in FLEET**

| Abstraction | Simplification | Effect on analysis |
|---|---|---|
| Passenger air travel on WWLMINET 257 subset | U.S. airport has at least the origin or destination on flights between these airports | 1) Route/city reduction<br>2) 169 airports<br>3) 80% of passenger traffic based on 2005 BTS data (65% of flights) |
| Aircraft fleet represented by 24 aircraft | 1) One aircraft represents all aircraft in a class based on seat count<br>2) Reflect technology "age" | 1) Reduction from 100+ different aircraft types<br>2) Resolution in fleet reduced |
| Single airline serves all routes in the network | Single airline provides service on routes currently served by many airlines | 1) Omits competitive behaviors<br>2) Simplifies revenue/profit modeling<br>3) Single airline is very large |
| Aircraft allocation assumes round trips | 1) Avoid time of day scheduling<br>2) Assume symmetric demand between cities | 1) Reduction in number of decision variables<br>2) Removes "balance constraint"<br>3) Omits some time of day issues |



APMT as one of the necessary elements in the plan to implement their recommendations.

In summary, several research efforts studied aircraft technology and its impact on the environment. The motivation of the work presented herein is to incorporate a simultaneous assessment of environmental impacts of aviation and modeling of airline decision making about fleet operations along with an evolution of passenger demand and airline fleet mix and technology level. Rather than rely of external forecasts, a model-based approach toward providing this capability is the objective for development of the Fleet-Level Environmental Evaluation Tool. The FLEET models airline decisions about operations as a resource allocation problem using a mixed-integer programming (MIP) formulation. This MIP problem resides within a system-dynamics-like approach that simulates airline decisions using models for aircraft retirement, acquisition, and calculation of ticket prices. The market demand forecast is based on a model that considers both underlying economic conditions and travel price elasticity. Each of these models can be independently modified, allowing for the simulation of a variety of scenarios of aviation's environmental impact. References [28–35] described the development of and studies conducted using this tool. Presently, FLEET focuses only on passenger demand and airline operations on routes that have either the origin, destination, or both in the United States.

## III. Technical Approach

The complexity of the U.S. air transportation system, with its numerous airlines, aircraft types, airports, and routes, makes it challenging for any tool to model and simulate in its entirety. To keep the model size manageable while still accounting for the components crucial to its purpose, FLEET uses several layers of abstraction, as shown in Table 1. An example of a simplification is using a single airline to operate all aircraft in the network, making the simulation easier to run at the expense of excluding the effects of competition. The airline, however, does not exploit its status of a monopoly and charges passengers based on a revenue model developed especially for this tool. This section discusses the setup of the input data for FLEET as well as the resource allocation problem formulation; the details of some important modules are given in the following section, and sample runs of the tool are given in the Studies and Results section (Sec. V) later.

### A. Initial Fleet, Airport, and Network Setup

The first step in the development of FLEET is to determine the fleet size, its composition, and the airline network for the initial year of the simulation. Based upon the initial development of FLEET in support of NASA's Subsonic Fixed-Wing (SFW) project, the FLEET simulations described in this paper use 2005 as the starting year for all simulations; 2005 corresponds to the N generation of aircraft described by the SFW goals. This FLEET setup process uses data from the Bureau of Transportation Statistics (BTS) [36]. The airports included in the FLEET network are a subset of the "World-Wide LMI Network (WWLMINET) 257" airports as reported by Logistics Management Institute to be those "worldwide" airports that have the most operations. Routes in the FLEET network are those that connect all domestic U.S. airports included in the list of WWLMINET 257 and those international airports, also from this list, that have a direct flight to any U.S. airport. This gives 103 airports in the United States and 66 international airports that have a direct passenger-carrying connection to a U.S. airport. In 2005, these 169 airports accounted for approximately 65% of all passenger flights and 80% of all passengers transported, including both domestic and international passengers traveling to and from the United States [36]. Counting only those airport pair connections with demand greater than 10 passengers on a typical day of the year, the FLEET network had a total of 2134 routes. The lower limit value of 10 passengers, although arbitrary, removed a large number of very low demand routes from the data.

To represent the airline fleet, FLEET aggregates all available aircraft into six classes based on their seat capacity and into four technology groups based on date of entry into service of the aircraft. The technology groups are referred to as representative-in-class, best-in-class, new-in-class, and future-in-class. Representative-in-class aircraft are those that have the highest number of operations in 2005 within each seat class; generally, these are older aircraft. The best-in-class aircraft are those that have the most recent entry-in-service date within each seat class as of 2005, and thus incorporate more 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 will enter into service at a date further in the future. Table 2 lists the aircraft used in the FLEET. Classes 1, 2, 5, and 6 of the future-in-class aircraft are the same as the corresponding new-in-class aircraft, with their fuel burn scaled down to reflect the expected technology improvement by the time of their introduction. The advance single-aisle transport (ASAT) is Purdue University's version of an aircraft with geometries similar to a B737-800 and calibrated performance and weight data for that aircraft, though with a slightly increased design range of 3250 n miles. The ASAT model was developed using Flight Optimization System (FLOPS). Additional details of aircraft modeling appeared in [37].

The final step in the FLEET setup is to determine the number of aircraft that the single airline has in 2005 in its inventory. This calculation assumes that an average day of an aircraft comprises only block hours (BHs), equivalent maintenance hours (EMHs), and turnaround time. Block hours $BH_{k,j}$ account for the taxi-out time, en route flight time, and taxi-in time of aircraft type $k$ on route $j$. The turnaround time $t$ accounts for the time needed to unload, service, and then load the aircraft between flights. The value of $t$ can vary with aircraft type; for simplicity, the current allocation problem uses 1 h for all aircraft types.[§] Because the allocation problem does not track

[§]Henkle, A., Lindsey, C., and Bernson, M., "A Review of the Operational and Cultural Aspects of Southwest Airlines".

**Table 2 Aircraft modeled in FLEET**

| Class (seats) | Representative in class | Best in class | New in class | Future in class |
|---|---|---|---|---|
| 1 (20–50) | Canadair RJ200/RJ440 | Embraer ERJ145 | Small Regional Jet | — |
| 2 (51–99) | Canadair RJ700 | Embraer 170 | CS100 | — |
| 3 (100–149) | Boeing 737-300 | Boeing 737-700 | Boeing 737-700 reengined | Purdue small ASAT with N + 1/N + 2-level technology |
| 4 (150–199) | Boeing 757-200 | Boeing 737-800 | Boeing 737-800 reengined | D-8 "double bubble" |
| 5 (200–299) | Boeing 767-300 | Airbus A330-200 | Boeing 787 | — |
| 6 (300+) | Boeing 747-400 | Boeing 777-200ER | Large twin aisle | — |

individual aircraft, an aggregated approach accounts for the unavailability of some aircraft owned by the airline due to maintenance. To do this, the ratio $(\mathrm{EMH/BH})_k$ describes the number of "equivalent maintenance hours per block hour of flight" for aircraft type $k$.

The values of $(\mathrm{EMH/BH})_k$ rely upon data from the Airline Data Project [38]. The Airline Data Project presents the average number of daily departures and the daily block hour utilization of aircraft operated by main and regional domestic U.S. carriers in three categories of aircraft type: small narrow body, large narrow body and wide body. Using $\mathrm{departures}_a$ as the reported average daily departures of aircraft type $a$ and $\mathrm{BH}_a$ as the reported average daily block hour utilization of aircraft type, along with the turnaround time between operations $t$, a simple equation [Eq. (1)] can account for the "average" activity of an aircraft of type $a$ in a representative 24 h day:

$$\mathrm{BH}_a * (1 + \mathrm{EMH}_a/\mathrm{BH}_a) + t * \mathrm{departures}_a = 24 \qquad (1)$$

With the assumption of only the aforementioned three contributors to an average day of an aircraft, Eq. (1) leads to the ratio of equivalent maintenance hours per block hour $(\mathrm{EMH/BH})_a$ for aircraft type $a$.

Applying the EMH/BH ratio of small narrow-body aircraft to classes 1, 2, and 3, the ratio of large narrow-body aircraft to class 4, and the ratio of wide-body aircraft to classes 5 and 6 converts from the three Airline Data Project aircraft types to the six FLEET classes. With finer data resolution and different turnaround time values, each aircraft class can have a different ratio of maintenance hours per block hour. Additionally, each of the technology groups of aircraft can have a different ratio because newer aircraft designs explicitly address improved maintainability and reliability. The studies presented later in this paper do not use a finer resolution; Table 3 presents the values of $(\mathrm{EMH/BH})_k$ used in the studies.

Using the aforementioned three constituents, block hours, equivalent maintenance hours, and turnaround times, of a typical aircraft usage, the approach estimates the aggregate utilization hours for all aircraft in the United States. Dividing this value of aggregate utilization hours by the total possible hours in a given year gives the total number of aircraft for each class in the FLEET. This completes the initial setup of the tool. Because information about the initial year comes from historical data, all of these values remain constant, regardless of any future scenarios considered for study.

### B. Resource Allocation Problem Formulation

At the heart of the FLEET is an aircraft allocation problem formulated as a mixed-integer programming problem. Using performance and cost descriptions of the aircraft in the airline's fleet, the problem seeks to maximize profit while meeting demand and operational constraints; this provides the FLEET with a model (simple as it may be) of airline operations and decision making. Equations (2–6) describe the objective function, constraints, and design variables that make up the allocation problem:

$$\text{maximize} \sum_{k=1}^{K}\sum_{j=1}^{N}(\mathrm{pax}_{k,j}\cdot P_{k,j}) - \sum_{k=1}^{K}\sum_{j=1}^{N}(C_{k,j}\cdot x_{k,j}) \qquad (2)$$

$$\text{subject to} \sum_{k=1}^{K}\mathrm{pax}_{k,j} \le \mathrm{dem}_j, \qquad \forall\ j \qquad (3)$$

$$\sum_{k=1}^{K}\mathrm{pax}_{k,j} \ge 0.2\cdot\mathrm{dem}_j \qquad (4)$$

$$2[x_{k,j}\cdot \mathrm{BH}_{k,j}(1 + (\mathrm{EMH/BH})_k) + t] \le 24\cdot \mathrm{fleet}_{k,j=1} \qquad (5)$$

$$\mathrm{pax}_{k,j} - x_{k,j}\cdot \mathrm{cap}_k \le 0 \qquad (6)$$

The integer decision variable $x_{k,j}$ is the number of trips that aircraft type $k$ flies on route $j$. The variable $\mathrm{pax}_{k,j}$ is the number of passengers that fly on aircraft type $k$ on route $j$. In practice, the number of passengers per flight is also an integer, but this formulation treats $\mathrm{pax}_{k,j}$ as a continuous variable because this greatly improves solution time. Routes correspond to a single subscript in this formulation because of a round-trip assumption, described in the following. Equation (2) is the objective function; this 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 $\mathrm{pax}_{k,j}$. 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. (3) ensures that the airline does not transport more passengers than the market demand on each route, whereas the constraint in Eq. (4) ensures that the airline meets at least 20% of the demand on each route. This approach of bounded inequality with a lower value of 20% facilitates faster solution times for the MIP problem as compared to enforcing an equality constraint on demand while ensuring that the airline still serves all routes. In our experience, a solution with a route at this lower bound on demand is extremely rare, and the total system-level demand served always remains in excess of 96%. Moreover, having a positive-valued lower bound is consistent with the notion that the single airline does not exploit its monopoly status by completely dropping a route.

The constraint in Eq. (5) counts the number of aircraft necessary to satisfy segment 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 left-hand side of the constraint includes the factor of two, and the right-hand side accounts for all 24 h in a day. This is a reasonable assumption because the fleet allocation problem estimates the cost and profit of representative daily operations, and BTS data show that average daily demand is nearly symmetric although a given passenger may not fly a return trip on the same day. Additionally,

**Table 3 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 |

the round-trip simplification removes the need for flow-balance constraints in the allocation problem and reduces the number of decision variables. When the constraint in Eq. (5) is satisfied, the total number of hours for block time, turnaround time, and maintenance time for each aircraft type does not exceed 24 h times the number of aircraft of that type owned by the airline. The constraint in Eq. (6) ensures that the airline flies a sufficient number of trips to meet passenger demand while considering the seat capacity of each aircraft type $cap_k$. The seating capacity of the aircraft can account for a load factor, so that $cap_k$ may be smaller than the number of seats installed on the aircraft. 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.

Finally, integer programming methods can solve the allocation problem presented by Eqs. (2–6). The General Algebraic Modeling System (GAMS) software package [39] facilitates the formulation and solution of this MIP problem. GAMS provides an algebraically based high-level language for the compact representation of large and complex optimization models and uses the CPLEX [40] solver to solve the MIP problem.

After solving the MIP problem, the FLEET uses the number of trips allocated to each route along with corresponding values of fuel burn (which relates directly to $CO_2$) and $NO_x$ emissions for each aircraft on each route to determine fleet-level values of these environmental impacts. A fleet-level metric for noise is more difficult to define. The metric used here of total noise area is not a commonly used metric; rather, aviation noise metrics deal with noise associated with a local airport and rely upon concepts like the number of people exposed to noise at or above some given level or like area exposed to noise at or above a given level. The "total noise area" metric used here is the sum of the predicted area inside the 65 dB Day-night average sound level contour at all 103 domestic airports in the LMI Network, and it serves as a single metric to describe the broad fleet impact. A fleet allocation with a larger total noise area would indicate more "fleet-level" noise. This metric does not include international airports because the airline model does not attempt to represent a significant number of operations at those airports; the current airline model more nearly represents all operations at U.S. airports. The daily cost, $CO_2$ emissions, total $NO_x$, and total noise area values reflect the allocated fleet to optimize profit while meeting demand, with the assumptions described previously.

## IV. System-Dynamics Model

The FLEET's resource allocation problem lies at the center of a system-dynamics-type framework that mimics market demand evolution, airline fleet retirement and acquisition, and airline ticket pricing policies. Figure 2 provides a graphical representation of this framework in which the allocation problem is solved for a given year and the many constituent models update input values in advanced of the next year's run. This section briefly describes the most important ones among these modules.

### A. Market Factors

In the FLEET, two main factors influence the evolution of passenger demand for the air transportation market. One depends on the prevailing economic conditions, referred to as the inherent demand. The other depends on passengers' response to changing ticket prices relative to the distance of desired travel and availability of alternative modes of transport, referred to as the elastic demand.

The rationale behind inherent demand growth is that a favorable economic environment would lead higher consumer income, which in turn would lead to an increase in demand for air travel. The FLEET implements this using the concept of income-demand elasticity where a change in income leads to a corresponding proportional change in demand. The coefficient of proportionality for income-demand elasticity in the FLEET is 1.4, based on [14], which implies that a 1% growth in the GDP leads to a 1.4% increase in inherent demand for air travel. This does not mean that a 1% growth in the GDP results in a 1% growth in income; rather, as mentioned in [14], the income-demand elasticity is only used to convert the change in GDP to change in demand. Studies using the FLEET in this paper apply this proportionality value to both domestic and international routes, and this coefficient remains constant throughout the simulation of any scenario.

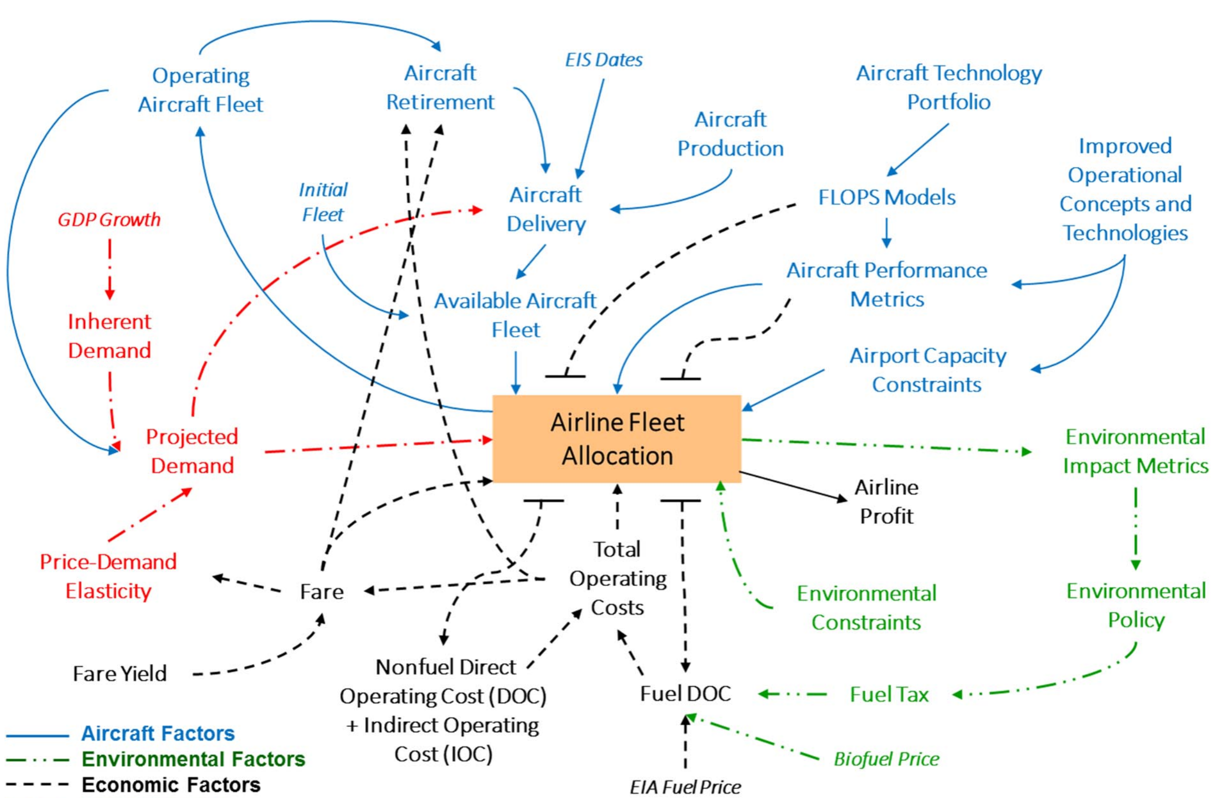



**Fig. 2 System-dynamics-like representation of the FLEET.**

Price-demand elasticity represents changes in air travel demand in response to ticket price variation. Two factors affect the passenger choice to fly: the distance of travel, and the availability of alternative modes of transport. Distance affects demand because passengers may choose to use alternative modes of transport in lieu of flying for short trips, especially as the airline ticket price increases. Potential passengers also value travel time and are more likely to continue to purchase airline tickets for longer trips as the airline ticket price increases. However, this behavior also depends on the availability of alternative modes of travel. The FLEET treats domestic routes as having alternate modes of transportation and treats international routes as though there are no alternate modes of transportation. Although not a perfect representation of the route structure, this does reflect that many international routes are overocean routes where alternative modes of travel are not feasible. Some exceptions to this include flights to Hawaii, which are characterized as international even though they are domestic, and flights to Canada, which are characterized as domestic because these are overland flights with alternative transportation available.

Reference [41] provided the price-demand elasticity value trends; these appear graphically in Fig. 3. International routes use the elasticity values from the "without alternative modes" curve, whereas domestic routes use those for the "with alternative routes" curve. For domestic flights with alternative modes of transportation, the short-range flights (less than 180 n miles) in the airline network are likely connecting flights, so the FLEET assumes that the passengers are equally likely to fly these routes and uses a constant value of elasticity for these short flights. For long-range domestic flights with alternative modes of operation (more than 650 n miles), the constant value of elasticity represents that passengers now make a fly/no-fly decision, regardless of how much longer the trip is. For international routes, the range threshold where price alone influences the fly/no-fly decision is shorter than for domestic (with alternate) routes.

### B. Aircraft Retirement

The FLEET's retirement model [37] accounts for a cost and revenue history of two competing aircraft and finds the age when it is economically feasible to replace the existing aircraft with a new aircraft of the same class of same or advanced technology level. Other retirement models in literature such as [42–44] use some rational logic to arrive at the retirement decision. Among these, the net present value (NPV) approach is the most popular one. These models compare the NPV of two scenarios. The first scenario keeps existing aircraft in service for one more year, whereas the second scenario brings in a new aircraft right away. The models decide to retire an aircraft when the second scenario has a greater NPV. The version of the value-based retirement model in the FLEET is similar to the concept cited in [42,43]. However, The FLEET's model assumes a finite time window of 10 years as the decision timeframe that the airline can foresee in the near future. In the process of calculating the NPV, all future operating cash flows are discounted with respect to the simulation year in the FLEET using a discount factor, including the acquisition cost that is spread over the financing period. With limited information about what rate the future cash flows are discounted in an airline setting, the model assumes the discount rate as suggested by the Office of Management and Budget [45]. The model evaluates, annually, the economic feasibility of retaining an aircraft for additional years versus its immediate replacement with a new aircraft.

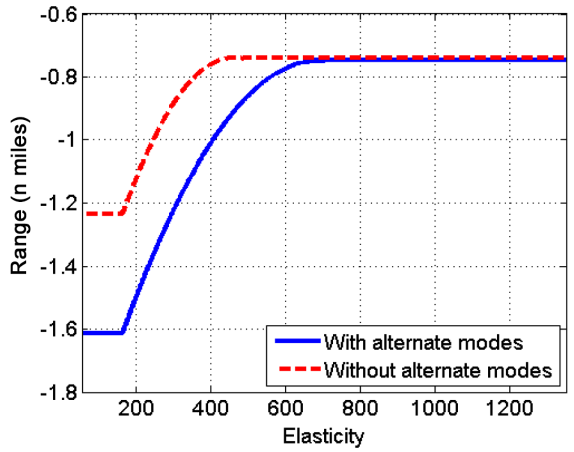



**Fig. 3 Demand Elasticity as a Function of Range.**

The BTS Schedule B-43 Aircraft Inventory database provides the entry-in-service (EIS) dates of the aircraft modeled in FLEET. This schedule contains detailed information on the EIS of passenger transport aircraft by their tail number; this provides a distribution that is applied to the aircraft "owned" by the FLEET airline. Keeping a track of the EIS dates and availability of the new aircraft in the market, the model seeks to find an optimal retirement age of the aircraft in the fleet. A cap has been set on the upper limit of the number of aircraft that can be retired per class per year. This is to account for the limitations in the manufacturer's delivery rate in a given year.

The model evaluates the net present value of $n = 10$ different retirement year options, which corresponds to the assumed time window of 10 years. For every simulation year in the FLEET, the airline foresees 10 years down the line and evaluates the NPV for 10 different options. Option 1 retires the existing aircraft right away and brings in a new aircraft in service. Option 2 keeps the existing aircraft for just one more year, and then the new aircraft enters in service the following year. However, option 10 keeps the existing aircraft for the entire 10 years of the time window. The retirement of the existing aircraft happens when one of the following criteria is satisfied:

1) Option 1 has the highest NPV.
2) The maximum airframe age of 40 years is reached.
3) The NPVs of all the options are negative.

Criterion 2 sets an upper limit on the retirement age of 40 years. This is a modeling assumption based on Boeing's maturity curve, as appeared in [46]. Criterion 3 forces the retirement of the aircraft because all the possible options of keeping the existing aircraft are economically infeasible. In this case, it is better to bring in a new aircraft (even though it also has a negative NPV), assuming a new aircraft is always better performing than an old one. The following are some of the key features of the retirement model.

#### 1. *Maintenance Cost with Age*

Although not modeled in the allocation problem within the FLEET, the retirement model does see an increase in the maintenance cost as the aircraft ages. This helps in the trade-off study between the maintenance cost of an old aircraft versus the acquisition cost of a new one to determine when it is economically feasible to retire the old aircraft and replace it with a new one. The model uses the "Boeing maturity curve" as presented in [46] to approximate the increase in the maintenance cost as the aircraft ages. Figure 4 shows the Boeing's maturity factor for two different manufacturing years. The trend shows a slightly steeper slope for aircraft manufactured before 1980.

#### 2. *Down Payment*

The module assumes a 20% downpayment scheme at the time of purchasing the aircraft. This is based on the discussion with someone involved with aircraft purchasing and financing.[¶] The remaining 80% of the acquisition cost is distributed in a financing scheme over a predefined period of time.

#### 3. *Financing Period*

The module assumes 15 years of financing period where the owner pays off the net acquisition cost (principal + interest) in a yearly installment plan equally spread over the span of 15 years. The principal amount is paid off in a linear scale, starting at 1% of the original acquisition cost. Interest is charged on the outstanding principal amount at a 5% interest rate per year. The module does

[¶]Private communication with Don Schenk, ACA Associates, New York, NY, 8 March 2012.

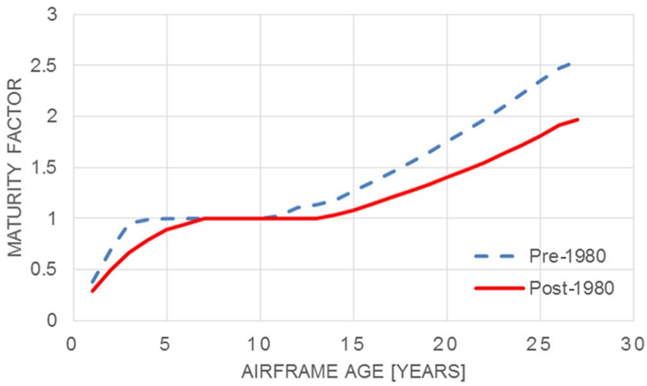



**Fig. 4 Maturity factor vs aircraft age (from [46]).**

impose the remaining burden of the acquisition cost on the owner if the aircraft retires before the 15-year financing period.

#### *4. Fuel Efficiency Degradation*

The fuel burn increases as the aircraft ages to partially capture the engine efficiency deterioration with age. In a more realistic scenario, airlines may consider airframe and engine retirement/replacement separately; in some cases, an existing airframe receives new engines. However, the retirement module in the FLEET assumes airframe and engine retirement are an integrated process.

The example in Fig. 5 demonstrates the working of the FLEET's retirement model. The example involves a B-737-300 aircraft under consideration, to be replaced with a new 737-700 aircraft (both belong to class 3 aircraft in the FLEET). The existing 737-300 aircraft is 22 years old and the retirement model needs to see if it is economically feasible to retire the aircraft at this age based on the aforementioned retirement criteria and replace it with a new B-737-700. Figure 5 shows the NPV values for the 10 different options. Option 1 here is the NPV of retiring the 737-300 right away (beginning of 2007) and buying in a new 737-700 model in the year 2007. Option 2 evaluates the NPV of keeping the existing 737-300 for one more year of service and retiring it at the starting of 2008 with a new 737-700 entering service in 2008. Similarly, option 10 is the NPV of keeping the existing 737-300 for the entire span of 10 years. The figure shows option 1 has the highest NPV; hence, the retirement model sees it as economically feasible to retire the 22-year-old 737-300 and buy a new 737-700 in 2007.

Note that the retirement does not take place even if any or all of the aforementioned retirement criteria are satisfied unless the aircraft is at least 10 years old or it has generated a return of investment of 5%. This check on the retirement is partially to account for the lack of actual airline cost and profit data. Also, other than the delivery rate, there are no monetary restrictions that could prevent the airline from buying as many aircraft as required to meet the demand.

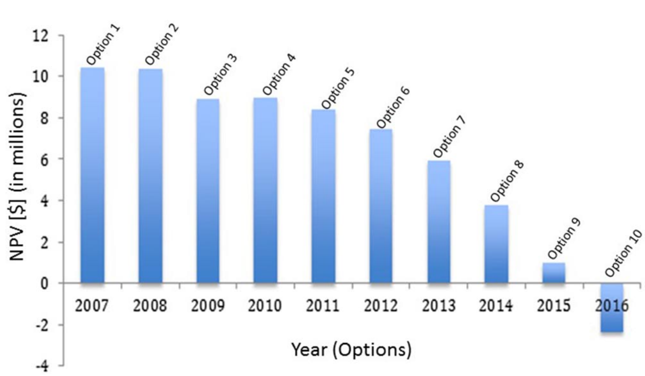



**Fig. 5 Net present values for different options.**

### C. Aircraft Acquisition

The aircraft acquisition module consists of delivering new aircraft to the airline based on estimated future demand and current aircraft capacity. To determine the number of new aircraft the airline will acquire, the FLEET projects the number of new aircraft needed to both replace retired aircraft and to meet increasing demand. The inherent demand growth rate and price elasticity calculations lead to an estimated future demand on the network. Without performing the resource allocation, the future number of seats needed in each aircraft class uses the distribution of seats flown by each class of aircraft in the previous year to estimate how many new seats, and therefore new aircraft in each class, will meet the future demand. This accounts for both aircraft needed to replace retirements from the NPV-based calculations (retirements) and to meet growth in demand ($\text{fleet\_needed}_i$). This approach does not account for delay between the order and the delivery of the aircraft; the module assumes that the airline has suitably placed orders in advance of the delivery.

New aircraft acquisitions in each class are the sum of two quantities: the number of aging aircraft being retired and the increase in required seat capacity to serve increasing market demand. The sums of these two quantities for each class are constrained by a production limit calculated for each class of aircraft. In other words, a classwise upper limit on number of aircraft produced in the current year constrains the number of acquisitions of aircraft within each class. These production limits are based on regression of historical data on actual deliveries of the aircraft used in the FLEET. Using these limits ensures the airline always has enough aircraft to meet the growing demand in its network. Note that, although the FLEET does not track individual aircraft, it does keep a record of how many aircraft of each class and technology age the airline has.

### D. Ticket Pricing

With the allocation problem in the FLEET attempting to simulate a profit-seeking airline, a ticket price model is an important feature. The ticket price module in the FLEET uses a relatively simple approach driven by data obtained from the BTS for the years 2005–2010. For each class of aircraft, a regression model determines a yield, or the profit margin per passenger nautical mile, that airlines collected based on reported ticket prices. This approach does not distinguish among ticket fare classes; it provides an average price per passenger. In addition, this approach does not address ticket price differences in specific city-pair markets; however, it does result in yield per passenger/nautical-mile values that balances aircraft size and segment range. For shorter routes, the model results in higher yield for smaller aircraft, reflecting the passengers' willingness to pay a higher fare for the increased frequency of service available from these smaller aircraft. For longer routes, the model results in higher yield for larger aircraft, reflecting the passengers' desire to pay a higher fare for the increased size (and perceived comfort) on longer flights [47].

In addition to a key role in the allocation problem's objective function, estimating ticket prices enables the calculation of elastic demand, which reflects the change in passenger demand in response to ticket price variations (see Sec. IV.A). To do this, the demand elasticity function in the FLEET calculates the year-over-year change in average ticket prices for each route based upon the previous years' allocation results. The average ticket price for each route changes every year because of the variation in the type of aircraft and number of trips flown on each route. Note that the FLEET uses historical demand for the years 2005–2008 and hence the demand elasticity factor is not accounted for during these years. In other words, passenger demand growth is not modeled for the years of 2005–2008; instead, the allocation problem in the FLEET uses historical demand information obtained from the BTS for those years. For the years of 2009–2050, the passenger demand growth in the FLEET is modeled as a combination of inherent demand and elastic demand. The previous years' allocation describes the number of each aircraft type operated on every route in the airline network. The FLOPS cost calculations provide the operating cost of each aircraft type $k$ on each route $j$. These two sources of information allow calculation of a

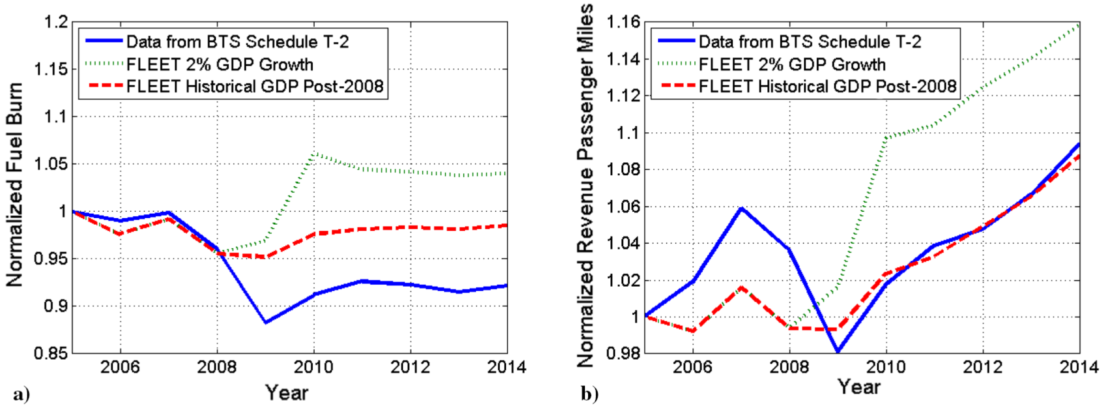



**Fig. 6 Comparison of a) fuel burn and b) revenue passenger miles.**



weighted average operating cost per passenger on route $j$. With the concept of a single large airline operating all of the aircraft in the FLEET network, the modeling approach here uses the idea that the airline will charge the same ticket price to any passenger flying on a route for the same aircraft type, regardless of technology group/age. Hence, the cost per passenger $\mathrm{Cost}_{k,j}$ estimate used in the calculation of ticket prices [see Eq. (7)] uses the weighted cost of all aircraft in the different technology groups for each aircraft class.

Equation (7) gives the process of calculation of ticket prices:

$$\mathrm{Price}_{k,j} = \mathrm{Cost}_{k,j} + \mathrm{Yield}_{k,j} \times \mathrm{Range}_j \tag{7}$$

The terms in Eq. (7) are the profit margin per passenger nautical mile for aircraft type $k$ on route $j$, $\mathrm{Yield}_{k,j}$, the ticket price per passenger for aircraft type $k$ on route $j$, $\mathrm{Price}_{k,j}$, the total operating cost per passenger for aircraft type $k$ on route $j$, $\mathrm{Cost}_{k,j}$, and the distance between the origin and destination in nautical miles for route $j$, $\mathrm{Range}_j$.

## V. Studies and Results

Studies using the FLEET account for airline operations, their economics, and market dynamics to assess aviation's environmental impacts in response to how airlines make use of new technologies and new aircraft. In the studies presented here, $CO_2$ is the environmental impact of interest. Due to growing demand, no single technological advancement will be sufficient to limit emissions growth. The studies presented examine the effects of inclusion of new aircraft technology and/or alternative fuels in an incremental fashion, with each scenario within a study building on top of the previous one. With reference to Fig. 1, the following studies demonstrate the FLEET's ability to assess environmental impacts of aviation:

1) For advanced aircraft technology, this study compares two different scenarios of advanced technology aircraft being introduced in the airline fleet against a "baseline" scenario in which no such aircraft are introduced. In one scenario, advanced technology tube-and-wing aircraft (the N + 3 generation) are introduced, whereas in another, the hybrid wing–body (HWB) aircraft is introduced. Details of the setup for this scenario are given in the following.

2) In this scenario of a low-carbon fuel mandate, the airline is required to use biofuels as an increasing fraction of its total fuel consumption through the period of simulation.

### A. Sanity Check

Before conducting studies of interest, some assessment of the plausibility of the FLEET's predictions is warranted. The FLEET simulation runs are difficult to validate due to the large number of modeling parameters included in the simulation and the inability to select values for all of the parameters needed to replicate the historical conditions and airline operations of recent years. However, to compare the results obtained from the FLEET with data from the airline industry, this section compares the values of a normalized fuel burn and normalized revenue passenger nautical miles (both relative to 2005) from the baseline FLEET run with normalized fuel burn values (relative to 2005) obtained from BTS Schedule T2 [48] for U.S. carriers in the "passenger configuration" only; Fig. 6 shows this comparison.

The two FLEET results shown in this figure differ only in the manner in which market demand is set. For years 2005–2008, where the FLEET uses historical demand data from the Bureau of Transportation Statistics, the normalized fuel consumption values resulting from the FLEET are reasonably close to the historical fuel consumption (Fig. 6a). After 2008, when the FLEET calculates its own demand based on the specified GDP growth rates and price elasticity, the FLEET-predicted fuel consumption is higher than the reported data. When using the historical GDP values (but not historical demand) after 2008, the FLEET's normalized fuel consumption prediction shows slightly higher fuel consumption than those published by the BTS; note that these are normalized and not absolute values, and they only serve to show the trend of fuel consumption change over the years.

Figure 6b compares the FLEET's results with historical data using another metric: that of total revenue passenger miles. In this case, the FLEET's airline serves slightly lower revenue passenger miles for the years 2005–2008, but thereafter, the FLEET's predictions are remarkably similar to historical data. Note again that these are normalized values, and hence show just the trend and not the true values of revenue passenger miles carried by the airlines. Given the abstractions used in the FLEET, the values given by this tool are understandably smaller than real network data. The historical network data are obtained from BTS Schedule T2 as in the case of the aforementioned fuel burn comparison. Also, the FLEET's estimates for the case where the GDP grows by a constant 2% per annum are higher. For comparison, the average GDP growth rate in the United States for years 2005–2014 was approximately 1.5% [49].

These "sanity check" results provide some assurance that the trends associated with the FLEET predictions are reasonable, and it demonstrates how the FLEET prediction trends may deviate from actual data when provided with a somewhat inaccurate parameter (here, the 2% per year GDP growth rate).

### B. Discussion of Results

#### *1. Study 1: Advanced Aircraft Technology*

Many advanced technologies, future aircraft configurations, and policies have the potential to influence the fleet-level $CO_2$ emissions from commercial aviation; however, a combination of these options is the most promising approach to obtain a substantial change in the current trend of increasing $CO_2$ emissions. This study is an effort to quantify the effects of advanced aircraft technologies on fleet-level environmental emissions under three different scenarios of technology availability.

To provide a starting point, the first scenario reflects a typical ongoing fleet renewal used by the airline, with technology stagnating with the new-in-class aircraft. The following ideas describe this scenario:

1) The FLEET simulations start in the year 2005 and run to 2050.

2) Jet fuel prices increase according to the Energy Information Administration (EIA) reference fuel price (increases slightly above predicted inflation) [50].

3) The GDP growth is 2% per annum, starting in 2009. (The FLEET uses historical demand data for 2005–2008. A 2% GDP growth rate leads to an annual inherent demand growth rate of 2.8%.)

4) No airport capacity constraints are imposed.

5) Only representative-in-class, best-in-class, and new-in-class aircraft are available. No future-in-class aircraft enter service.

6) No biofuel is introduced.

Scenario 2 builds upon the previous one, using the same setup, except that future-in-class aircraft become available to the airline at their respective EIS dates. These are tube-and-wing aircraft that make use of improving technologies and are generally more fuel efficient than the new-in-class aircraft. The impact of these future-in-class aircraft should be apparent in the later years in the FLEET simulation.

Finally, scenario 3 provides yet another alternative of technology evolution. The preceding scenario uses the conventional tube-and-wing aircraft types, including for the future-in-class aircraft (except for the FLEET version of the Massachusetts Institute of Technology double-bubble concept), which are yet to be developed. However, other advanced concepts for future commercial aircraft exist, with one of them being the hybrid wing–body design. The HWB promises many benefits, such as lower noise signature and lower $CO_2$ emissions, compared to a similar-capacity tube-and-wing concept. To model the potential impacts of a HWB aircraft on fleet-level metrics, and to compare these with the impacts of operating conventional tube-and-wing aircraft of the same class and technology level, this scenario introduces a HWB aircraft to the FLEET airline instead of a large twin-aisle aircraft as the new-in-class and future-in-class aircraft in class 6. All other aircraft are the same as those in the default setup of the FLEET simulations. Also, the new-in-class HWB aircraft is introduced into service in 2025, allowing for five years of additional development time for this aircraft compared with the 2020 EIS of the large twin-aisle new-in-class aircraft; the future-in-class HWB is introduced in 2035 compared with the 2030 of the large twin aisle for the same reason. Except for the introduction of HWB aircraft and their modified EIS date, this scenario is identical to the other two scenarios in this study.

*Results of the Advanced Aircraft Technology Study*: Figures 7a and 7b show the normalized demand served by the airline and $CO_2$ emissions in study 1. These figures show that the introduction of a HWB aircraft results in no significant difference between the demand levels when compared to the case with large twin aisle (LTA) aircraft available. The LTA, which enters service starting 2020, needs more than a decade to have enough fleet penetration to begin to show the effect of lowered $CO_2$ emissions. In contrast, the HWB, which enters service in 2025, leads to reduced emissions relatively more quickly, with emissions being lower than in scenario 1, beginning 2033. Despite this, the advantages of using an HWB aircraft disappear in the years after 2040. This could be because the large class 6 aircraft are used on few trips, mainly being reserved for long-distance international routes. For example, in both scenarios 1 and 3, the class 6 aircraft made 1172 trips in year 2050, compared with scenario 2 in which the number was 1112.

The demand served in all three scenarios is nearly identical, which helps make a direct comparison between them. Thus, the difference between the scenarios is due to the airlines' choices on aircraft utilization rather than market demand. This is fortunate in the case of a direct comparison between two different aircraft models; in this case, the HWB aircraft does not promise much benefit over the traditional tube-and-wing aircraft in the long run. Note that the model of the HWB aircraft has an identical number of seats as the LTA. With better models of these aircraft being available, the economics related to the use of aircraft might change, leading to different decision outcomes from the resource allocation problem. This, in fact, is the strength of the FLEET: that the allocation problem is responsive to available aircraft and can change which aircraft to fly and where in an attempt to increase profit.

### 2. *Study 2: Low-Carbon Fuel Mandate*

This study seeks to understand the potential environmental benefits of using biofuels. Of the three scenarios, the first two are identical to those in the advanced aircraft technology study. Scenario 3, however, builds on top of the first two, with the exception that the airline follows a mandated use of biofuels with lower $CO_2$ equivalent life-cycle emissions than petroleum-based Jet-A. Low-carbon biofuels are likely to become available at a gradually growing pace. In this scenario, the airline in the FLEET must use biofuels as 2% of its total fuel in 2023 and, by 2050, as much as 50% of the airline's fuel consumed must be biofuel. In the FLEET simulation, the effect is as if this percentage were mandated; the airline has to use the specified amount in any given year. This scenario assumes the biofuel is a "drop-in," requiring no substantial modification of any aircraft in the airline's fleet.

To consider the effect of using biobased jet fuel on $CO_2$ emissions, comparisons must use fuel life-cycle $CO_2$ equivalent values because a drop-in biofuel would produce essentially the same "tailpipe" emissions as petroleum-based Jet-A; but, over the life cycle, the biofuel feedstock would absorb $CO_2$ while growing. In the FLEET, for conventional petroleum-based Jet-A, the ratio of life-cycle $CO_2$ per unit of fuel is 3.67, whereas for biofuel, the ratio is 1.05. Also, the FLEET assumes that the biofuels will be more expensive when they are first introduced and their price will drop gradually. To account for this assumption, while preventing the introduction of any addition price effects, the FLEET sets the price of biofuel to be twice that of jet fuel throughout the period of the simulation. This scenario uses tube-and-wing aircraft for all four generations of aircraft technology.

*Results of the Low-Carbon Fuel Study*: Figure 8a shows the growth of demand in all three scenarios over the simulation period. Under all three scenarios, demand growth follows the same curve until 2025, when the first of the future-in-class aircraft become available in

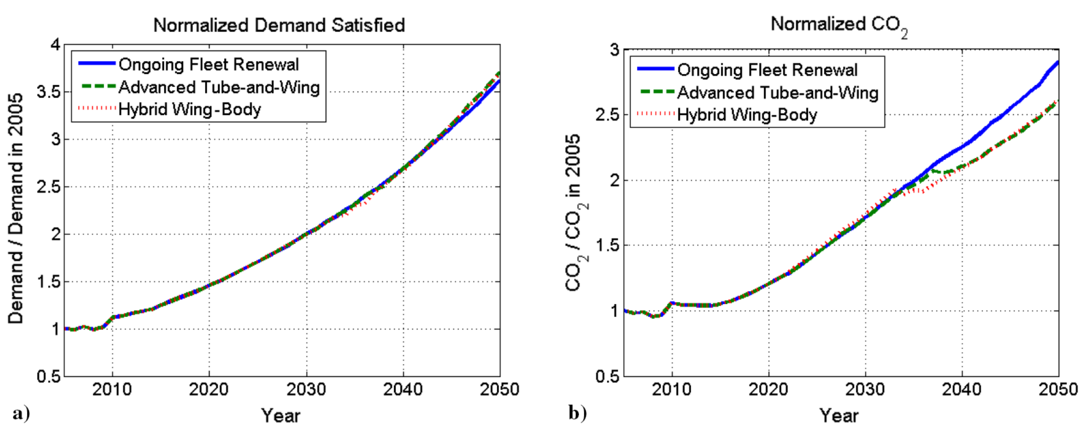



**Fig. 7 Normalized a) demand and b) $CO_2$ evolution for advanced aircraft technology study.**

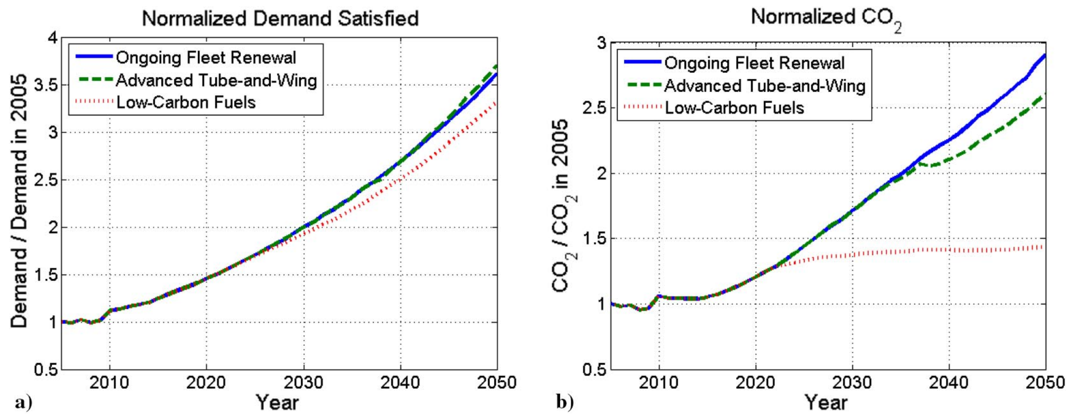
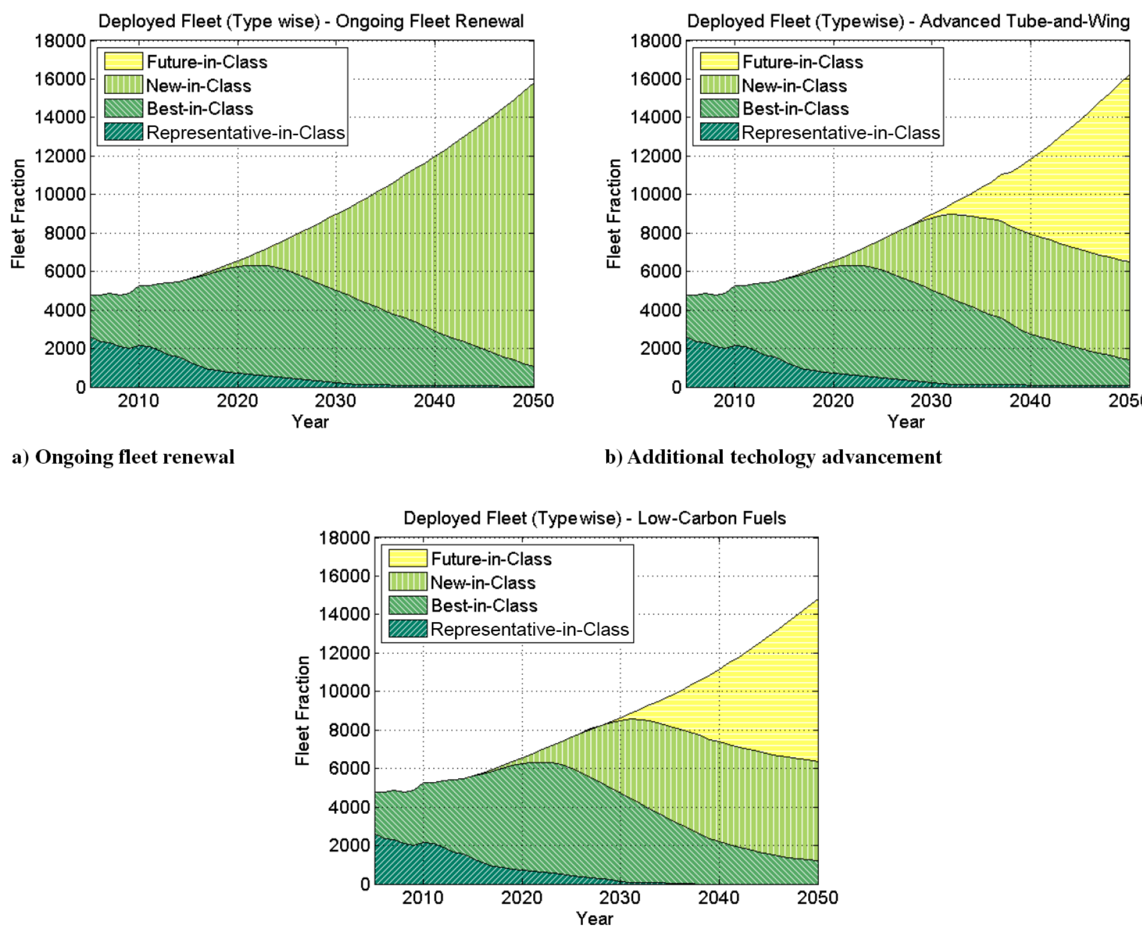



**Fig. 8 Normalized a) demand and b) $CO_2$ evolution under low-carbon mandate study.**




**a) Ongoing fleet renewal**

**b) Additional techology advancement**

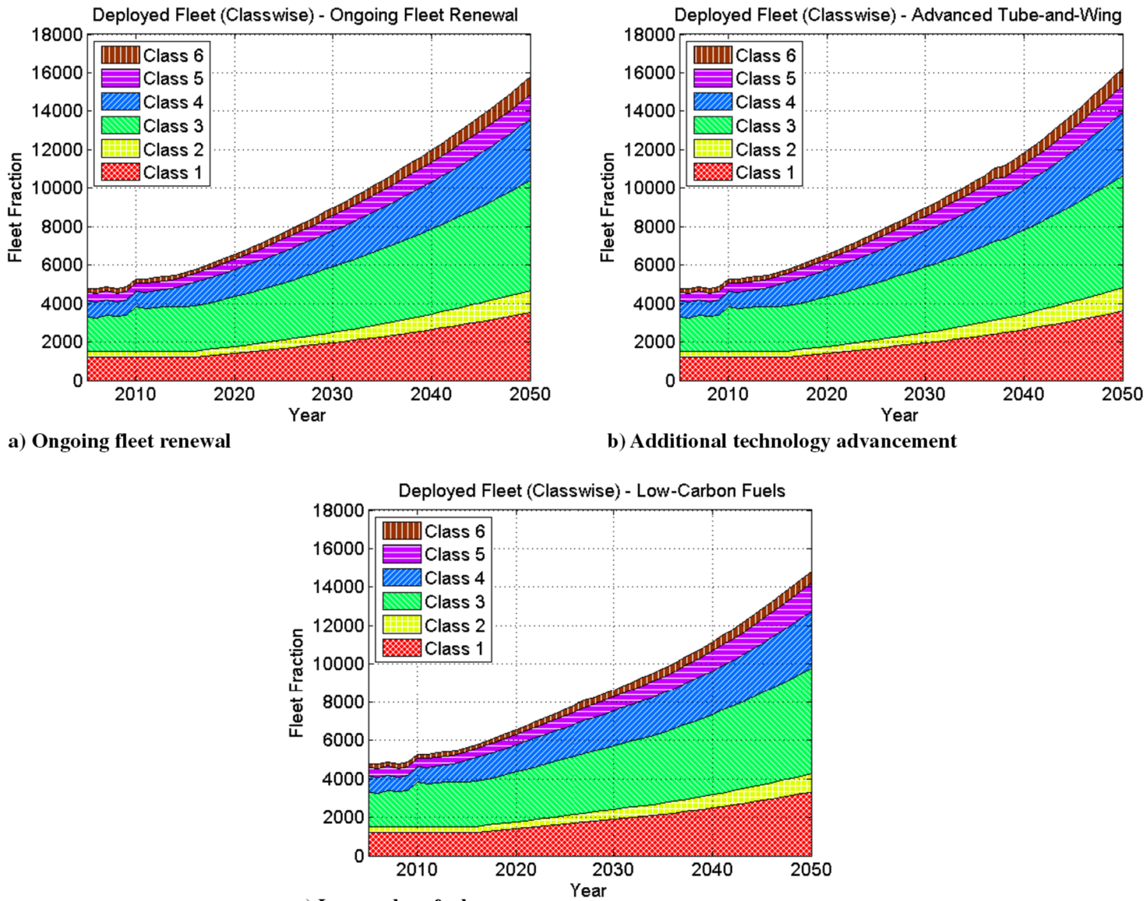
**c) Low carbon fuels**

**Fig. 9 Fleet by type evolution under different scenarios.**

scenarios 2 and 3. The future-in-class aircraft available in scenario 2 provide different costs for the airline, so the demand variations are due to price-elasticity effects. In scenario 2, the change in demand served is small relative to scenario 1; in 2050, the airline in the additional technology scenario serves a slightly greater demand of about 2.35% compared to scenario 1. This can be explained by the future-in-class aircraft that are more economically efficient than those it replaces: in part, due to their lower fuel burn. However, the $CO_2$ emissions plot shows substantial differences among the scenarios (Fig. 8b). For scenario 2, the emissions in 2050 are 10.44% lower than in scenario 1. This shows that the future-in-class aircraft help the airline reduce its total emissions despite serving higher demand.

The variation of demand served over the years under the low-carbon fuels scenario differs notably from the other two scenarios. The mandated use of biofuels starting in 2023 starts to increase the airline operating costs because of the higher biofuel cost. This leads to an increase in ticket prices and a corresponding drop in demand due to price-demand elasticity. By 2050, the demand served is 8.13% lower than the ongoing fleet renewal scenario. The advantage of using biofuels, however, appears via the significantly lower $CO_2$ emissions in this scenario that, in 2050, are 50.93% lower than scenario 1. Clearly, introduction of low-carbon fuels would be highly advantageous for the goal to reduce aviation carbon emission.

Figures 9a–9c show the total number of aircraft used by the airline, broken into the constituent technology types, in each of the three




a) **Ongoing fleet renewal**

b) **Additional technology advancement**

c) **Low carbon fuels**

**Fig. 10 Fleet by class evolution under different scenarios.**



scenarios. The ongoing fleet renewal scenario has no future-in-class aircraft; Fig. 9a has no future-in-class aircraft displayed and shows that all fleet growth in the future is the airline buying new-in-class aircraft. In the additional tube-and-wing technology scenario, the airline begins to use future-in-class aircraft as soon as they become available. However, in this scenario, the introduction and use of these future-in-class aircraft does not speed up the retirement of best-in-class aircraft. This is because some of the best-in-class aircraft are still relatively new; given the penalty associated with early retirement of aircraft, it would not be economically beneficial to replace them any more rapidly than in scenario 1 where no future-in-class are available. Moreover, the limit to the number of future-in-class aircraft produced in a given year means that the airline cannot buy as many aircraft as it needs.

The classwise distribution trend is similar across all three scenarios (Figs. 10a–10c). Although not very evident from these figures, the fraction of total trips flown by classes 1, 2, and 4 slowly but gradually increases as the year advances, coming at the expense of the fraction of trips by class 3. The trends here have a few differences from other published future fleet forecasts (e.g., Boeing Airplane Commercial Market Outlook [51]). Two notable differences are that the FLEET airline continues to use a large number of the class 1 and 2 regional jets and that the FLEET does not add a large percentage of wide-body aircraft, i.e., classes 5 and 6. Much of this is due to the combination of the ticket price model that favors smaller aircraft on shorter routes and the network that focuses upon operations touching the United States, so the FLEET airline is not reflective of the entire world market. With many short-range routes in the network, comparatively few long-range transoceanic routes, and no airport capacity constraints enforced in these simulations, the mix of aircraft in the FLEET airline is plausible.

The results present here are a small portion of the results that FLEET can generate. For example, Figs. 9 and 10 show the counts of the actual number of aircraft flown. No figures accompany this quoted number of trips flown, but they can be easily generated to show the trend over the period of simulation. The FLEET also generates and stores additional information such as profits generated and aircraft allocation to routes, as this information is useful for more detailed analysis of the modeled scenarios.

### C. Future Enhancements

The FLEET uses several abstractions to model the air transportation system and its various complex social, economical, and technological interactions. For example, the aircraft acquisition module in the FLEET assumes that the airline correctly forecasted its need and ordered aircraft so they were available exactly when needed. Furthermore, the modeling in the FLEET neither accounts for details of aircraft scheduling, which could help assess the propagation of capacity constraints throughout the network, nor consider improvements in airline operations. All these limitations would form part of future research and development efforts in the FLEET.

Currently under development is a model of the FLEET that divides the airlines operating in the U.S. air transportation network into two airlines [33], accounting for the presence of competition in the market. The two airlines are classified as low cost and legacy, based on their business model. Supporting this model is exploration of application of game theory as a means to modeling interaction of the two airlines.

The models within the FLEET system-dynamics framework interact by exchanging information. The airline's resource allocation decisions and aircraft acquisition decisions are done sequentially by separate models. Future efforts will explore how these two models can be made to interact such that the airline's aircraft acquisition decisions take into account its utilization of aircraft. This could be a way to model the real-world dynamic of the time delay between aircraft orders and delivery.

## VI. Conclusions

This paper presents the development of a model that predicts the fleetwide environmental impact, concentrating in this work on $CO_2$ emissions, of new aircraft concepts and technologies under fuel policy scenarios. The Fleet-Level Environmental Evaluation Tool goes beyond the aircraft-specific technological improvements reflecting relationships between emissions, market demand, ticket prices, and aircraft fleet composition over several years. At its core is an optimization problem that allocates aircraft to routes, providing a limited but useful simulation of the decisions of a profit-seeking airline. Taken together, these features enable the FLEET to make unique contributions to the difficult task of useful forecasting of the impact of aircraft technology and utilization on emissions.

Two studies executed using the FLEET (one on advanced aircraft technology introduction and a second on aggressive low-carbon fuel policy) suggest that aviation $CO_2$ emissions do not reach the levels associated with the stated goals of many organizations. With the prediction of served demand in 2050 at a level of over three times that of 2005, the $CO_2$ emissions increase only to a level about 1.5 times that of 2005. This demonstrates that, even if the individual aircraft operated in 2050 are far more fuel efficient than those operated in 2005, considering the way that airlines operate and how this impacts passenger demand over time is very important for predictions of future fleet-level environmental impacts.

## Acknowledgments

Much of this work was supported by NASA Cooperative Agreement NNX07AO13 with support from NASA Subsonic Fixed-Wing program and from the Environmentally Responsible Aviation program. The authors thank the following three individuals who together served to provide technical monitoring for the research effort summarized in this report: Bill Haller of NASA John H. Glenn Research Center, and Phil Arcara and Craig Nickol of NASA Langley Research Center. Their input and guidance were critical to the success of the work.

## References

[1] "The Economic Impact of Civil Aviation on the U.S. Economy," Federal Aviation Administration, Dec. 2009, https://www.faa.gov/air_traffic/publications/media/FAA_Economic_Impact_Rpt_2009.pdf [accessed Oct. 2016].

[2] "Reducing Transport Greenhouse Gas Emissions: Trends and Data 2010," International Transport Forum, April 2010 [Online], http://www.itf-oecd.org/reducing-transport-greenhouse-gas-emissions-trends-and-data-2010 [accessed Oct. 2016].

[3] Block, B., "Aviation Industry Outlines Ambitious Climate Goals," Worldwatch Inst., June 2009, http://www.worldwatch.org/node/6149 [accessed Oct. 2016].

[4] Del Rosario, R., Wahls, R., Follen, G., and Madavan, N., "Subsonic Fixed Wing Project," *NASA Fundamental Aeronautics Program 2011 Technical Conference*, Cleveland, OH, March 2011.

[5] "A Global Approach to Reducing Aviation Emissions. First Stop: Carbon-Neutral Growth from 2020," International Air Transport Association, Nov. 2009 [Online], http://www.aeronautics.nasa.gov/pdf/subsonic_fixedwing.pdf [accessed Oct. 2016].

[6] 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, 1995, pp. 211–232.

[7] Barnhart, C., Farahat, A., and Lohatepanont, M., "Airline Fleet Assignment with Enhanced Revenue Modeling," *Operations Research*, Vol. 57, Jan.–Feb. 2009, pp. 231–244.
doi:10.1287/opre.1070.0503

[8] Rexing, B., Barnhart, C., Kniker, T., Jarrah, A., and Krishnamurthy, N., "Airline Fleet Assignment with Time Windows," *Transportation Science*, Vol. 34, No. 1, Feb. 2000, pp. 1–20.
doi:10.1287/trsc.34.1.1.12277

[9] Lohatepanont, M., and Barnhart, C., "Airline Schedule Planning: Integrated Models and Algorithms for Schedule Design and Fleet Assignment," *Transportation Science*, Vol. 38, Feb. 2004, pp. 19–32.
doi:10.1287/trsc.1030.0026

[10] Huang, A. S., and Schleicher, D. R., "Futuristic US Flight Demand Generation Approach Incorporating Fleet Mix Assumptions," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, AIAA Paper 2008-6678, 2008.

[11] Reynolds, T. G., Barrett, S., Dray, L. M., Evans, A. D., Kohler, M. O., Morales, M. V., Schafer, A., Wadud, Z., Britter, R., Hallam, H., and Hunsley, R., "Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Project," *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, AIAA Paper 2007-7751, Sept. 2007.

[12] Vera-Morales, M., and Hall, C., "Modeling Performance and Emissions from Aircraft for the Aviation Integrated Modeling Project," *Journal of Aircraft*, Vol. 47, No. 3, 2010, pp. 812–819.
doi:10.2514/1.44020

[13] Dray, L., Evans, A., and Schafer, A., "The Impact of Economic Emissions Mitigation Measures on Global Aircraft Emissions," *13th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2010-9250, Sept. 2010.

[14] Winchester, N., Wollersheim, C., Clewlow, R., Jost, N., Paltsev, S., Reilly, J., and Waitz, I., "The Impact of Climate Policy on US Aviation," *Journal of Transport Economics and Policy (JTEP)*, Vol. 47, No. 1, 2013, pp. 1–15.

[15] Pfaender, H., Jimenez, H., and Mavris, D., "Environmental Impact Analysis of Fleet and Policy Options of Aircraft Operators Using System Dynamics," *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, AIAA Paper 2010-9251, Sept. 2010.

[16] Kernstine, K., Boling, B., Bortner, L., Hendricks, E., and Mavris, D., "Designing for a Green Future: A Unified Aircraft Design Methodology," *Journal of Aircraft*, Vol. 47, No. 5, 2010, pp. 1789–1797.
doi:10.2514/1.C000239

[17] Hollingsworth, P., Pfaender, H., and Jimenez, H., "A Method for Assessing the Environmental Benefit of Future Aviation Technologies," *26th International Congress of the Aeronautical Sciences*, ICAS2008-P10.2, Anchorage, AK, Sept. 2008.

[18] Sherry, L., Ferguson, J., Hoffman, K., and Donohue, G., "The Economics of the Airline Transportation System," Center for Air Transportation Systems Research, George Mason Univ., NRA NNH09ZEA00IN-APIR, 2011.

[19] Christensen, C., Anthony, S., and Roth, E., "Disruption Spreads Its Wings," *Seeing What's Next*, 1st ed., Harvard Business School Press, Brighton, MA, 2004, pp. 129–153.

[20] Kim, B. Y., Fleming, G. G., Lee, J. J., Waitz, I. A., Clarke, J.-P., Balasubramanian, S., Malwitz, A., Klima, K., Locke, M., Holsclaw, C. A., Maurice, L. Q., and Gupta, M. L., "System for Assessing Aviation's Global Emissions (SAGE), Part 1: Model Description and Inventory Results," *Transportation Research, Part D: Transport and Environment*, Vol. 12, No. 5, 2007, pp. 325–346.

[21] Lee, J. J., Waitz, I. A., Kim, B. Y., Fleming, G. G., Maurice, L., and Holsclaw, C. A., "System for Assessing Aviation's Global Emissions (SAGE), Part 2: Uncertainity Assessment," *Transportation Research, Part D: Transport and Environment*, Vol. 12, No. 6, 2007, pp. 381–395.

[22] "Aviation Environmental Portfolio Management Tool for Economics (APMT-Economics) and its Application in the CAEP/8," Committee on Aviation Environmental Protection, 2010 [Online], http://web.mit.edu/aeroastro/partner/reports/caep8/caep8-economics.pdf [accessed Oct. 2016].

[23] Pfaender, H., and Mavris, D., "Technology Effects on Aircraft Fleet Decisions," *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, AIAA Paper 2011-6926, 2011.

[24] Pfaender, H., and Mavris, D., "Effect of Fuel Price on Aviation Technology and Environmental Outcomes," *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, AIAA Paper 2012-5467, 2012.

[25] Tetzloff, I., and Crossley, W., "Measuring Systemwide Impacts of New Aircraft on the Environment," *Journal of Aircraft*, Vol. 51, No. 5, 2014, pp. 1483–1489.
doi:10.2514/1.C032359

[26] Truong, P., and Post, J., "Assessing the Environmental Benefits of NextGen Improvements in the National Airspace System," *Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2013-4314, 2013.
doi:10.2514/6.2013-4314

[27] Waitz, I., Townsend, J., Cutcher-Gershenfeld, J., Greitzer, E., and Kerrebrock, J., "Aviation and the Environment," *Partnership for Air Transportation Noise and Emissions Reduction*, Report to the United States Congress, Dec. 2004 [Online], http://web.mit.edu/aeroastro/partner/reports/congrept_aviation_envirn.pdf [accessed Oct. 2016].

[28] 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)*, AIAA Paper 2009-6979, Sept. 2009.

[29] Zhao, J., Agusdinata, D. A., and DeLaurentis, D., "System Dynamics Fleet Forecasting with Technology, Emission, and Noise Goals," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2009-7040, Sept. 2009. doi:10.2514/6.2009-7040

[30] Zhao, J., Tetzloff, I. J., Tyagi, A., Dikshit, P., Mane, M., Agusdinata, D. A., Crossley, W. A., and DeLaurentis, D., "Assessing New Aircraft and Technology Impacts on Fleet-Wide Environmental Metrics Including Future Scenarios," *48th Aerospace Sciences Meeting*, AIAA Paper 2010-282, Jan. 2010. doi:10.2514/6.2010-282

[31] Mane, M., Agusdinata, D. A., Crossley, W. A., and DeLaurentis, D. A., "Fleet-Wide Environmental Impacts of Future Aircraft Technologies," *10th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2010-9207, Sept. 2010. doi:10.2514/6.2010-9207

[32] Moolchandani, K. A., Agusdinata, D. B., Mane, M., Crossley, W. A., and DeLaurentis, D. A., "Impact of Development Rates of Future Aircraft Technologies on Fleet-Wide Environmental Emissions," *11th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2011-6843, Sept. 2011. doi:10.2514/6.2011-6843

[33] Moolchandani, K. A., Agusdinata, D. B., DeLaurentis, D. A., and Crossley, W. A., "Airline Competition in Duopoly Market and Its Impact on Environmental Emissions," *12th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2012-5466, Sept. 2012. doi:10.2514/6.2012-5466

[34] Moolchandani, K. A., Agusdinata, D. B., DeLaurentis, D. A., and Crossley, W. A., "Developing Optimal Airline Fleets Under Environmental and Capacity Constraints," *28th International Congress of the Aeronautical Sciences (ICAS)*, ICAS Paper 2012-7.10.1, Brisbane, Australia, Sept. 2012.

[35] Moolchandani, K. A., Agusdinata, D. B., DeLaurentis, D. A., and Crossley, W. A., "Assessment of the Effect of Aircraft Technological Advancement on Aviation Environmental Impacts," *51st Aerospace Sciences Meeting*, AIAA Paper 2013-0652, Jan. 2013. doi:10.2514/6.2013-652

[36] *Airline Origin and Destination Survey (DB1B)* [online database], U.S. Dept. of Transportation, Bureau of Transportation Statistics, http://www.transtats.bts.gov/DatabaseInfo.asp?DB_ID=125&Link=0 [retrieved Dec. 2012].

[37] Crossley, W. A., and DeLaurentis, D. A., "System-of-Systems Approach for Assessing New Technologies in NGATS," Purdue Univ., West Lafayette, IN, 2013.

[38] *The Airline Data Project* [online database], Massachusetts Inst. of Technology Global Airline Industry Program, Cambridge, MA, http://web.mit.edu/airlinedata/www/default.html [retrieved Aug. 2010].

[39] *General Algebraic Modeling System*, Software Package, Distribution 21.2, GAMS Development Corp., Washington, D.C., Sept. 2003.

[40] McCarl, B. A., "GAMS User Guide: 2004," Ver. 21.3, GAMS Development Corp., Washington, D.C., Jan. 2004.

[41] Pulles, J. W., Lowe, S., van Drimmelen, R., Baarse, G., and McMahon, P., "Aviation Emissions and Evaluation of Reduction Options, Part I: Description of the AERO Modelling System," *Ministry of Transport, Public Works and Water Management*, Air Transport Infrastructure Policy, Den Haag, The Netherlands, Dec. 2000 [Online], http://www.dlr.de/consave/library/Aero-Model.pdf [accessed Oct. 2016].

[42] Keating, E., and Dixon, M., "Investigating Optimal Replacement of the Aging Air Force Systems," *Project Airforce*, RAND Corp., Santa Monica, CA, 2003.

[43] Keating, E., Snyder, D., Dixon, M., and Loredo, E., "Aging Aircraft Repair-Replacement Decisions with Depot-Level Capacity as a Policy Choice Variable," *Project Air Force*, RAND Corp., Santa Monica, CA, 2005.

[44] Pfaender, H., and Mavris, D., "Technology Effects on Aircraft Fleet Decisions," *AIAA Aviation Technology and Operations (ATIO)*, AIAA Paper 2011-6926, 2011. doi:10.2514/6.2011-6926

[45] Circular A-94 Appendix C, "Office of Management and Budget," The White House [Online], http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c [accessed Oct. 2016].

[46] Dixon, M., "The Maintenance Cost of Aging Aircraft—An Insight from Commercial Aviation," *RAND Project Air Force*, RAND Corp., Santa Monica, CA, 2006, pp. 48–49, Chap. 4.

[47] Govindaraju, P., and Crossley, W. A., "Profit Motivated Airline Fleet Allocation and Concurrent Aircraft Design for Multiple Airlines," *Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA Paper 2013-4391, Aug. 2013. doi:10.2514/6.2013-4391

[48] Air Carrier Summary, T2: U.S. Air Carrier TRAFFIC and Capacity Statistics by Aircraft Type, Bureau of Transportation Statistics, [Online], http://www.transtats.bts.gov/Fields.asp?Table_ID=254 [accessed Dec. 2012].

[49] Economic Research Service, International Macroeconomic Data Set [online database], U.S. Dept. of Agriculture, http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx [retrieved July 2016].

[50] *Annual Energy Outlook 2011* [online database], 2011, U. S. Energy Information Administration, www.eia.gov/forecasts/aeo/ [accessed Oct. 2016].

[51] *Boeing Commercial Airplanes Current Market Outlook 2011*, The Boeing Company, 2011 [Online], http://www.boeing.com/commercial/market/ [accessed 2016].