MEASURING SYSTEM-WIDE IMPACTS OF NEW AIRCRAFT ON THE ENVIRONMENT

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Abstract

Many efforts to mitigate the environmental impact of aviation – like NASA's Subsonic Fixed Wing (SFW) Project – place high importance on reducing fuel burn, nitrous oxide (NO_X) emissions and noise of future aircraft. However, the environmental and economic impact of a new aircraft is not solely a function of the aircraft's performance, but also how airlines use new aircraft along with other existing aircraft to satisfy the passenger demand for air transportation.

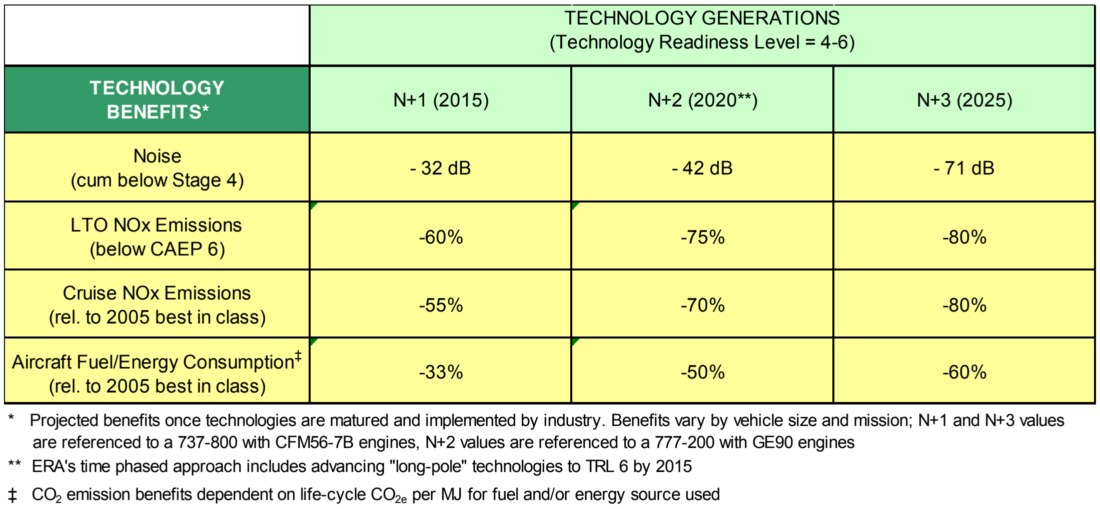
In this paper, an optimization problem allocates existing and future aircraft to routes representing commercial air transportation within or to / from the United States. Examining fleet-level environmental metrics from the optimization problem helps assess how aircraft meeting NASA's SFW goals could impact fleet-level environmental goals established by the International Air Transport Association (IATA). Results indicate that goals set forth by IATA for 2050 CO_2 emissions appear attainable with an aircraft allocation to minimize fuel burn and future aircraft that meet the NASA N+2 and N+3 SFW fuel consumption goals.

1 Introduction and Motivation

The NASA Subsonic Fixed Wing (SFW) Project's key research areas and goals emphasize the importance of reducing both noise and emissions in future generations of aircraft. In the SFW Project, NASA uses a nomenclature to indicate the "age" of future aircraft and aircraft technologies. The "N" generation of aircraft are today's in-production aircraft. The next major generation of aircraft are N+1, which are followed by the N+2 generation, and then by the N+3 generation. Based on the SFW's goals originally presented in 2008 [1] and then subsequently updated [2], NASA hopes to reduce individual aircraft fuel burn by 33% compared today's current aircraft and landing and takeoff nitrogen oxide (LTO NO_X) emissions by 60% relative to the CAEP/6 limits in the N+1 generation aircraft, which have a notional entry in service date of 2015. With initial operating capability by 2020, NASA's N+2 generation aircraft goals hope to reduce fuel burn by 50% compared to today's aircraft and LTO NO_X by 75% from the CAEP/6 limits. The goals for the N+3 generation aircraft, with an expected entry in service between 2030 and 2035, hope to reduce fuel burn by 60% and LTO NO_X by 80%. Additionally, these future generation aircraft hope to have reduced noise and shorter field lengths for landings and departures. [2] Figure 1 summarizes the NASA SFW goals for noise, LTO NO_X emissions, cruise NO_X emissions, and fuel burn.

In June 2009, the International Air Transport Association (IATA) released fleet-level emissions goals for aviation, rather than individual aircraft emissions goals. IATA's emission goals include three main components: [3]

1. A cap on aviation CO_2 emissions from



	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
TECHNOLOGY BENEFITS*	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption[‡] (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission; N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

Fig. 1 Summary of NASA SFW Goals (image from [2])

2020,

2. An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020,
3. A reduction in CO_2 emissions of 50% by 2050, relative to 2005 levels.

The goals set forth by NASA are for individual aircraft. However, airlines utilize new aircraft in concert with existing aircraft; therefore, to properly assess the impact of these new generations of aircraft on the environment, they must be integrated into the fleet. With the development of a tool that calculates fleet-level metrics such as carbon dioxide (CO_2) emissions, LTO and cruise NO_X emissions, and total area inside the 65db Day/Night Level (DNL) noise contour at airports, one can assess how future generations of aircraft and new aircraft technologies impact the fleet's emissions and noise levels. Whereas aircraft metrics evaluate the performance of a single aircraft model, a fleet-level metric encapsulates the entire aircraft fleet – new and existing aircraft and how airlines use them – and gives a high-level view of how the introduction of a new aircraft of aircraft technology affects the entire system. The environmental and economic impact of new aircraft is a function of both aircraft performance and the airline's use of new and existing aircraft, so the tool needs to incorporate not only the performance of the new aircraft, but also how these new and existing aircraft are used by the airlines. A formalized approach that relies upon an aircraft allocation problem can determine whether having new aircraft that meet the NASA SFW goals is sufficient to lower fleet-level CO_2 emissions and achieves the goals set forth by IATA.

The NASA SFW goals are oftentimes considered "corners of the trade space", and future aircraft may not achieve all of the goals simultaneously. Since fuel costs comprise a large percentage of an airline's operating costs, and fuel consumption is directly related to CO_2 production (3.16 pounds of CO_2 is produced by every pound of fuel burned [4]), studies presented here focus on NASA's fuel consumption goals.

2 Methodology and Problem Formulation

To assess a new 150-seat aircraft, one could simply assume that the new aircraft would fly all the routes of the current 150-seat aircraft. However, airlines might use this new aircraft in different ways than its predecessor, and a "direct replacement" might be a naïve approach. Therefore, the new aircraft should not simply replace the older models when predicting fleet-level environmental metrics; the entire fleet should be reallocated to find the optimal use of the new aircraft when it is added to the older fleet. For instance, if it provided a profit and / or operating cost advantage, an airline might use one new "advanced technology" 150-seat single aisle transport with higher fuel efficiency instead of multiple, older, less-efficient 50-seat aircraft to provide service on a route. An allocation approach would determine how this new aircraft, along with existing aircraft in the fleet, might be used to meet passenger demand while addressing environmental and economic considerations.

In reality, daily airline operations usually work from a scheduling problem that assigns individual aircraft by tracking their unique tail numbers. [5] The formulation of a scheduling problem requires tracking the individual aircraft, time-of-day issues, etc., and is substantially more difficult to solve than an allocation problem because of the large increase in the number of decision variables, constraints, etc. By removing the scheduling component in this formulation, the allocation model finds a feasible allocation to meet all the constraints in a matter of seconds. With the solve time reduced for the allocation problem formulation, changes in the fleet-mix, constraints or any other parameter of the model are evaluated quickly and allow a quick analysis of how fleet-level metrics are impacted. The fast solve time also allows for studying scenarios that require multiple allocation problems, such as concurrently evaluating different fuel burn reductions and demand assumptions in the year 2050.

This airline allocation formulation assumes one benevolent, monopolistic airline. By modeling only one airline and no scheduling, there is no need to model complexities such as route and passenger sharing, competitive pricing, time-of-day issues and tracking individual aircraft. This keeps the problem size small, but does remove some actual issues that airlines do consider.

2.1 Aircraft

The airlines currently serving the US transportation network use a multitude of aircraft models. The model developed here categorizes these aircraft into six aircraft classes that correspond to the number of seats available in the aircraft. The technology level or age of the aircraft is also important, so in addition to the six aircraft seat classes, four aircraft categories were created to represent the relative technology age of the aircraft flown by airlines, which results in only 24 different aircraft for the allocation problem. The four technology "age" categories are:

1. The representative-in-class category,
2. The best-in-class category,
3. The new-in-class category,
4. The future-in-class category.

The representative-in-class category consists of the aircraft models that had the most operations in each class during 2005; i.e. these were the most commonly used model in each seat class. The best-in-class category consists of the aircraft models with the most recent entry-in-service date as of 2005; these were the newest aircraft operating in each seat class and generally represent the newest set of technology. The new-in-class category consists of aircraft models that are currently not in the fleet but will be in the near future. For example, one of the new-in-class aircraft is the Boeing 787, which recently entered service in class 5 with All Nippon Airways. Other new-in-class aircraft are based on future production aircraft (the CSeries) or advanced concept studies done at Purdue (Purdue Advanced Single Aisle Transport) and NASA. Lastly, the future-in-class category represents aircraft that will not enter the fleet until the distant future (i.e. "N+3" generation). For this paper, future-in-class aircraft consist of best-in-class aircraft with scaled down fuel consumption; these aircraft are not "resized" to account for the improved technology. Table 1 provides a summary of the six aircraft seat classes and four aircraft categories. Note that since the future-in-class aircraft are simply scaled fuel burn versions of the best-in-class aircraft, they are simply labeled by their relative size: small regional jet (SRJ), regional jet (RJ), small / large narrow-body (S/LNB) and small / large wide-body (S/LWB).

To assess the emissions and costs of each aircraft, the characteristics of these aircraft must be appropriately and consistently modeled. For this work, the NASA computer software Flight Optimization System (FLOPS) [6] provides estimates

Table 1 Aircraft Models Used for Each Category and Seat Class

Class	Seats	Representative-in-Class	Best-in-Class	New-in-Class	Future-in-Class
Class 1	20 - 50	Bombardier CRJ200	Embraer ERJ145	Small Regional Jet	Future SRJ
Class 2	51 - 99	Bombardier CRJ700	Embraer E-170	Regional Jet	Future RJ
Class 3	100 - 149	Boeing 737-300	Boeing 737-700	Bombardier CS100	Future SNB
Class 4	150 - 199	Boeing 757-200	Boeing 737-800	Purdue ASAT	Future LNB
Class 5	200 - 299	Boeing 767-300ER	Airbus A330-200	Boeing 787-8	Future SWB
Class 6	300+	Boeing 747-400	Boeing 777-200ER	Large Twin Aisle	Future LWB

of aircraft performance and cost. First, the aircraft is "sized" to perform a design mission using FLOPS; this sets the design takeoff gross weight and the empty weight of the aircraft. This sizing uses publicly-available information (e.g. airport compatibility guides with payload range diagrams, product information cards, etc.) to calibrate the FLOPS predictions so that they reflect the actual aircraft as reasonably as possible. After completing the calibrated sizing, FLOPS predicts the cost, block hours, and fuel consumed on various operating missions with different passenger loads and trip ranges.

To allocate the aircraft, the problem formulation requires coefficients that describe the cost, block hours, fuel consumed, LTO and mission NO_X for each aircraft on each route of the network. Lookup tables provide a means to organize these coefficients as functions of payload and range that come from the aforementioned FLOPS calculations. Through interpolation of these lookup tables, the fuel burn, DOC, LTO and mission NO_X and block hours for every aircraft on every route are easily calculated. For the studies conducted here, each aircraft flew at 80% load factor (i.e. 80% of the seats had passengers).

2.2 Air Transportation Network

Modeling all of the airports used throughout the world would create too large of an allocation problem. The Logistics Management Institute (LMI) identified 102 airports in the United States that constitute approximately 60% of operations and 70% of demand with an origin and / or destination in the United States. LMI also has a worldwide airport network that adds 122 European and 33 other airports outside of the United States and Europe to the 102 domestic airports. [7] This WWLMINET 257 network of airports capture 65% of operations and 80% of demand with an origin and / or destination in the United States. This serves as a surrogate for the entire operations of commercial air travel with at least the origin or destination in the US.

The allocation problem assumes that each aircraft performs a round trip operation on its allocated route. This means that if an aircraft is allocated to fly from City A to City B, the aircraft will also fly back from City B to City A. This assumption cuts the number of decision variables in half and ensures that aircraft will not accumulate at any one airport, thus eliminating the need for network flow (or balance) constraints at each airport.

2.3 Airline Fleet Size

To address the fleet size and aircraft count constraints, several assumptions regarding turn-around and maintenance time for each aircraft are required. According to Southwest Airlines, the average turn-around time for an aircraft at an airport is between 45 and 60 minutes. [8] Based on this statistic, the allocation tool assumes that each aircraft has a turn-around time of one hour per round trip. In addition to turn-around time, aircraft maintenance and servicing also requires time that limits the number of hours an aircraft can be flown within a day of operations. This maintenance time is accounted for by examining the equivalent maintenance hours (EMH) as a direct relation to hours flown by the aircraft (block hours – BH). The values for for EMH were determined by analyzing data put together by the MIT Airline Data Project. [9] Values for EMH per BH were found to be 0.936 for classes 1, 2 and 3; 0.948 for class 4; and 0.866 for classes 5 and 6.

The allocation tool allocates for daily operations. However, instead of picking an arbitrary day for passenger demand information, dividing annual data by 365 days created demand for a "typical day". Because the allocation tool uses a "typical day" to represent an entire year, the airline fleet needs to be larger than the number of aircraft operated on this "typical day", because some aircraft will be unable to fly due to maintenance. BTS data provides a breakdown of operations for each class of the representative-in-class and best-in-class families during the baseline year of 2005. The relative percentages of operations for each of these 12 aircraft provided a composition of the fleet in 2005. To determine the 2050 fleet composition, the 2011 to 2050 MITRE Fleet Forecast [10] provided a predicted breakdown of the aircraft fleet in terms of the six seat classes, shown below in Table 2.

Table 2 2050 Fleet Breakdown from MITRE Fleet Forecast

Class	Percentage of Fleet
Class 1	2.01%
Class 2	28.14%
Class 3	22.07%
Class 4	22.40%
Class 5	11.94%
Class 6	13.44%

2.4 Passenger Demand

For 2005 demand (the baseline year), the actual annual demand on each route (as reported by BTS) was used to create the demand of a "typical day". In 2005, the total annual demand over the WWLMINET 257 airports was 663,034,817. Any route with a demand of less than 20 passengers (the minimum number of seats in a class 1 aircraft) during the "typical day" was assumed to have zero demand and was ignored. To predict the 2050 passenger demand, the actual annual demand on each route from 2011was increased by 2% annually to create a "typical day" in the future. In 2011, the total annual demand was 648,607,606, which leads to a predicted total annual demand of 1,404,069,922 in 2050.

2.5 Mathematical Formulation

Ideally, airlines allocate and / or schedule their aircraft to maximize profit, which is a function including both revenue and cost. With a revenue model, the allocation tool would allocate aircraft to maximize profit – revenue minus costs – for the airline. However, for this paper, the studies focus on the feasibility of fleet-level goals for CO_2 emissions; therefore, minimizing fuel burn (and thus CO_2) serves as the objective function for the airline. This approach gives a "best case" scenario in terms of environmental impact, but the resulting aircraft allocation will likely not be the most profitable for the airline.

With these given assumptions and abstractions, the current allocation model can be mathematically formulated as follows:
Minimize:

$$\sum_{i \text{ aircraft}} \sum_{j \text{ routes}} f_{ij} \cdot x_{ij} \tag{1}$$

Subject to:

$$\sum_{i \text{ aircraft}} x_{ij} p_i \geq d_j \tag{2}$$

$$\sum_{j \text{ routes}} 2x_{ij} \cdot (BH_{ij} + TH + MH_{ij}) \leq 24 n_i \tag{3}$$

The allocation problem uses the number of round trips of aircraft i on route j as decision variables x_{ij}. Equation (1) serves as the objective function to minimize the fleet's CO_2 emissions via minimizing fuel burn, where f_{ij} is the fuel consumed by aircraft i on route j. The constraints in equation (2) ensure the allocation meets the demand on every route j given the number of passengers on each aircraft type (p_i), where each aircraft has an 80% load factor. Any aircraft model can serve the passenger demand of each route between a given city-pair, as long as route length does not exceed the aircraft's range and the aircraft is able to land on the origin and destination airport's longest runway. As an example, a class 1 aircraft (e.g. a 50-seat regional jet) is not able to fly from New York (JFK) to London (LHR) because the route is too long. Equation (3) ensures that the number of each aircraft type i allocated does not exceed the number of aircraft type i available, n_i. This constraint is enforced as a time constraint by requiring the block hours flown (BH_{ij}), maintenance hours performed (MH_{ij}, where $MH_{ij} = BH_{ij} \cdot \frac{EMH_i}{BH_{ij}}$) and turn-around time for each operation (TH) be less than 24 hours for each of the aircraft type i available. The round trip assumption discussed previously is enforced via the factor of 2 in Equation (3). This constraint often considered a "count" constraint.

The allocation problem is solved using the General Algebraic Modeling System (GAMS) [11] using the CPLEX solver. [12]

3 Studies Conducted

The studies presented investigate the impact of new aircraft concepts and new aircraft technology on fleet-level environmental metrics. By infusing the aircraft fleet with new aircraft concepts and technologies, the studies determine if the fleet-level goals set forth by IATA are achievable, and if the NASA SFW goals for future aircraft are enough for the fleet meet to the IATA goals, specifically, whether the CO_2 emissions in 2050 are 50% of the CO_2 emissions in 2005. An allocation representing a "typical day" in 2005 provides the baseline for CO_2 emissions in 2005. Remaining allocations model "typical days" in 2050 under different scenarios for future-in-class aircraft and adoption rates of these future-in-class aircraft.

To provide a "baseline" for 2050, the airline fleet only consisted of new-in-class aircraft. Many of the new-in-class aircraft are believed to meet or come close to the N+1 or N+2 fuel consumption goals set forth by NASA; therefore, a fleet consisting of only new-in-class aircraft in 2050 should make progress towards the IATA goal for 2050 fleet-wide emissions. After establishing a baseline, the fleet is infused with different amounts of future-in-class aircraft. Four different infusion scenarios simulate the fleet consisting of 25%, 50%, 75% and 100% future-in-class aircraft.

As mentioned previously, the future-in-class aircraft are modeled by simply taking the fuel burn of the best-in-class aircraft and reducing it by a fixed factor. Therefore, different "versions" of the future-in-class aircraft can be created by changing the fuel burn reduction factor. The studies presented reduced the fuel consumption of the best-in-class aircraft from 0% (a fuel burn reduction factor of 1) up to a 95% reduction in fuel burn (a fuel burn reduction factor of 0.05). Since the NASA SFW Project goals are all relative to current best-in-class aircraft, this method to create the future-in-class aircraft evaluates how well these goals set forth by NASA help the entire fleet meet IATA emission goal. However, under some fuel burn reduction factors, the future-in-class aircraft still does not outperform the new-in-class aircraft in terms of fuel consumption. Therefore, under the four scenarios with future-in-class aircraft, the future-in-class aircraft did not enter service until the fuel burn reduction factor allowed the future aircraft to consume less fuel than its new-in-class counterpart. Table 3 shows the required fuel burn reduction factor required for the future-in-class aircraft to consume less fuel than the new-in-class aircraft.

Table 3 Fuel Burn Reduction Factor Required for Future-in-Class Aircraft to Enter Service

Class	Fuel Burn Reduction Factor
Class 1	0.75 (25% Reduction)
Class 2	0.80 (20% Reduction)
Class 3	0.75 (25% Reduction)
Class 4	0.90 (10% Reduction)
Class 5	0.80 (20% Reduction)
Class 6	0.65 (35% Reduction)

Even with substantial gains in aircraft technology, the IATA goal of CO_2 aviation emissions in 2050 equal to 50% of the 2005 CO_2 aviation emissions may be difficult to meet while maintaining a high growth in demand for air transportation. However, decreasing the growth rate for air transportation demand or even reducing the total demand for air transportation would also decrease CO_2 emissions, if lower demand reduces the number of aircraft operations. Therefore, the studies presented here also considered a decrease and slight increase in the predicted 2050 demand (2% annual growth from 2011 demand values).

By varying both fuel burn reduction and predicted demand at the same time, these studies will be able to answer the following three questions:

1. If demand in 2050 reaches the level projected by 2% annual growth per year from 2011, how much more fuel efficient do the future-in-class aircraft have to be (relative to best-in-class) to meet IATA's goal of 50% of 2005 CO_2 levels?
2. If the efficiency of the future-in-class aircraft remains the same as the best-in-class counterparts, what reduced demand would meet IATA's goal of 50% of 2005 CO_2 levels?
3. What combinations of reduced demand and fuel efficiency lead to CO_2 levels at or below 50% of 2005 levels?

4 Results

For the results presented, passenger demand varied from 125% (≈2.6% annual growth from 2011) to 25% (≈–1.6% annual growth from 2011) of the projected 2050 demand in increments of 25%. The fuel burn reduction factor was varied from 1.0 (0% reduction in fuel consumption) to 0.05 (95% reduction in fuel consumption) in increments of 0.05. These variations in fuel burn and passenger demand led to 100 unique allocation formulations for each of the scenarios. These results were than interpolated by 0.01 increments using a combination of the `meshgrid` and `interp2` Matlab functions. After interpolation of the allocation results, the data was normalized to 50% of the 2005 CO_2 emission levels. Therefore, any combination of fuel burn reduction and passenger demand that resulted in a normalized value of less than one signifies achieving the IATA goal and was set to a value of "1" to ensure all feasible combinations appear as white in the contour plots shown below.

Figure 2 provides a contour plot of combinations of passengers served and improvement in fuel efficiency when the fleet is made up of *only* new-in-class aircraft (the 2050 baseline run). Any combination of fuel burn reduction factor (x-axis) and passenger demand (y-axis) that results in the white region satisfies IATA's goal of 2050 CO_2 emissions at or below 50% of 2005 CO_2 emissions. All points in the colored region correspond to a combination of passenger demand and fuel efficiency that exceeds 50% of 2005 CO_2 levels. The color bar on the right hand side of the figure indicates by what multiplicative factor that combination exceeds 50% of 2005 CO_2 emissions.

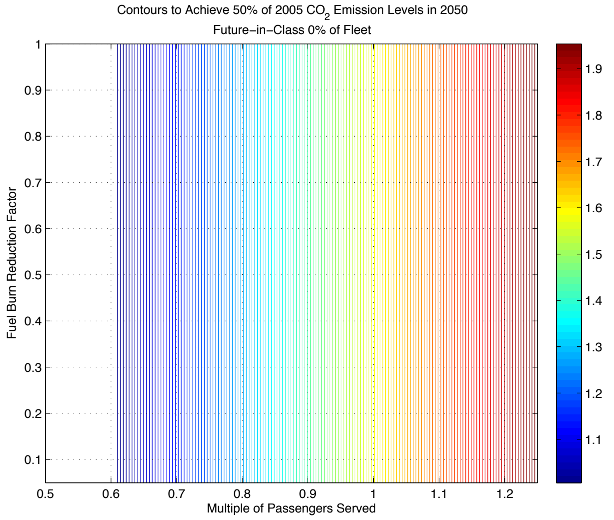


Fig. 2 Contours of Exceedance of the IATA Goal – 0% Future-in-Class

Under the baseline scenario, the contour plot is rather simplistic since there are no future-in-class, thus, the fuel burn reduction factor has no effect. Therefore, according to the results in Figure 2, to achieve IATA's goal for emissions in 2050 with only new-in-class aircraft, the projected 2050 demand has to be reduced by 39% (0.61 of projected demand). This value of demand results from a 0.7% annual growth from 2011 demand. If the 2050 projected demand is accurate, then CO_2 emissions will exceed the IATA goal by a factor of 1.6 (i.e. 2050 CO_2 emissions are 1.6 times 50% of 2005 emissions, or 80% of 2005 levels).

When future-in-class aircraft are introduced into the fleet, the contour plots begin to morph as the fuel burn reduction factor impacts the future-in-class aircraft. Figure 3 presents the results when the 25% of the fleet is future-in-class aircraft. As seen in Figure 3, the future-in-class aircraft help to improve the feasibility of the IATA fleet-level CO_2 goals. If the 2050 predicted demand is an accurate prediction, the fuel burn reduction factor required to meet the IATA goal is 0.4, which corresponds to a 60% reduction in fuel consumption. This results aligns directly with NASA's N+3 SFW Goal for fuel consumption, indicating that the SFW goal is likely sufficient to help achieve the IATA fleet level goal.

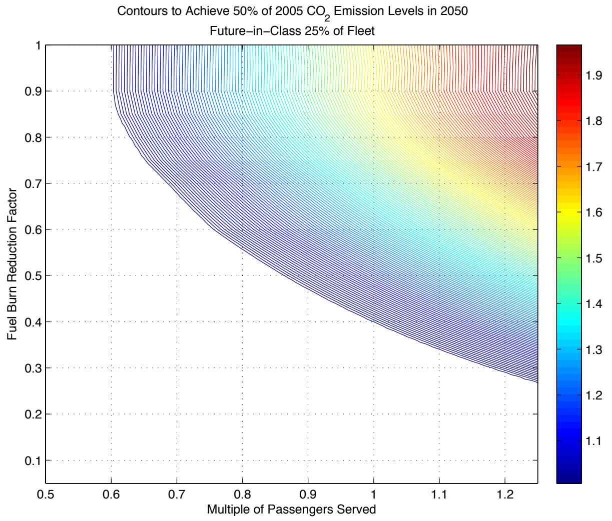


Fig. 3 Contours of Exceedance of the IATA Goal – 25% Future-in-Class

Figure 3 also identifies different combinations that lead to satisfying the IATA goal. For example, if fuel burn can be reduced by an additional 10% to 70%, a 20% increase in demand can be served while still achieving CO_2 emissions equal to 50% of 2005 levels. If only a 50% improvement in fuel burn relative to today's best-in-class aircraft is possible, then reducing demand by 14% will make the IATA goal feasible.

Under the other infusion scenarios, when the future-in-class aircraft make up 50%, 75% and 100% of the 2050 fleet, the contour lines shift upwards, allowing more passengers to be served and requiring less aggressive fuel burn reductions in future aircraft to meet the IATA goal. Figures 5 to 7 show the contour plots for the three other future-in-class fleet scenarios.

Figure 4 is a "composite" image of the four contour plots from the future-in-class infusion scenarios. Each line in the plot corresponds to the leading edge of the color portioned from the four scenarios. As expected, as more of the fleet becomes future-in-class, achieving the IATA emission goal becomes easier. Under the current predicted demand for 2050, if the entire fleet is future-in-class aircraft, then the fuel burn improvement required drops from 60% (when 25% of the fleet is future-in-class) to 52%, which is closer to NASA's N+2 goal for fuel consumption.

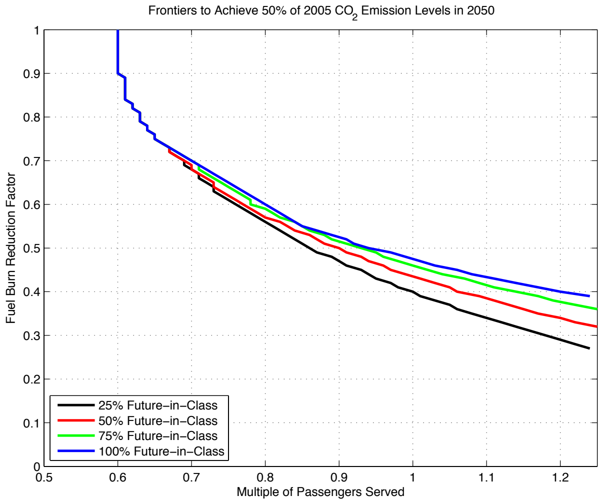


Fig. 4 Contours of Exceedance of the IATA Goal – 25% Future-in-Class

However, replacing the entire fleet with brand new aircraft in 15 years from a 2035 entry in service date might be difficult, because the typical operational lifespan of an aircraft is 25 to 30 years. Furthermore, aircraft entering service in the 2015 to 2020 time frame may have design lifetimes that exceed 30 years, which makes the propagation of new aircraft and new aircraft technology into the fleet a slow process. Nonetheless, if future-in-class aircraft can meet the N+3 SFW goal, only 25% of the fleet has to become future-in-class aircraft to meet the IATA goal.

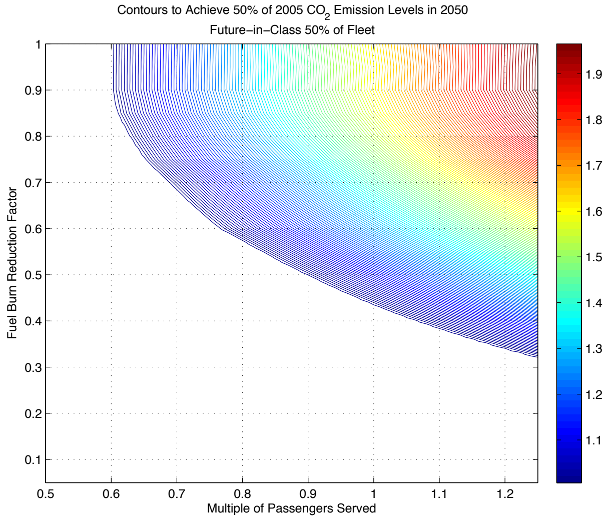


Fig. 5 Contours of Exceedance of the IATA Goal – 50% Future-in-Class

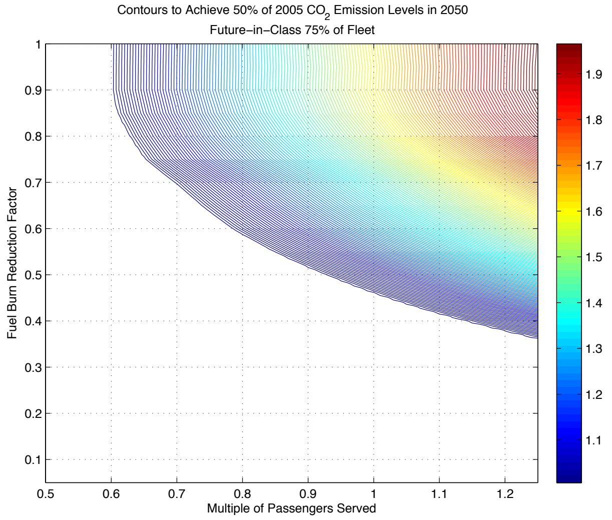


Fig. 6 Contours of Exceedance of the IATA Goal – 75% Future-in-Class

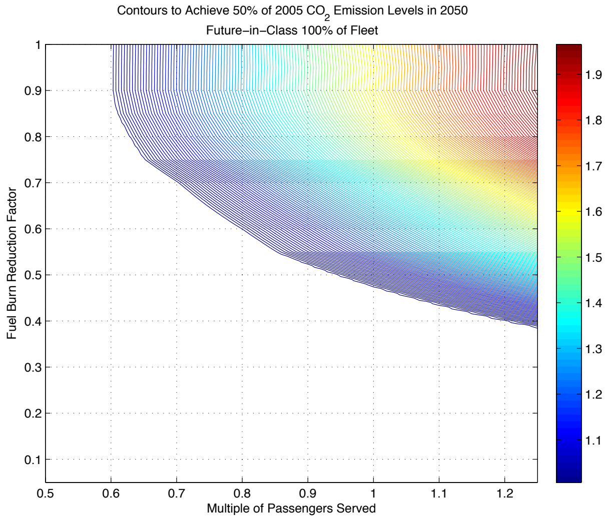


Fig. 7 Contours of Exceedance of the IATA Goal – 100% Future-in-Class

5 Conclusions

The results presented here demonstrate that an aircraft allocation formulation provides an approach to evaluate how new aircraft impact fleet-level metrics. While several abstractions and assumptions simplify the allocation problem to a tractable size, the network of routes accounts for 65% of all aircraft traffic with an origin and / or destination in the United States and 80% of all passenger traffic with an origin and / or destination in the United States (based on 2005 data). The MITRE Fleet Forecast provided a projection of the aircraft fleet composition for the year 2050, which has an influence on the results presented.

These results indicate that if NASA's fuel consumption goal for the N+3 generation aircraft is achieved, then the goals set forth by IATA for 2050 emissions are achievable with a fleet consisting of 25% of these future-in-class aircraft (given the demand and fleet composition projections). Furthermore, if the entire fleet is composed of future-in-class aircraft, than NASA's N+2 fuel consumption goal is close to sufficient to meet the IATA goal for 2050 CO_2 emissions.

Additionally, the objective function used to solve the aircraft allocation did not take into account airline profit. While the optimal aircraft allocations presented here are best for CO_2 emissions, they are likely not the most profitable allocation for the airline. Therefore, future work needs to take into account airline profit *and* CO_2 emissions to get a more realistic prediction of

2050 emissions. Nonetheless, these results indicate a possible “lower bound” for 2050 CO_2 emissions and indicate that the NASA SFW goals are a strong step in the right direction to meet fleet-level emissions goals set forth by IATA.

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