Impact of Future Generation Aircraft on Fleet-Level Environmental Emission Metrics

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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 ($\mathbf{NO_X}$) 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. The results of this allocation allow calculation of the fleet-level fuel burn, ($\mathbf{NO_X}$), and airport noise. Examining fleet-level environmental metrics helps assess how aircraft meeting NASA's SFW goals could impact fleet-level environmental goals established by the International Air Transport Association (IATA). The allocation approach developed and implemented here evaluated the resulting fleet mix and associated emissions metrics for a series of years from 2005 to 2050. With the models and assumptions used here, the results show that, even with new aircraft that meet aggressive technology development goals, the total fleet emissions will continue to increase as travel demand increases, but the emissions per passenger mile will decrease. Furthermore, goals set forth by IATA appear unattainable without drastic decreases in passengers served, substantial improvements in fuel burn efficiency, or a substantially different introduction rate of new aircraft.

Nomenclature

BH_{ij}	Block Hours for Aircraft i on Route j
d_j	Demand on Route j
κ	Scaling Factor
MH_{ij}	Maintenance Hours for Aircraft i on Route j
η	Demand Scaling Factor
n_i	Number of Aircraft i Available
p_i	Passengers on Aircraft i
r_j	Range of Route j
TH	Turn-Around Time
x_{ij}	Number of Aircraft i on Route j

Subscripts

i	Aircraft Type
j	Route Number

I. 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

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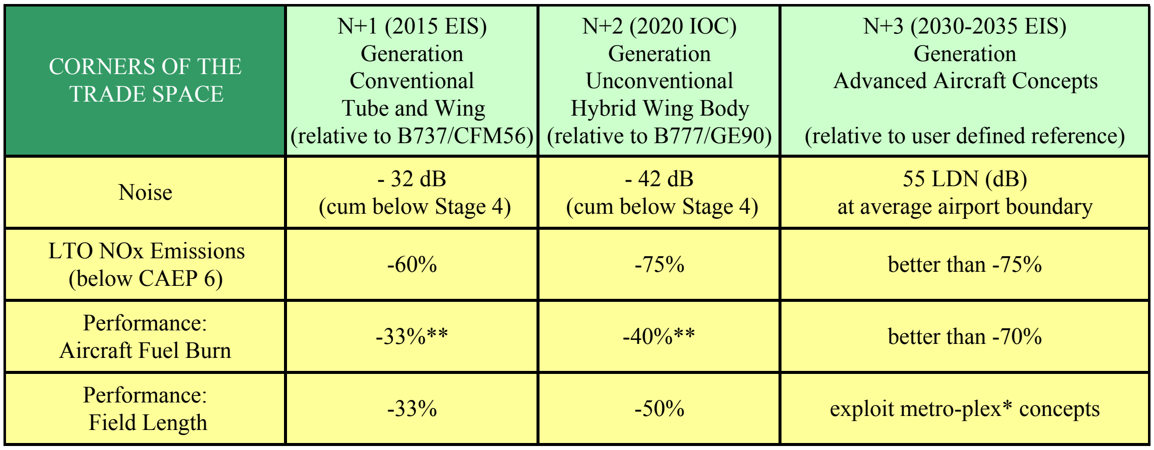
are today's in-production aircraft. The next major generation of aircraft are N+1, which are followed by the N+2 generation and then by the N+3 generation. Based on the SFW's goals presented in 2008, NASA hopes to reduce individual aircraft fuel burn by 33% compared today's current aircraft and landing 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 40% 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 more than 70% and LTO NO_X by more than 75%. Additionally, these future generation aircraft hope to have reduced noise and shorter field lengths for landings and departures.[1] Figure 1 summarizes the NASA SFW goals for noise, LTO NO_X emissions, fuel burn and field length.



CORNERS OF THE TRADE SPACE	N+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020 IOC) Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2030-2035 EIS) Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	55 LDN (dB) at average airport boundary
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

** An additional reduction of 10 percent may be possible through improved operational capability
* Concepts that enable optimal use of runways at mutiple airports within the metropolitan areas
EIS = Entry Into Service; IOC = Initial Operating Capability

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

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:[2]

1. A cap on aviation CO_2 emissions from 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 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.

Because the NASA SFW goals make up the "corners of the trade space", a future generation aircraft may only achieve one of the NASA goals at a time, so the studies presented here focus upon NASA's SFW fuel burn reduction goals. Additionally, since 3.16 pounds of CO_2 is produced by every pound of fuel burned,[3] reducing fuel burn reduces CO_2 emissions.

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, but no other routes. The fleet-level emission changes with this "direct replacement" would help illustrate the impact of the new 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.

Resource allocation is a common problem in the operations research community and often takes the form of a large integer program. For airline operations, these tools take the form of maintenance scheduling, crew assignment, trip assignments, and fleet allocation. Typically, the objective is to maximize profit or minimize cost. Research efforts in this field have focused on the development of problem formulation strategies and algorithms to reduce the computation time and problem complexity;[4–6] however, none of the referenced allocation models incorporate fleet-level environmental metrics, such as total fleet emissions and noise area around airports, as the objective or constraints in the problem formulation.

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 minutes. 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 allocating aircraft each year from 2005 to 2050.

II. Problem Formulation

In addition to simplifying the problem to an allocation problem rather than a scheduling problem, the formulation also assumes one benevolent, monopolistic airline. By modeling only one airline and no scheduling, there is no need to model such 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.

The airlines currently serving the domestic 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, three aircraft categories were created to represent the relative technology age of the aircraft flown by airlines, which results in only 18 different aircraft for the allocation problem. The three technology "age" categories are:

1. The representative-in-class category
2. The best-in-class category
3. The new-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. Lastly, the new-in-class category consists of aircraft models that are currently not in the fleet but will be in the future. One of the new-in-class aircraft is the Boeing 787, which will soon enter service in class 5. The other new-in-class aircraft is a class 4 aircraft that will replace the Boeing 737 and Airbus A320 families. For this work, the 164-seat Advanced Single-Aisle Transport (ASAT) aircraft developed by Purdue and based on work by Mark Guynn of NASA Langley Research Center provides the guidelines for the new-in-class aircraft in class 4. One of the main advantages of the Purdue ASAT aircraft is the use of a geared turbofan engine.[7] There will be additional new aircraft in each class over the next several decades, but there are no clear examples of what these aircraft might look like. Therefore, the remaining new-in-class aircraft are concepts created by taking the fuel burn values from their best-in-class counterpart and adjusting them based on the NASA SFW goals for either the N+1 or N+2 generation aircraft; these aircraft are not "resized" to account for the improved technology. Table 1 provides a summary of the six aircraft seat classes and three aircraft categories.

Table 1. Aircraft Models Used for Each Category and Seat Class

Class	Seats	Representative-in-Class	Best-in-Class	New-in-Class
Class 1	20 - 50	Canadair RJ200/RJ440	Embraer ERJ145	N+2 ERJ145
Class 2	51 - 99	Canadair RJ700	Embraer 170	N+1 Embraer 170
Class 3	100 - 149	Boeing 737-300	Boeing 737-700	N+1 737-700
Class 4	150 - 199	Boeing 757-200	Boeing 737-800	Purdue ASAT
Class 5	200 - 299	Boeing 767-300	Airbus A330-200	Boeing 787
Class 6	300+	Boeing 777-200ER	Boeing 777-200ER	N+1 777-200ER

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.[8] 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.

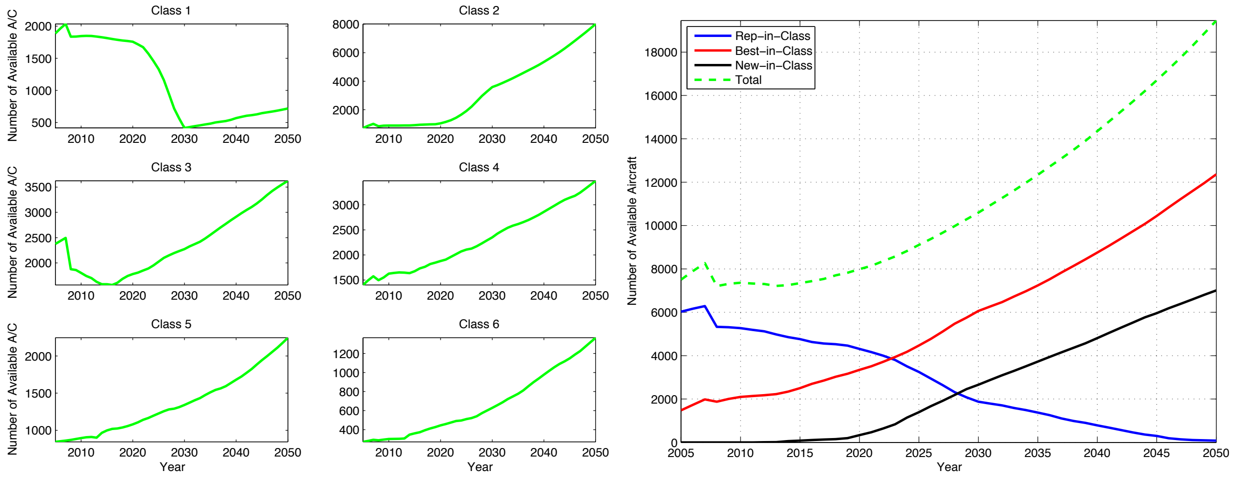
Ideally, airlines allocate and / or schedule their aircraft to maximize profit, which is a function including both revenue and cost. With a revenue model, the allocation tool would allocate aircraft to maximize profit – the difference of revenue minus costs – for the airline. However, without an appropriate revenue model for the benevolent monopoly airline, the allocation tool currently minimizes cost under the assumption that minimizing costs maximizes profit. Using DOC as a surrogate for profit typically leads to assigning larger aircraft in an allocation problem than typically seen in actual operations, because it does not reflect the impact of providing schedule flexibility to passengers, which can generate additional revenue for the airline.

Airlines do not typically fill up aircraft with passengers when they service a route. This is usually due to revenue management, or in some instances, a reduced passenger load extends the range of an aircraft to service a longer route. The ratio of passengers flown to seats available is the load factor of the aircraft. To make each category of aircraft equally capable of meeting the demand constraints in the allocation problem, each aircraft within a class will have the same number of loaded passengers based on historical averages in each class.

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.[9] 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. According to a Boeing on-line publication, "For every hour that a plane is in flight, maintenance crews spend roughly three-and-a-half hours working to maintain it."[10] Based on this statistic, for every block hour flown by an aircraft, the aircraft will receive 3.5 hours of maintenance. Since maintenance hours are dependent on block hours, the values for MH_{ij} equal $3.5 \times BH_{ij}$. Because aircraft need 3.5 maintenance hours per flight hour, the aircraft fleet needs to be larger than the number of aircraft operated on a "typical day", because some aircraft will be in maintenance all day.

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”. For 2005 through 2008, the actual annual demand on each route (as reported by BTS) was used to create the demand of a “typical day”. 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. From 2009 onward, the total demand on each route amongst the WWLMINET 257 airports in 2008 was increased by 2% annually to create a “typical day” in the future.

To reflect airline operations, only a fixed number of aircraft are made available for allocation. The MITRE Corporation provided two different forecast models for the fleet size of US airlines. Figure 2(a) shows the sum of all aircraft available per class from 2005 to 2050, and Figure 2(b) shows the total number of aircraft available per category from 2005 to 2050.



(a) Total Aircraft Available by Class

(b) Predicted Total Aircraft Available

Figure 2. MITRE Fleet Forecast for 2005 to 2050

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)[11] provides estimates 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. For the new-in-class 787 model, the calibration uses published expected performance; the Purdue version of the Advanced Single-Aisle Transport calibration uses the NASA-published studies.

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. From the FLOPS output and engine characteristics, estimates of landing and take-off (LTO) NO_X as well as total mission NO_X for the various operating missions are also available. To allocate the aircraft, the problem formulation requires coefficients that describe the cost, block hours, fuel consumed, LTO NO_X 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 with its equivalent load factor are easily calculated.

With all assumptions, abstractions and modeling in place, a formal statement of the allocation problem is

Minimize

$$\sum_{i=1}^{\overset{l}{\text{aircraft}}} \sum_{j=1}^{\overset{m}{\text{routes}}} DOC(x_{ij}, r_j, p_i) \text{ or } \sum_{i=1}^{\overset{l}{\text{aircraft}}} \sum_{j=1}^{\overset{m}{\text{routes}}} CO_2(x_{ij}, r_j, p_i) \tag{1}$$

Subject to

$$\sum_{i=1}^{\overset{l}{\text{aircraft}}} x_{ij} p_i \geq d_j \text{ for all routes } j = 1 \ldots m \tag{2}$$

$$\sum_{j=1}^{\overset{m}{\text{routes}}} x_{ij}(BH_{ij} + TH + MH_{ij}) \leq 12 n_i \text{ for all aircraft } i = 1 \ldots l \tag{3}$$

Optionally

$$CO_2 \leq \kappa \cdot CO_{2_{2005}} \text{ for total fleet CO}_2 \tag{4}$$

$$LTO\ NO_{\text{X}} \leq \kappa \cdot LTO\ NO_{X_{2005}} \text{ for total fleet LTO NO}_{\text{X}} \tag{5}$$

$$NO_{\text{X}} \leq \kappa \cdot NO_{X_{2005}} \text{ for total fleet NO}_{\text{X}} \tag{6}$$

$$Noise\ Area_k \leq \kappa \cdot Noise\ Area_{k_{2005}} \text{ for each US airport } k \tag{7}$$

$$DOC \leq \kappa \cdot DOC_{2005} \text{ for total fleet DOC} \tag{8}$$

The allocation problem uses the number of round trips of aircraft i on route j as the decision variable, x_{ij}. Since the values of x_{ij} can only take on integer values (i.e. a third of a round trip is not possible), the allocation problem is an integer programming (IP) problem. Eq. 1 makes up the objective of the IP, while Eq. 2 through Eq. 8 serve as constraints.

As shown in Eq. 1, studies presented here will consider one of two objectives individually:

1. Minimizing daily Direct Operating Cost (DOC)
2. Minimizing CO_2 emissions.

As discussed previously, the allocation problem minimizes DOC as the objective, rather than profit, and uses fuel consumed by the fleet as a surrogate for fleet CO_2 emissions.

The constraints in Eq. 2 ensure that all passenger demand is met. 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 capabilities 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. The allocation of aircraft must provide enough capacity to transport sufficient passengers to meet the demand on all of the routes between the 257 WWLMINET airports. The demand in either direction of the route is equal to the maximum of the two one-way segments reported by BTS. For example, BTS reports that for the 2005 typical day, 945 passengers flew from ATL to IND and 915 passengers flew from IND to ATL. In this study, the demand from ATL to IND and from IND to ATL will both equal 945 passengers. Taking the maximum demand of each segment ensures that the capacity allocated to a roundtrip will meet or exceed the demand for each of the two one-way segments.

Because the amount of aircraft available for allocation is finite, the allocation problem contains an aircraft flight hour limit. The constraints in Eq. 3 ensure that an aircraft is not flying, being serviced (i.e. airport turn-around) or undergoing maintenance for more than 24 hours in a given day. Under the round trip assumption, the operations (and thus block and maintenance hours) are automatically doubled by the round trip assumption, so the right hand side Eq. 3 only allows 12 hours of operations and maintenance for all aircraft in the fleet. This is often considered a "count" constraint.

The fleet-level environmental metrics may also serve as constraints (Eq. 4 through Eq. 8). By using the fleet-level metrics as constraints, the allocation tool will allocate aircraft to routes that keep fleet-level metrics below a specified level, usually based on the 2005 level of the metric. By changing the scaling factor, κ, the problem seeks a feasible allocation of aircraft that does not allow specified emissions (or noise area) to go above κ% of the 2005 (or other baseline year) value.

III. Studies Conducted

The goal of these studies was to 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 hope to 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.

Different scenarios, each showing a different adoption rate of new technology, can show the impact of new technology and / or new aircraft concepts on fleet-level metrics. Under a “New No Technology” scenario, only the representative-in-class and best-in-class aircraft are made available for allocation. This represents the current (2005) fleet. Over time, without new-in-class aircraft, the fleet does not see improved technology, so it becomes old and inefficient compared to an expected development of technology. Because the NASA SFW goals – and goals set forth by IATA – account for the introduction of new technology in future aircraft, this scenario serves as a baseline for comparison to other scenarios.

FLOPS models exist for two projected new-in-class aircraft, the Boeing 787 and the NASA ASAT; these models provide calibrated performance coefficients that create lookup tables for these aircraft. Therefore, this second scenario that adds only the Boeing 787 and Purdue ASAT as new-in-class aircraft for class 5 and class 4, respectively, represents a minor penetration of new technology into the fleet.

The third scenario studied involves introducing new-in-class aircraft into every seat class. In classes 1, 2, 3 and 6 technology multipliers adjust the lookup tables of the best-in-class aircraft to reflect future improvements. There are two approaches for representing the new-in-class aircraft via technology multipliers. One assumes that the NASA goals for fuel burn are attainable; the other is slightly more conservative. These multipliers are not tied to specific technology improvements; they assume that some technology development will provide these improvements. Because the goals for IATA and ICAO emphasize CO_2 emissions and fuel burn, these concepts use scaled values from the lookup tables of the corresponding best-in-class aircraft to represent new aircraft with reduced fuel burn that correspond to NASA SFW N+1 or N+2 goals. Other metrics, such as LTO and mission NO_X, could also be scaled in future studies.

A. Study 1: Minimize Fleet DOC and CO_2 Emissions from 2005 to 2050

The first study examines two different minimizations over the period from 2005 to 2050. The change in passenger demand between 2005 and 2008 uses historical data from BTS. By growing demand 2% annually from 2009 to 2050, demand will more than double from 2008 levels to 2050 (2.3 times 2008 demand), and DOC and CO_2 are also likely to increase in absolute terms as more aircraft operate to satisfy the large growth in demand. Because more demand will likely drive fleet-level DOC and CO_2 up, the relative metrics of DOC and CO_2 per passenger mile (calculated via post processing after allocation) can examine how these fleet-level “efficiency” metrics change. An allocation will be solved to minimize DOC or minimize CO_2 for a “typical day” for each year between 2005 and 2050.

B. Study 2: Minimize CO_2 while Varying Demand and Fuel Burn in 2050

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 appears to be incredibly 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. Varying the fuel burn technology multipliers discussed previously allows the allocation problem to find solutions identifying combinations of technology improvement required with levels of air transportation demand to meet the IATA goal in 2050.

Passenger demand is varied from the projected 2050 levels by 200% (2 times the projected 2050 demand, which used a 2% yearly growth rate starting in 2008) to 25% (one-fourth the amount of the projected 2050 demand) in increments of 25%. The 200% increase in demand corresponds to roughly a 3.7% annual growth rate from 2008 demand, whereas demand equal to 25% of 2050 demand corresponds to roughly a -1.3% annual growth rate (i.e. a decrease in demand per year). Such a drastic decrease in demand is unlikely; however, in the presence of strict environmental constraints on CO_2 emissions, airlines might have to refuse passengers service, if their fleet lacks the necessary fuel efficiency.

In addition to varying passenger demand, allocations conducted in this study examine various fuel burn technology multipliers, which simulate increases in fuel burn efficiency. This study applies a technology multiplier to adjust the fuel consumption of all the best-in-class aircraft to represent the new-in-class aircraft; this allocation does not use the Boeing 787 or ASAT models. The fuel burn coefficients of all best-in-class aircraft are scaled uniformly from 100% (i.e. no reduction in fuel burn) down to 5% (i.e. 95% reduction in fuel burn) in 5% increments to represent the best-in-class aircraft.

C. Study 3: Examine the Impact of a Discrete Technology in 2008

The previous studies examine the impact of new aircraft concepts under various conditions and scenarios; however, many of these new-in-class conceptual aircraft will incorporate various new technologies to achieve their desired performance. This last study investigates how a discrete technology – winglets – impacts the fleet-level environmental metrics.

The IATA Technology Roadmap cites that retrofits can impact fuel burn by 7% to 13%.[2] Even though winglets can reduce fuel burn, in practice, the reduction is typically not as high as the IATA Technology Roadmap. Fuel burn can by reduced by up to 6.5% by adding winglets to the Boeing 767-300ER.[12] However, the 6.5% reduction occurs on the most utilized, long routes flown by the Boeing 767-300ER, so shorter routes might see less improvement.

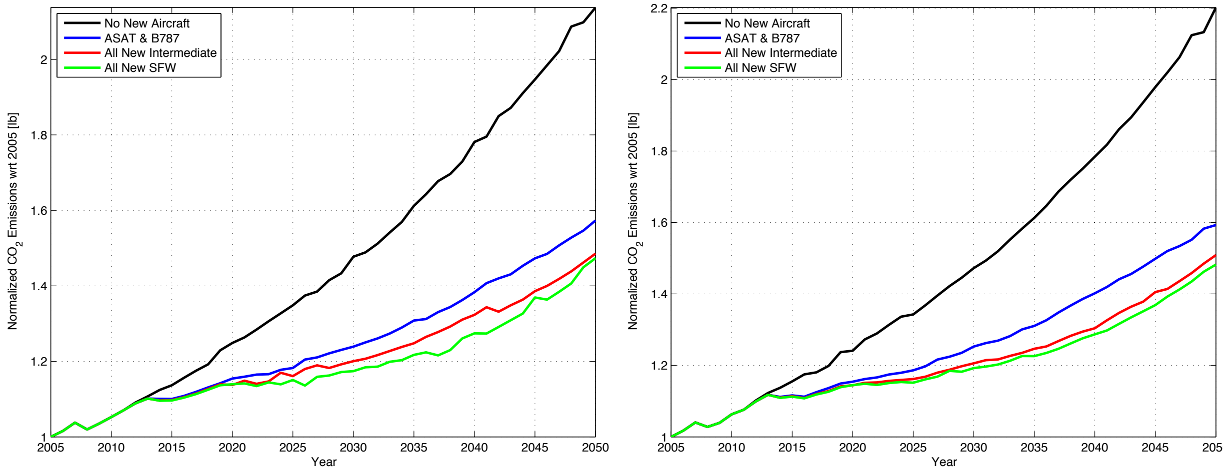
For this study, class 4 and class 5 representative-in-class aircraft separately receive winglet retrofits. With these new retrofits in place, the allocation tool minimizes fleet-level CO_2 emissions to investigate how the winglets on one class of aircraft impact the entire fleet. For each of the two substudies (one with only class 4 getting winglets and the other with only class 5 getting winglets) the fuel burn savings from the winglets varied from 0% to 7% in 1% increments to address a range of potential fuel savings. The 0% fuel burn savings scenario serves as a baseline, because the representative-in-class aircraft will not have any fuel burn reductions from the currently predicted values. 2008 is the year for this study, because the fleet numbers reported by the MITRE Fleet Forecast are actual numbers reported by US airlines and not forecasted.

Similar to the Study 2, only the aircraft's fuel burn numbers are adjusted to account for the winglets. In reality, there will be a cost and change in empty weight associated with retrofitting the fleet with winglets. The aircraft would have to be resized to account for empty weight changes, DOC changes, and improved fuel burn (e.g. the aircraft might be able to fly further with winglets, if the empty weight increase is not substantial).

IV. Results

A. Study 1: Minimize Fleet DOC and CO_2 Emissions from 2005 to 2050

After running the allocations to minimize fleet DOC and CO_2 emissions for a typical day of each year from 2005 to 2050, plots of the fleet-level metrics allow for analysis. Figure 3(a) shows the CO_2 emissions normalized to the 2005 baseline result when minimizing CO_2 for each of the four scenarios, and Figure 3(b) shows the CO_2 emissions when minimizing DOC for each of the four scenarios. As expected, because passenger demand grew 2% annually from 2009 to 2050, CO_2 emissions continued to increase over time.

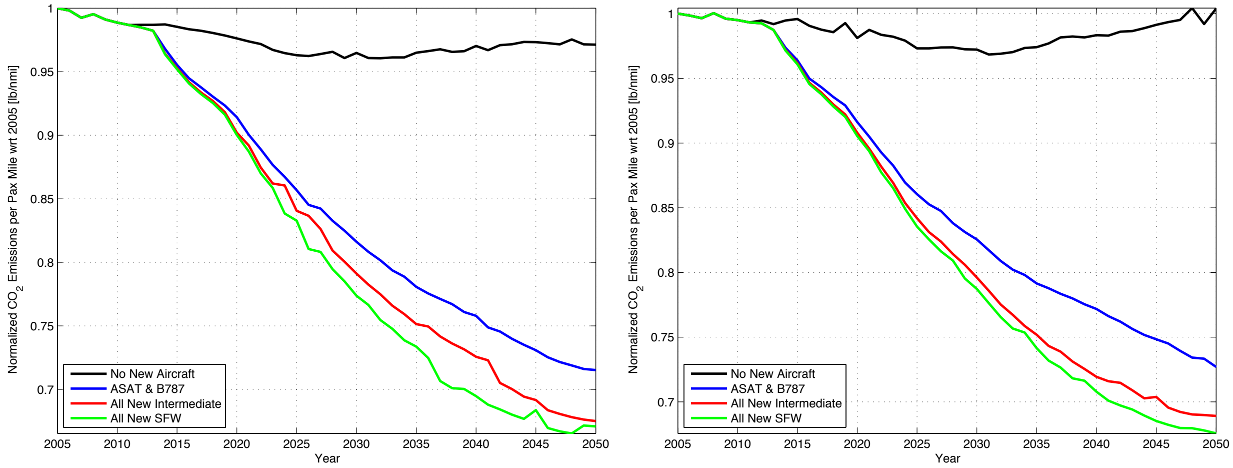


(a) Minimizing CO_2 (b) Minimizing DOC

Figure 3. Normalized CO_2 Emissions from 2005 to 2050

While the general trends appear to be the same, there are some differences. The difference between the two objectives is most noticeable in 2050 where all scenarios have more fleet-level CO_2 emissions when the objective is to minimize DOC. When considering the allocation problem, this result is intuitive, because as the airline tries to minimize costs, they will have no concern for how much CO_2 is emitted. Another difference occurs in the separation of the trends for each of the different scenarios, especially the two scenarios that include concepts for all classes of new-in-class aircraft (red and green lines in Figure 3(a) and Figure 3(b)). When the objective is minimizing CO_2, these two scenarios appear to have a larger difference between them, whereas when minimizing DOC, the separation is not as large.

Complementing Figure 3(a) and Figure 3(b), Figure 4(a) and Figure 4(b) plot the normalized "efficiency" metric of CO_2 emissions per passenger mile from solving the allocation problem to minimize CO_2 and DOC, respectively. When looking at emissions at a per passenger mile level, CO_2 emissions dropped between 2005 and 2050 in all of the scenarios studied. As discussed previously, airlines typically seek to maximize profit, but the tool instead minimizes costs to maximize assumed profit. Since total costs include fuel cost, minimizing cost also, to an extent, minimizes fuel burn. This is why an allocation problem to minimize DOC also minimizes fuel consumed, even with no new technology. In addition, minimizing costs leads the airline to use larger aircraft to reduce the total number of operations, which can further reduce fuel burn. This indicates that while absolute CO_2 emissions continue to grow, the number of passengers served grows at a faster rate. Intuitively, scenarios with more new-in-class aircraft and / or more fuel-efficient new-in-class aircraft lead to the lowest CO_2 emission levels.



(a) Minimizing CO_2

(b) Minimizing DOC

Figure 4. Normalized CO_2 Emissions per Passenger Mile from 2005 to 2050

Whether emissions are evaluated at the fleet-level or at the passenger mile level, under the assumptions and fleet mixes of these studies, the goals set forth by IATA are unattainable. The abstractions and assumptions of this approach are significant enough that the goals set forth by IATA cannot be invalidated by these results, but their achievability is questioned.

Table 2 and Table 3 compare the fleet-level and passenger mile level results for CO_2 emissions in 2005 and 2050.

Table 2. CO_2 Emissions – 2005 to 2050 when Minimizing CO_2

Scenario	Fleet Level			Passenger Mile Level		
	2005 CO_2 [lb]	2050 CO_2 [lb]	Percent Change	2005 CO_2 [lb/nmi]	2050 CO_2 [lb/nmi]	Percent Change
No New	8.63×10^8	1.85×10^9	+ 114%	0.3735	0.3628	- 3%
ASAT & B787	8.63×10^8	1.36×10^9	+ 57%	0.3735	0.2671	- 29%
All New Inter.	8.63×10^8	1.28×10^9	+ 49%	0.3735	0.2521	- 33%
All New SFW	8.63×10^8	1.27×10^9	+ 48%	0.3735	0.2506	- 33%

Table 3. CO_2 Emissions – 2005 to 2050 when Minimizing DOC

Scenario	Fleet Level 2005 CO_2 [lb]	Fleet Level 2050 CO_2 [lb]	Fleet Level Percent Change	Passenger Mile Level 2005 CO_2 [lb/nmi]	Passenger Mile Level 2050 CO_2 [lb/nmi]	Passenger Mile Level Percent Change
No New	8.64×10^8	1.90×10^9	+ 120%	0.3729	0.3744	+ 1%
ASAT & B787	8.64×10^8	1.38×10^9	+ 60%	0.3729	0.2711	- 27%
All New Inter.	8.64×10^8	1.30×10^9	+ 51%	0.3729	0.2569	- 31%
All New SFW	8.64×10^8	1.28×10^9	+ 48%	0.3729	0.2520	- 33%

Similarly, minimizing fleet-level DOC was also examined. Like CO_2 emissions, fleet-level DOC continued to increase over time, because passenger demand grew 2% annually from 2009 to 2050 requiring additional operations to satisfy demand. However, because the new-in-class concepts used in two of the four scenarios have the same non-fuel DOC as their best-in-class counterparts, the difference in DOC is not as pronounced as it might be if the new-in-class aircraft using the technology multiplier approach had actual performance estimates based on new sizing studies. Any differences in DOC in these scenarios would be the lower fuel cost per flight resulting from the better fuel efficiency of the new-in-class aircraft. Fleet-level DOC per passenger mile shows similar trends to that of the CO_2 emissions per passenger mile where all scenarios lead to a lower value for DOC per passenger mile. Table 4 and Table 5 compare results for 2005 and 2050 using the fleet-level and passenger mile level results for DOC.

Table 4. Fleet-Level DOC – 2005 to 2050 when Minimizing DOC

Scenario	Fleet Level 2005 DOC [$]	Fleet Level 2050 DOC [$]	Fleet Level Percent Change	Passenger Mile Level 2005 DOC [$/nmi]	Passenger Mile Level 2050 DOC [$/nmi]	Passenger Mile Level Percent Change
No New	1.92×10^8	4.16×10^8	+ 117%	0.0829	0.0820	- 1%
ASAT & B787	1.92×10^8	3.33×10^8	+ 74%	0.0829	0.0657	- 21%
All New Inter.	1.92×10^8	3.28×10^8	+ 71%	0.0829	0.0647	- 22%
All New SFW	1.92×10^8	4.16×10^8	+ 117%	0.0829	0.0820	- 11%

Table 5. Fleet-Level DOC – 2005 to 2050 when Minimizing CO_2

Scenario	Fleet Level 2005 DOC [$]	Fleet Level 2050 DOC [$]	Fleet Level Percent Change	Passenger Mile Level 2005 DOC [$/nmi]	Passenger Mile Level 2050 DOC [$/nmi]	Passenger Mile Level Percent Change
No New	1.97×10^8	4.15×10^8	+ 110%	0.0853	0.0815	- 4%
ASAT & B787	1.97×10^8	3.35×10^8	+ 70%	0.0853	0.0660	- 23%
All New Inter.	1.97×10^8	3.34×10^8	+ 69%	0.0853	0.0657	- 23%
All New SFW	1.97×10^8	3.50×10^8	+ 17%	0.0853	0.0689	- 19%

B. Study 2: Minimize CO_2 while Varying Demand and Fuel Burn in 2050

The next study examined minimizing CO_2 emissions in 2050 while varying the total number of passengers served and the fuel efficiency for all of the new-in-class aircraft. By varying both of these factors at the same time, this study 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 2009, how much more efficient do the new-in-class aircraft have to be to meet IATA's goal of 50% of 2005 CO_2 levels?
2. If the efficiency of the new-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?

Previous results discussed in Section A indicate that IATA's goal is unattainable given the assumptions made about assumed demand growth and future fleet mixes.

These studies varied the fuel efficiency technology multiplier for all new-in-class aircraft from 1.0 (current best-in-class fuel burn) to 0.05 (95% reduction in fuel burn from best-in-class aircraft) in 0.05 increments. Additionally, the allocations varied the passenger demand multiplier from 2 (twice as much demand in 2050) to 0.25 (25% as much demand in 2050) in 0.25 increments. These variations led to 160 unique allocation formulations. 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.

Figure 5 provides a contour plot of combinations of passengers served and improvement in fuel efficiency. Under the fleet mix forecasted by the MITRE Fleet Forecast, IATA's goal for emissions appears impossible unless fuel efficiency is greatly increased *AND* passenger demand is greatly reduced. Even if NASA's SFW N+3 goal of a 70% improvement in aircraft fuel efficiency relative to current aircraft is possible on the new-in-class airframes, meeting the IATA CO_2 emissions goal requires that passenger demand in 2050 be only 33% of the initially projected value (Point 1 in Figure 5). 33% of the projected 2050 passenger demand is equivalent to 76% of the actual demand in 2005; therefore, air traffic demand must decrease between 2005 and 2050 to achieve this result even with new aircraft meeting fairly aggressive goals for fuel consumption improvements.

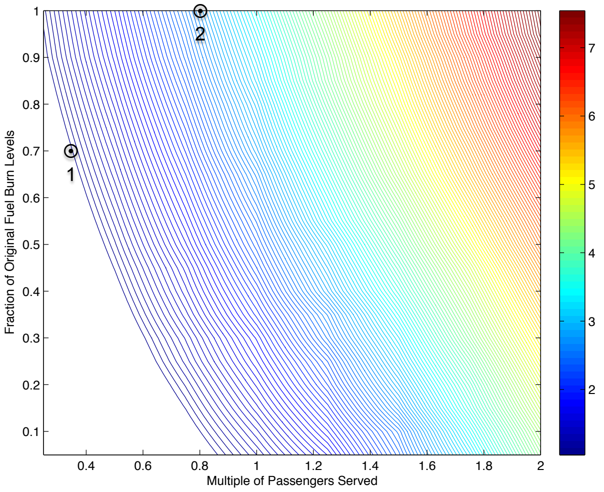


Figure 5. Contours of Exceedance of the IATA 50% of 2005 CO_2 Emission Levels by 2050 Goal – All Categories of Aircraft

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 factor that combination exceeds 50% of 2005 CO_2 emissions. For example, if projected passenger demand and fuel efficiency remain at their current levels (both multipliers = 1.0), 2050 CO_2 emissions will exceed 50% of 2005 levels by over a factor of 3 (or 300%) (Point 2 in Figure 5).

Another scenario explored represents the best case for investigating the IATA 2050 CO_2 goal. In 2050, the only aircraft available in the fleet are the new-in-class aircraft, and they all receive the same improvement in fuel efficiency. While this scenario is a bit unlikely given the unlikely assumption that the retirement of old aircraft and acquisition of new aircraft is such that every aircraft in the fleet has a 70% reduction in fuel consumption relative to the 2005 "best-in-class" aircraft, it still allows the evaluation of IATA's emission goals.

Figure 6 presents the results. If demand reaches the projected 2050 level (2% annual growth from 2008 levels to 2050), a fuel efficiency improvement of 70% across the entire fleet would result in 2050 CO_2 emissions that are 50% of the 2005 CO_2 emissions (Point 1 in Figure 6). This 70% reduction in fuel consumption for aircraft operating in 2050 relative to their current (2005) counterparts aligns with NASA's SFW N+3 fuel burn goal, which is intended for aircraft entering service around 2030 to 2035. The NASA SFW goals rely upon systems analysis studies that suggest this kind of fuel reduction is technically possible by 2050; however, the result obtained here requires that all aircraft in the 2050 fleet have this improvement. Replacing the entire fleet with brand new aircraft in 15 years from the 2035 entry in service date to 2050 might be difficult, because the typical operational lifespan of an aircraft is 25 years and aircraft entering service in the 2015 time frame may have design lifetimes that exceed 30 years. This makes the propagation of new aircraft and new aircraft technology into the fleet a slow process, at least under the approach provided by following the MITRE Fleet Forecast. The MITRE Fleet Forecast predicts approximately 19,500 aircraft in the US commercial fleet in 2050; therefore, a minimum of 1,300 of these new aircraft would have to be produced every year from 2035 to 2050 to replace the entire fleet (assuming a constant production and purchase rate).

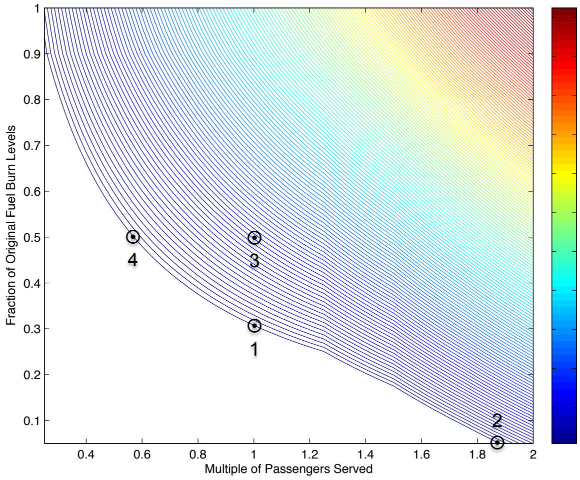


Figure 6. Contours of Exceedance of the IATA 50% of 2005 CO_2 Emission Levels by 2050 Goal – Only New-in-Class Aircraft

By further examining the results assessing the IATA CO_2 goal for 2050, Point 2 in Figure 6 indicates that with the aggressive assumption that the entire fleet has a 95% improvement in fuel consumption compared to the best-in-class aircraft, the fleet could support a passenger growth of 86% above (i.e. passenger multiple of 1.86) the projected 2050 demand and still meet the IATA goal.

Under a possibly more realistic scenario of the entire fleet having a 50% improvement in fuel burn relative to today's best-in-class aircraft to serve the projected 2050 demand, CO_2 emissions would exceed the IATA goal by 1.69 times (Point 3 in Figure 6); however, this scenario would produce less CO_2 than 2005 emissions, which is definitely a step closer to achieving the goal set forth by IATA. To achieve the IATA goal with only a 50% improvement in fuel burn, passenger demand would have to be reduced by 45% below the predicted level for 2050 (Point 4 in Figure 6).

Using carbon credits and / or considering lifecycle CO_2 emissions for bio-fuels (i.e. taking credit for CO_2 absorbed by the bio-mass during its growth), it may be possible to "book keep" CO_2 emissions to IATA's desired level. However, in a practical sense, IATA's emission goals are very ambitious and will be a challenge for the aviation industry to achieve, if continued growth in air travel demand is also an objective.

C. Study 3: Examine the Impact of a Discrete Technology in 2008

The previous results demonstrated that new concepts influence the amount of CO_2 emitted from aircraft, and the results from this study also show that a discrete technology (here, winglets) also impact fuel burn and thus CO_2 emissions. As shown in Table 6, the winglets have an immediate impact on reducing CO_2 emissions, even when fuel burn decreases by 1% in only one class of aircraft. In each of the scenarios, the total fleet-level CO_2 decreased with the addition of winglets to the class 4 and class 5 representative-in-class aircraft. Additionally, in all but one case (2% fuel reduction with class 4 winglets) the total fleet-level DOC also decreased. While the 2% fuel reduction for class 4 winglets case leads to a 0.22% increase in DOC, the relative gap for that case is noticeably higher for that case (at 1.81%) than for others in the study. While another solution at a lower relative gap might have led to a similar reduction in DOC, since 1.81% falls under the 2% required gap, the branch-and-cut algorithm stopped.

The results for class 4 aircraft with winglets and class 5 aircraft with winglets in Table 6 can be compared directly against each other, because the baseline scenario with no winglets has the same result for the two different studies. While retrofitting winglets to class 4 and class 5 aircraft both reduced the fleet-level CO_2 emissions and DOC, the class 4 representative-in-class aircraft with winglets reduced CO_2 emissions by a larger percentage than the class 5 representative-in-class aircraft with winglets. Conversely, class 5 aircraft with winglets led to a reduction in DOC greater than twice that of the scenarios with class 4 winglets.

In 2008, 1,130 class 4 and 830 class 5 representative-in-class aircraft were available for allocation. Evaluating the fleet-level change in CO_2 emissions and DOC at the aircraft level, the change in CO_2 is greater when class 4 aircraft receive winglets only when the fuel burn reduction is between 1%, 3% and 4%, otherwise the class 5 aircraft with winglets reduce fuel burn by a larger amount per aircraft. However, at the aircraft level, retrofitting class 5 aircraft with winglets results in a larger decrease in DOC under every fuel burn reduction scenario; oftentimes there is over a 300% difference between class 4 and class 5 DOC reductions.

Table 6. Impact of Retrofitted Winglets on Fleet-Level Metrics

	Winglet Fuel Imprv.	**Fleet $\Delta \mathrm{CO_2}$ [%]**	**Fleet ΔDOC [%]**	**Fleet $\Delta \mathrm{CO_2}$ per A/C [lb]**	**Fleet ΔDOC per A/C [$]**	**Norm. Tot. Miles Flown [nmi]**	**Tolerance Gap**
Rep Class 4	- 1%	- 0.53%	- 0.28%	- 4,112	- 491	0.959	0.83%
	- 2%	- 0.57%	+ 0.22%	- 4,429	386	0.991	1.81%
	- 3%	- 1.20%	- 0.38%	- 9,309	- 680	1.005	0.94%
	- 4%	- 1.72%	- 0.90%	- 13,429	- 1,611	1.016	0.55%
	- 5%	- 2.06%	- 1.04%	- 16,024	- 1,857	1.019	0.55%
	- 6%	- 2.39%	- 1.11%	- 18,631	- 1,981	1.020	0.48%
	- 7%	- 2.72%	- 1.21%	- 21,179	- 2,155	1.021	0.49%
Rep Class 5	- 1%	- 0.19%	- 0.25%	- 1,998	- 611	1.000	1.77%
	- 2%	- 0.45%	- 0.70%	- 4,737	- 1,708	1.053	1.79%
	- 3%	- 0.77%	- 1.15%	- 8,121	- 2,785	1.233	1.78%
	- 4%	- 1.05%	- 1.88%	- 11,084	- 4,567	1.399	1.87%
	- 5%	- 1.55%	- 2.56%	- 16,453	- 6,222	1.634	1.77%
	- 6%	- 1.80%	- 2.59%	- 19,073	- 6,292	1.793	1.95%
	- 7%	- 2.24%	- 2.75%	- 23,759	- 6,686	1.834	1.94%

Lastly, when looking at how the utilization of the aircraft with winglets changes in the allocation, Table 6 shows that, generally, the allocation tool selects aircraft retrofitted with winglets for a larger amount of miles flown with respect to the baseline allocation. The increase in miles flown by the class 4 aircraft with winglets is quite modest, only 2.1% at most, and in a few scenarios (-1% and -2% in fuel burn), the total mileage of the class 4 aircraft with winglets was lower than without winglets. On the other hand, the class 5 aircraft with winglets flew significantly more total mileage with winglets than without winglets. When the winglets provided the largest fuel burn improvement of -7%, the allocation solutions allocated class 5 representative-in-class aircraft to fly 84% more mileage than this aircraft flew in the baseline solution. Even when the fuel burn reduction from the winglets is only 2%, class 5 representative-in-class aircraft flew a total of 5% more miles, which is a larger change than the best case for the winglets on class 4 aircraft.

Since the DOC of the class 4 and class 5 representative-in-class aircraft are not adjusted to account for the winglets, the change in DOC at the aircraft level could indicate if the additional cost of the winglets is worth the savings in fuel. For example, the change in DOC at the aircraft level for the class 5 aircraft when the winglets reduce fuel consumption by 3% is -$2,785. Therefore, if the cost of adding the winglets to all the class 5 aircraft is less than the equivalent of $2,785 per day, then the investment in the winglets will be beneficial to the airline. While this might not be an exact method, this ability to do a rough estimation of a cost-benefit analysis is a useful outcome of the allocation tool.

As indicated by the results in Table 6, when the class 5 representative-in-class aircraft receives winglets, the amount of mileage flown by that aircraft increases by up to 84%. To provide a better understanding of how the allocation "shuffles" around aircraft, Table 7 presents the normalized total mileage (with respect to the baseline with no winglets) for all of the 12 aircraft available for allocation.

The baseline scenario has been omitted from the table because all of the values are equal to 1.00, since the baseline scenario is used to normalize the winglet scenarios. The class 5 representative-in-class allocation has been highlighted in red. Even though for some of the earlier scenarios there is an increase in miles flown – with 1% fuel burn improvement there is a large increase – the class 3 representative-in-class aircraft sees the largest decrease in mileage, up to -95%. Other aircraft that see a noticeable decrease in mileage flown are class 4 representative-in-class aircraft and class 1, class 2 and class 3 best-in-class aircraft. While the class 5 best-in-class aircraft maintains the most consistent mileage, the class 6 best-in-class aircraft flies additional mileage as winglets improve fuel burn. However, the class 6 representative-in-class aircraft is flown for less mileage when winglets are introduced, and since the class 6 aircraft are identical in both categories, the increase for the best-in-class aircraft is offset by the decrease in the representative-in-class aircraft.

Table 7. Normalized Total Mileage in 2008 with Class 5 Winglets [nmi]

Aircraft	1% Winglet	2% Winglet	3% Winglet	4% Winglet	5% Winglet	6% Winglet	7% Winglet
Rep Class 1	1.01	1.03	1.08	0.92	0.91	0.86	0.86
Rep Class 2	0.96	0.94	0.92	0.80	0.76	0.80	0.80
Rep Class 3	1.73	1.15	0.85	0.05	0.10	0.05	0.05
Rep Class 4	0.97	0.86	0.77	0.71	0.62	0.61	0.61
Rep Class 5	1.05	1.23	1.40	1.63	1.79	1.83	1.84
Rep Class 6	1.00	0.98	0.96	0.84	0.89	0.88	0.86
Best Class 1	0.87	0.78	0.69	0.57	0.57	0.53	0.53
Best Class 2	1.07	0.98	0.80	0.54	0.61	0.52	0.52
Best Class 3	0.99	0.99	0.98	0.78	0.66	0.66	0.65
Best Class 4	0.99	0.97	0.95	0.93	0.93	0.92	0.92
Best Class 5	1.00	0.99	0.99	1.00	0.99	1.00	1.00
Best Class 6	1.00	1.03	1.02	1.08	1.08	1.06	1.08

V. Future Work

Currently, all aircraft are allocated using a single IP problem. By decomposing the problem into several smaller subproblems that are more easily solved, the time required to solve the entire allocation problem may reduce as well. Such a decomposition strategy may also allow larger problems to be solved in a similar time as the current large IP problem; a larger problem will allow more airports and aircraft to be modeled. Additionally, the possibility of implementing a complex revenue model and / or some form of elementary aircraft scheduling becomes viable if the problem can be effectively decomposed. Furthermore, solving many smaller allocations may allow the relative tolerance gap between the integer and linear solutions to be further reduced, providing solutions closer to the best estimate.

The collaborative optimization approach is a strategy for designing large-scale aerospace systems using multidisciplinary design optimization (MDO).[13] By decomposing the problem into subproblems (usually each subproblem is a single discipline of the multidisciplinary problem) and using a top-level problem to coordinate the subproblems, the problem may be solved more efficiently and the optimum solution accounts for all of the disciplines. This kind of concept may provide guidance for decomposition of this fleet-wide allocation problem. Following this concept, possible decompositions include creating a separate problem for each airline or create separate problems for each route. These two possibilities are illustrated in Figure 7.

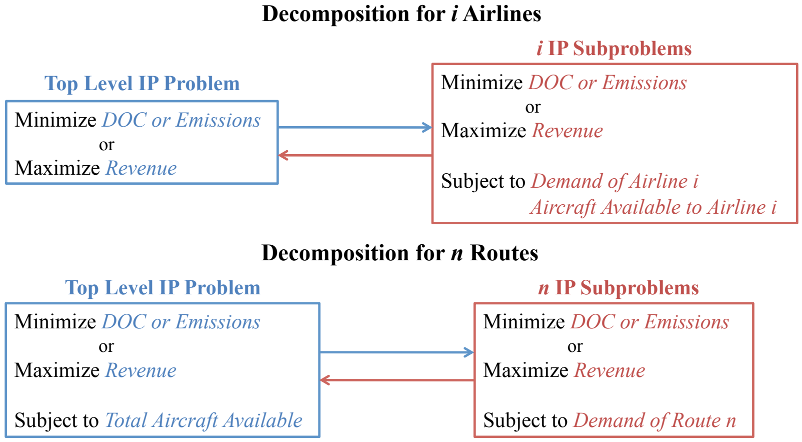


Figure 7. Possible Decompositions for Future IP Formulations

Studies will explore if decomposing the problem formulation to reduce run time could also remove some of the abstractions currently made in this fleet-level assessment tool. The possibility of removing round trip assumptions or increasing the number of airports and aircraft, which increase the size of the problem as currently formulated, will increase the detail of the allocation tool.

In addition to decomposing the problem into smaller IP problems, other features such as using a revenue model to enable maximization of profit, representing multiple airlines – perhaps with some representation of competition – and including more aircraft from a "closed" sizing process are of interest for further development and investigation. These additions will allow the aircraft allocation to better represent airline operations.

VI. Conclusions

The studies and work presented here have shown that an allocation problem provide an approach to evaluate how new aircraft and new aircraft technology 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 an estimate of aircraft numbers and types that allowed for fleet compositions into the year 2050. Through these studies, several general trends and significant results emerged.

With the improvement in aircraft fuel efficiency modeled, CO_2 emissions and fleet DOC will continue to grow from 2005 through 2050, because the assumption of a 2% yearly increase in passenger demand outpaces the ability of introducing new technology to the commercial aircraft fleet operating within and to/from the United States. However, the improved technology does limit these increases in CO_2 emissions and fleet DOC to occur at a slower rate than the increase in passenger traffic. Therefore, while minimizing either DOC or CO_2 emissions as the objective in the allocation problem, the fleet CO_2 emissions per passenger mile and DOC per passenger mile flown do decrease from 2005 through 2050.

The allocation tool also demonstrated that it could represent how a discrete technology, such as winglets, retrofitted onto older aircraft could also reduce fleet fuel burn. Even though the aircraft were not resized and the DOC for the aircraft was not updated to reflect the retrofits, the allocation tool provides information as to how much the DOC per aircraft changes as a result of the winglets, which could be used for a cost-benefit analysis. Additionally, the allocation tool shows that typically aircraft with retrofits become more attractive for allocation due to their decreased fuel burn; thus, they are allocated to fly more miles than they flew without winglets. Given the modeling used here, when the class 4 representative-in-class aircraft received the best performing winglets, the largest benefit to CO_2 emissions occurred. When the class 5 representative-in-class aircraft received the best performing winglets, the largest benefit to total fleet DOC occurred.

The results in Section B indicate that if NASA's fuel burn goal for the N+3 generation aircraft is achieved and these new aircraft make up the entire fleet, then the goals set forth by IATA for 2050 emissions are achievable. However, NASA's SFW goals are intended targets for individual aircraft and not the entire fleet. For NASA's goals to be effective at meeting fleet-wide goals like the IATA goal for 2050 CO_2 emissions to be 50% of the 2005 emissions, the new aircraft that meet these NASA SWF goals must have a large penetration into the aircraft fleet mix.

While IATA's emission goals are commendable, if the assumptions and abstractions used in the studies described above are reasonable, that the future fleet-level goals for CO_2 emissions might be too aggressive and are possibly unattainable. To achieve 50% of 2005 CO_2 emissions, the *ENTIRE* fleet needs to reduce fuel burn by 70% relative to the best-in-class aircraft modeled here. The long operational life of aircraft greatly reduces the ability for new aircraft to quickly saturate a market, which complicates meeting aggressive fleet-wide emissions goals. Additionally, developing and then producing a new aircraft with substantially improved technology is not without difficulty. Nonetheless, if improvements estimated by IATA's Technology Roadmap[2] are attainable and economically appealing to the airlines, improvements in CO_2 emissions will be inevitable.

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