

An Allocation Approach to Investigate New Aircraft Concepts and Technologies on Fleet-Level Metrics

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Aircraft noise and emissions have gained importance in recent environmental discussions. This paper presents the development of an allocation tool that assesses how new aircraft concepts and technologies impact fleet-wide emissions and noise by computing fleet-level metrics such as direct operation cost (DOC), CO₂ emissions, LTO NO_x emissions and total area under the 65db noise contour. By modeling 12 different aircraft and a 102-airport network, the tool is able to quickly assess if an aircraft fleet can feasibly be allocated throughout the network to minimize direct operating costs and still maintain a given level of emissions. Initial results indicate that if 2005 emission levels are desired in 2015 and beyond, the efficiency of aircraft must increase or the amount of passengers served must decrease.

Nomenclature

α_a	=	Weighted Importance of Factor a in Objective Function
BH_{ij}	=	Block Hours for Aircraft i on Route j
d_j	=	Demand on Route j
κ	=	Scaling Factor
MH	=	Maintenance Hours
n_i	=	Number of Aircraft i
p_i	=	Passengers on Aircraft i
r_j	=	Range of Route j
TH	=	Turn Time Hours
x_{ij}	=	Number of Aircraft i on Route j

I. Introduction and Motivation

THE NASA Subsonic Fixed Wing (SFW) Project key research areas and goals emphasize the importance of reducing both noise and emissions in future generations of aircraft. NASA hopes to reduce fuel burn by 33% and landing and takeoff nitrogen oxide (LTO NO_x) by 60% in their N+1 generation aircraft, which has an expected entry in service date of 2015. With initial operating capability by 2020, NASA's N+2 generation aircraft hopes to reduce fuel burn by 40% and LTO NO_x by 75%. The N+3 generation aircraft, with an expected entry in service between 2030 and 2035, hopes to reduce fuel burn by more than 70% and LTO NO_x by more than 75%.¹ With the development of a tool that calculates fleet-level metrics such as carbon dioxide (CO₂) emissions, LTO NO_x emissions and total area under the 65db noise contour, one can quickly 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 and gives a high-level view of how the entire system is affected with the introduction of a new aircraft or aircraft technology. The environmental and economical impact of new aircraft is a function of both aircraft performance and the airline's use of new and existing aircraft. To properly gauge the impact of future aircraft and new technology, 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.

One approach to evaluate the changes that result from the introduction of a new technology or aircraft is to simply "replace" existing aircraft in the system with new and improved aircraft while keeping the network of

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operations unchanged. While easy to implement, this approach ignores important aspects of airline operations. Airlines might use new aircraft in different ways depending on their velocity, range, passenger capacity, fuel efficiency, etc. If the aircraft are not optimally allocated on existing routes, the observed changes caused by the new aircraft may not reflect the full potential of the new aircraft and aircraft technology. Therefore, once the new aircraft are introduced into the system, reallocating them in the air transportation system will give a more realistic picture of their utilization and ultimately, the fleet-wide emissions and noise levels. By giving the assessment tool the ability to optimally allocate the flights amongst the available routes, the objective can be varied to minimize fleet-wide direct operating costs (DOC), CO₂ emissions, LTO NO_x emissions, total area under the 65db noise contour, or a weighted combination of the fleet-wide metrics. The tool can quickly explore numerous “what if” scenarios and provide a means to explore various tradeoffs from different scenarios, objectives, regulations and allocations.

In addition to future generations of aircraft and new aircraft technologies, ambitious noise and emissions goals are expected in the foreseeable future.¹ These goals are modeled as emission and noise restrictions placed on the fleet. While future aircraft and aircraft technologies will help reduce noise and emissions, they will operate in concert with current generation aircraft, which means that the technology assessment tool should consider the utilization of both current and future aircraft. In order to simulate these changing goals, 2005 is established as the baseline year for the study and the emissions and noise of future aircraft allocations will be compared the values of this baseline allocation.

Resource allocation is a common problem in the operations research community and often takes the form of a large integer program. The objectives vary from optimizing maintenance, to optimizing scheduling, to optimizing crew assignments. Oftentimes, these integer programs require high computational time and effort. Various efforts have developed algorithms and methods to reduce the computation time and complexity of an aircraft allocation problem^{2,3,4}; however, none of the referenced allocation models incorporate fleet-level metrics such as emissions and noise area in the problem formulation.

In an effort to reduce the size and complexity of the allocation problem, several abstractions are made. They include reducing the size of the air transportation network, reducing the number of aircraft models and airlines, and assuming that each aircraft performs a round-trip operation on its allocated route. However, many barriers still exist in creating an efficient allocation tool to allow a wide array of studies that are time efficient and have consistent solutions. This study presents a tool that, while simplified, provides the means to assess the environmental impact of new aircraft and technologies at the fleet level.

II. Problem Statement

To properly assess the impact of new technology and aircraft concepts on fleet-level metrics, the allocation tool needs to quickly and consistently allocate flights throughout the air transportation network and calculate the fleet-level metrics based on the new allocation. In order to properly optimize the allocation of the fleet using the tool, an objective function, decision variables and constraints must all be defined. While the objective function and constraints can change for various scenarios, minimizing fleet-wide DOC and constraining CO₂ and LTO NO_x emissions are the focus of this study.

In order to reduce the complexity of the aircraft allocation problem, several abstractions are made. The tool assumes that only one benevolent, monopolistic airline exists to meet all passenger demand. This eliminates the need to model multiple agents within the allocation problem. Additionally, the tool assumes that the LMINET 102 airports⁵ make up the entire US air transportation network. In 2005, approximately 70% of all US flights (cargo and passenger) had their origin or destination at one of the LMINET 102 airports.⁶

Additional abstractions help reduce the size of the aircraft allocation problem. Since the airlines currently serving the LMINET 102 airports use a multitude of aircraft models, the allocation model groups all aircraft into six classes based on their passenger capacity. Twelve unique aircraft models, two for each class, were chosen to represent all aircraft models used by airlines. The first group consists of the representative-in-class aircraft; these are the aircraft that had the most operations in 2005 in their class. The second group of six aircraft, the best-in-class aircraft, consists of the aircraft with the latest entry in service date within the class. Table 1 lists the aircraft of each group. Since the Boeing 777-200 was the most used class six aircraft in 2005 and had the latest entry in service date, it was used in both representative-in-class and best-in-class groups.

The decision variables are the number of trips each aircraft in each class performs on a specific route in the network. The tool assumes that each aircraft performs a round trip on its allocated route (i.e. the aircraft flies from City A to City B and then from City B to City A), which halves the number of decision variables. The passenger demand of each route between a given city pair can be served by any aircraft model.

Table 1: Aircraft Used for Representative-in-Class and Best-in-Class.

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

With these abstractions, the aircraft allocation problem is modeled as an integer program (IP) formulated as:

$$\text{Minimize } \alpha_1 DOC(x_{ij}, r_j, p_i) + \alpha_2 CO_2(x_{ij}, r_j, p_i) + \alpha_3 LTO NO_X(x_{ij}, r_j, p_i) + \alpha_4 Noise Area_k(x_{ai}) \quad (1)$$

$$\text{Subject to } \sum x_{ij} p_i \geq d_j \quad \text{for all routes } j \quad (2)$$

$$\sum x_{ij} (BH_{ij} + TH + MH) \leq 12n_i \quad \text{for all aircraft } i \quad (3)$$

$$\text{Optionally } CO_2 \leq \kappa CO_{2,2005} \quad \text{for total fleet } CO_2 \quad (4)$$

$$LTO NO_X \leq \kappa LTO NO_{X,2005} \quad \text{for total fleet } LTO NO_X \quad (5)$$

$$Noise Area_k \leq \kappa Noise Area_{k,2005} \quad \text{for each airport } k \quad (6)$$

$$DOC \leq \kappa DOC_{2005} \quad \text{for total fleet } DOC \quad (7)$$

The objective function of the IP formulation (Eq. 1) consists of a combination of the various fleet-level metrics. For fleet-level metrics, the allocation problem uses DOC as a surrogate for profit and revenue under the assumption that the lowest DOC will provide the largest profit, fuel burn as a surrogate for CO₂ emissions, LTO NO_X emissions, and the area under the 65dB noise contour as airport noise area. Using a conceptual aircraft design software package developed by NASA, values for DOC and emissions, such as fuel burn and LTO NO_X, were generated for each aircraft. This software, FLight OPTimization System (FLOPS)⁷, simulates an aircraft mission and determines the amount of fuel burned by the aircraft and how much NO_X was emitted during landing and takeoff. FLOPS simulated various missions with different ranges and aircraft load factors to create tables for DOC, fuel burn and LTO NO_X. These data tables determined DOC, fuel burn and LTO NO_X emissions on every route for every aircraft using linear interpolation. The area under the 65dB noise contour is calculated using a linear regression model developed by Dikshit.⁸

The constraints in Eq. 2 ensure that all passenger demand is met. The allocation of aircraft must provide enough capacity to transport sufficient passengers to meet the demand on all of the routes between the 102 LMINET airports. The demand on each route is based on the Bureau of Transportation Statistics (BTS) reported passengers for 2005.⁹ Because a round trip approach is implemented, the roundtrip demand is equal to the maximum demand of the two one-way segments between the two cities. Taking the maximum demand of each segment ensures that a roundtrip will meet the demand for each of the two one-way segments.

Lastly, because the amount of aircraft available for allocation is finite, the allocation problem contains an aircraft flight hour limit (Eq. 3). The flight hour limit consists of three components: (1) block hours flown on the route, (2) turn-around time at the airport, and (3) maintenance hours on the aircraft. FLOPS generates the block hours for each aircraft on each route. The average turn-around time for an aircraft at an airport is between 45 and 60 minutes,¹⁰ so a turn-around time of one hour per roundtrip is assumed here. According to Boeing's website, "For every hour that a plane is in flight, maintenance crews spend roughly three-and-a-half hours working to maintain it,"¹¹ so for every block hour flown, 3.5 hours of maintenance time is assumed. The constraints in Eq. 3, therefore, ensure that an aircraft is not utilized for more than 24 hours in a given day. This set of constraints also ensures that passenger demand must be met with the available fleet of aircraft. In some allocation studies, the fleet-level metrics also serve as constraints (Eqs. 4,5,6,7). 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. Typically, the fleet-level constraints are set not to exceed the emission levels of 2005, the baseline year for the studies presented here.

Originally the tool was developed as a spreadsheet-based tool using Microsoft Excel and Frontline Systems Premium Solver Platform¹²; however, due to the large model size and slow solving speeds the tool is currently modeled using GAMS and CPLEX¹³, which greatly improves performance. With the LMINET 102 network this IP problem has 123,624 decision variables. The large number of decision variables increases the size of the problem

and the computation time required to solve the problem. By assuming each aircraft performs a round trip operation the actual number of decision variables is cut in half to 61,812. However, before the allocation tool is run, all routes that have zero demand and aircraft that cannot fly a given route because of their limited design range or runway length limitations are removed from the problem, which reduces the decision variables by approximately one-fifth.

III. Allocation Studies

Several options exist for assessing the technological, environmental, and market impacts of introducing new technologies and aircraft to the current fleet. It is possible to model and allocate conceptual future aircraft, introduce new aircraft into the fleet at different rates, or replace specific aircraft types with future aircraft concepts. In an attempt to provide an orderly analysis, this study considers two approaches for measuring the impact of new technologies on future operations. The first is a direct replacement approach and the second is an allocation approach.

Before any allocations take place, the tool can simply use a “direct replacement” technique to get a general idea of how newer aircraft benefit the fleet. By first replacing all aircraft that flew in 2005 with their corresponding representative-in-class aircraft we can establish a direct replacement baseline. The best-in-class aircraft then replace the representative-in-class aircraft and the tool shows how fleet-wide metrics of emissions and noise are affected. These simple direct replacement studies provide a first-cut look at the changes in the fleet-wide metrics the new aircraft provide; however, to better understand the potential savings offered by the new aircraft, all aircraft need to be re-allocated across the network.

Several different scenarios can be used to assess technological, environmental and market impacts to the fleet-level metrics based on the fleet composition; varying the mix of aircraft types in the fleet creates each scenario. The best-in-class aircraft have the latest entry in service date, thus representing newer technology being introduced into the fleet. Varying the fleet mix from 100% representative-in-class to 100% best-in-class simulates the infusion of newer technology into the fleet. A matrix of allocation scenarios to assess the impact of technology and environmental restrictions easily organizes our approach (see Figure 1). The pink box in the upper left-hand corner represents the baseline allocation of 100% representative-in-class aircraft and no environmental constraints. The results of this allocation provide the fleet-level metric values that serve as the constraints for future scenarios and as a comparison of the other scenarios. From this baseline scenario, moving right across the matrix represents an increase in the technology level, while moving down the matrix represents more strict environmental restrictions. For example, the middle box of the matrix represents a fleet with 50% representative-in-class aircraft and 50% best-in-class aircraft (infusion of “newer” technology), and CO₂ and LTO NO_x emissions are constrained to be below 2005 baseline levels (environmental restrictions). For this study, the first row assumes 2005 demand and fleet size levels, the second row assumes 2015 demand and fleet size levels and the third row assumes 2025 demand and fleet size levels. Moving along a row does not affect demand and fleet sizes.

		New Technology Level		
		None (2005)	Some (2015)	Significant (2025)
Environmental Constraints	Current (2005)	100% Rep-in-Class Min: DOC Constraints: Pax demand, flight hour limits	50%-50% Rep/Best-in-Class Min: DOC Constraints: Pax demand, flight hour limits	100% Best-in-Class Min: DOC Constraints: Pax demand, flight hour limits
	Loose (2015)	100% Rep-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2005}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2005}$ Pax demand, flight hour limits	50%-50% Rep/Best-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2005}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2005}$ Pax demand, flight hour limits	100% Best-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2005}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2005}$ Pax demand, flight hour limits
	Strict (2025)	100% Rep-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2015}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2015}$ Pax demand, flight hour limits	50%-50% Rep/Best-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2015}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2015}$ Pax demand, flight hour limits	100% Best-in-Class Min: DOC Constraints: $CO_2 \leq \kappa CO_{2\ 2015}$ $LTO\ NO_x \leq \kappa LTO\ NO_{x\ 2015}$ Pax demand, flight hour limits

NOTE: $\kappa \leq 1.0$ and is used as a scaling factor to simulate the “strictness” of the environmental constraints.

Figure 1: Matrix of Allocation Scenarios.

The objective in these allocation problems is to minimize the fleet DOC. For the baseline scenario there are no constraints on CO₂ and LTO NO_x emissions. This is meant to represent current practices or policies in the air transportation industry and will serve as a baseline for determining the limits for fleet-wide CO₂ emissions and fleet-wide LTO NO_x emissions. Changing the fleet mix to include best-in-class aircraft begins to infuse new technology and new aircraft into the fleet. For example, setting the fleet mix to 50% representative-in-class and 50% best-in-class corresponds to a possible fleet in 2015, where newer aircraft models are just as common as the older aircraft models. Changing the fleet mix to 100% best-in-class aircraft corresponds to a possible fleet in 2025 where all newer aircraft models are used. While the shift to 100% best-in-class aircraft is unlikely by 2025, the desire for implementing newer technologies and reducing emissions can be easily modeled without adding more aircraft models (and complexity) to the allocation.

The next set of scenarios contains CO₂ and LTO NO_x constraints. Incorporating these constraints into the allocation simulates the enforcement of environmental restrictions by forcing the allocation to use less fuel and emit less LTO NO_x than the baseline allocation. If one wants to simulate loose environmental goals and restrictions, the constraint is set to a high percentage of 2005 values (for example 99% of the 2005 value), but if strict environmental goals and restrictions are desired the constraint is set to a lower percentage of 2005 values (for example, 90% of the 2005 values). Similar to the previously discussed scenarios, changing the fleet mix simulates the penetration of new technology into the fleet. With the emission constraints active, the allocation tool determines how the new technology improves the fleet-level metrics. Under some restrictions (via the constraints), a fleet mix of 100% representative aircraft might not be feasibly allocated, which would represent the impossibility of meeting environmental restrictions using an older fleet. However, under the same constraints, a fleet that has a certain percentage of best-in-class aircraft may be allocated, thus showing that with an infusion of new technology emissions can remain at the 2005 baseline level.

Depending on the scenario analyzed, DOC, CO₂ and LTO NO_x can all be used in the objective function or as constraints. For example, an objective function that minimizes CO₂ evaluates how low CO₂ emissions can be driven and at what cost to the airlines. Different combinations of objective functions and constraints easily simulate varying economical, environmental and political policies and explore how these policies shape fleet-level metrics. However, for this study the objective function is set to minimize fleet-wide DOC while maintaining 2005 fleet-level CO₂ and LTO NO_x emissions.

IV. Results

As previously mentioned, two approaches for measuring the impact of new technologies on future operations are considered here. The first is a direct replacement of the existing fleet while the other is based on the allocation of aircraft to serve passenger demand in the air transportation network. Results from these two approaches follow.

A. Direct Replacement

The direct replacement study shows the impact of replacing representative-in-class aircraft with best-in-class aircraft. Replacing all aircraft flown in 2005 with their representative-in-class counterparts determines an initial value for the fleet-wide environmental metrics and a comparison point for the best-in-class aircraft fleet. Since there is no allocation in this initial direct replacement problem, one-way segments replace the round trip segments used for the allocation problem, thus providing a slightly higher fidelity to actual 2005 operations Table 2 summarizes the results from the direct replacement study.

Table 2: Summary of Results from Direct Replacement Study.

Metric	Rep-in-Class	Best-in-Class	Percent Change
DOC [\$ US 2005]	3.181×10^{10}	3.046×10^{10}	- 4.26%
CO ₂ [lb]	1.782×10^{11}	1.635×10^{11}	- 8.27%
LTO NO _x [g]	6.358×10^{10}	3.574×10^{10}	- 43.79%

When comparing the representative-in-class fleet-wide metrics to the best-in-class fleet-wide metrics, the impact of the new aircraft is quite substantial. Total CO₂ emissions are reduced by 8.27%, DOC is reduced by 4.26% and LTO NO_x emissions are reduced by 43.79%. Again, these results indicate the level of impact that a fleet of new aircraft – and hence newer technology – has on both cost and emissions. Figure 2, Figure 3, and Figure 4 show a breakdown by aircraft class of fleet-wide CO₂ emissions, DOC and LTO NO_x emissions, respectively, for both representative- and best-in-class aircraft.

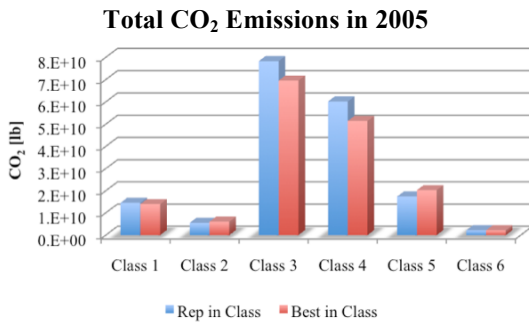


Figure 2: Class breakdown of CO₂ emissions from direct replacement study.

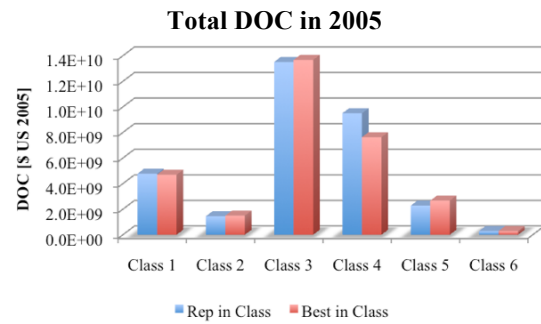


Figure 3: Class breakdown of DOC from direct replacement study.

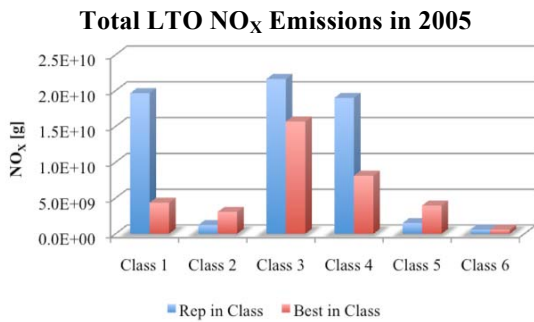


Figure 4: Class breakdown of LTO NO_x emissions from direct replacement study.

Figure 2 and Figure 3 show that in most aircraft classes the total CO₂ emissions and DOC decrease by replacing the representative-in-class aircraft with the best-in-class aircraft. In class three, there is a large decrease in total CO₂ emissions but an increase in total DOC. This illustrates that with some aircraft lower emissions result in high costs – some aircraft have lower emissions but higher operating costs than others. Figure 2 also shows that the class five best-in-class aircraft does not outperform the class five representative-in-class aircraft in terms of CO₂ emissions, yet the entire fleet has lower CO₂ emissions with the best-in-class aircraft. Figure 4 shows a large difference in LTO NO_x emissions between the representative-in-class aircraft and best-in-

class aircraft for class one and class four. The engine deck used by FLOS for several of these aircraft have varying levels of detail in the NO_x emissions, so the representative-in-class aircraft for class one and class four were simply scaled based on equivalent engine models with detailed NO_x values. This results in less accurate estimation of LTO NO_x emission for these two aircraft classes and the trends observed in Figure 4.

B. Allocation Studies

To optimize the utilization of the new aircraft, the allocation model minimizes the fleet DOC while allocating the representative-in-class and best-in-class aircraft throughout the LMNET network. Nine different allocation results based on the scenario matrix (Figure 1) show how various fleet mixes and emission regulations affect the CO₂ and LTO NO_x emissions of the fleet. These allocations are done based on daily operations and demand on each route instead of the annual operations and demand that the direct replacement study explored. The first three allocation studies, corresponding to the first row of Figure 1, do not constrain the CO₂ and LTO NO_x emissions; the goal is to minimize the fleet-wide DOC while meeting demand on every route and not exceeding flight hour limits. For these studies, the demand remained unchanged at 2005 levels as did number of aircraft in each class. For each scenario, the fleet mix changed from 100% representative-in-class aircraft, to 50% representative-in-class 50% best-in-class, to 100% best-in-class aircraft. Table 3 shows the values of the fleet-level metrics from the first three allocation studies.

Table 3: Summary of Results from 2005 Allocations without Environmental Constraints.

Metric	100% Rep-in-Class	50% Rep-in-Class 50% Best-in-Class	100% Best-in-Class
DOC [\$ US 2005]	1.213 x 10 ⁸	1.099 x 10 ⁸	1.078 x 10 ⁸
CO ₂ [lb]	1.603 x 10 ⁸	1.420 x 10 ⁸	1.382 x 10 ⁸
LTO NO _x [g]	1.265 x 10 ⁸	9.803 x 10 ⁷	8.332 x 10 ⁷

As the best-in-class aircraft replaced the representative-in-class aircraft, DOC, CO₂ emissions and LTO NO_x emissions decreased. These decreases in the fleet-wide metrics illustrate that at the fleet-level the best-in-class

aircraft have lower emissions and are less expensive to operate. While some individual best-in-class aircraft might not outperform their representative-in-class counterpart in terms of DOC, CO₂ or LTO NO_x emissions (e.g. the class five aircraft in terms of fuel burn as illustrated in Figure 2), at the fleet level the performance of the best-in-class fleet outperforms the representative-in-class fleet.

The second series of scenarios simulated 2015 environmental constraints by constraining the fleet-level CO₂ and LTO NO_x levels to be less than the levels from the 2005, 100% representative-in-class allocation (1.603 x 10⁸ lb and 1.265 x 10⁸ g). These three allocations correspond to the second row in Figure 1. Because these allocations model 2015 environmental constraints both the route demand and fleet size are assumed to increase by 2% annually to reflect 2015 levels. However, when the fleet-level CO₂ and LTO NO_x emissions were constrained to 2005 levels, the allocation became infeasible for each of the three different fleet mixes. By lifting the emission constraints, the allocations became feasible. Table 4 shows the values of the fleet-level metrics and the amount by which each emission metric exceeds its 2005 level from the second set of scenarios.

Table 4: Summary of Results from 2015 Allocations with Environmental Constraints.

Metric	100% Rep-in-Class	50% Rep-in-Class 50% Best-in-Class	100% Best-in-Class
DOC [\$ US 2005]	1.459 x 10 ⁸	1.345 x 10 ⁸	1.294 x 10 ⁸
CO ₂ [lb]	1.936 x 10 ⁸	1.749 x 10 ⁸	1.669 x 10 ⁸
Percent Over 2005 CO ₂	20.75%	9.10%	4.10%
LTO NO _x [g]	1.492 x 10 ⁸	1.241 x 10 ⁸	9.979 x 10 ⁷
Percent Over 2005 LTO NO _x	17.94%	- 1.89%	- 21.11%

With the 100% representative-in-class fleet mix, the 2015 CO₂ and LTO NO_x emissions exceeded the 2005 CO₂ and LTO NO_x emissions by 20.75% and 17.94%, respectively. With the 50% representative-in-class 50% best-in-class fleet mix, the 2015 CO₂ and LTO NO_x emissions exceeded the 2005 CO₂ and LTO NO_x emissions by 9.10% and -1.89%, respectively. Lastly, with the 100% best-in-class fleet mix, the 2015 CO₂ and LTO NO_x emissions exceeded the 2005 CO₂ and LTO NO_x emissions by 4.10% and -21.11%, respectively. Since the 50% representative-in-class 50% best-in-class fleet mix emitted less LTO NO_x than 2005 levels, infusing around 50% of the best-in-class aircraft into the fleet allows the fleet to maintain 2005 LTO NO_x emission levels; however, CO₂ levels never fall to 2005 levels with best-in-class aircraft.

Lastly, the third series of scenarios studies simulated 2025 environmental constraints by constraining the fleet-level CO₂ and LTO NO_x levels to be less than the levels from the 2015 100% representative-in-class allocation (1.936 x 10⁸ lb and 1.492 x 10⁸ g). These three allocations correspond to the third row of Figure 1. Similar to the second series of scenarios, the demand and fleet size were increased 2% annually to reflect 2025 levels. Originally, the 2015 emission levels were constrained to be below the 2005 emission levels; therefore, constraining 2025 emission levels to be below 2015 emission levels also constrains 2025 emission levels to be below 2005 emission levels. However, since these constraints resulted in an infeasible allocation for 2015, constraining 2025 emissions to be below 2005 emission levels would also be infeasible.

Once again, by lifting the emission constraints, the allocations became feasible. Table 5 shows the values of the fleet-level metrics and the amount each emission metric exceeds its 2015 level from the third three allocation studies.

Table 5: Summary of Results from 2025 Allocations with Environmental Constraints.

Metric	100% Rep-in-Class	50% Rep-in-Class 50% Best-in-Class	100% Best-in-Class
DOC [\$ US 2005]	1.763 x 10 ⁸	1.639 x 10 ⁸	1.607 x 10 ⁸
CO ₂ [lb]	2.338 x 10 ⁸	2.149 x 10 ⁸	2.064 x 10 ⁸
Percent Over 2015 CO ₂	20.76%	10.97%	6.58%
LTO NO _x [g]	1.855 x 10 ⁸	1.543 x 10 ⁸	1.265 x 10 ⁸
Percent Over 2015 LTO NO _x	24.36%	3.41%	- 15.19%

With the 100% representative-in-class fleet mix, the 2025 CO₂ and LTO NO_x emissions exceeded the 2015 CO₂ and LTO NO_x emissions by 20.76% and 24.36%, respectively. With the 50% representative-in-class 50% best-in-class fleet mix, the 2025 CO₂ and LTO NO_x emissions exceeded the 2015 CO₂ and LTO NO_x emissions by 10.97% and 3.41%, respectively. Lastly, with the 100% best-in-class fleet mix, the 2025 CO₂ and LTO NO_x emissions

exceeded the 2015 CO₂ and LTO NO_x emissions by 6.58% and -15.19%, respectively. Similar to the second series of scenarios, LTO NO_x emissions are able to drop below 2015 emission levels, but a larger percentage of the fleet must be best-in-class to achieve sub-2015 LTO NO_x levels.

These different scenarios illustrate the challenge of keeping emissions at 2005 levels while passenger demand and fleet size increases. While improvements in technology lower fleet-wide emissions, the newer technology fails to drive CO₂ emissions to levels at or below the 2005 baseline.

C. Improving Fuel Burn Technology and Varying Passengers Served

Many of the allocation studies generated infeasible solutions when demand increased (i.e. from 2005 levels to 2015 levels) and environmental constraints were imposed. This is an expected result because the allocation model determines the optimal aircraft allocation to minimize cost, hence minimizing fuel burn. When demand increases, the expectation to serve more demand with the same amount of fuel is not realistic. A better approach would be to identify how many fewer passengers must be served with the current technology level or how much improvement in fuel burn technology at the current demand would ensure that 2005-level emissions are not exceeded. Furthermore, if fuel burn is improved to meet 2005 emission levels, how many more passengers can be served while still maintaining 2005 emission levels? A study assuming an initial fleet mix of 50% representative-in-class and 50% best-in-class with fleet size and passenger demand reflecting 2015 levels was conducted to determine if reducing fuel burn and/or passengers would lead to CO₂ levels below the 2005 CO₂ levels.

To mimic technology improvements, the fuel burn of the aircraft was reduced by several values ranging from the original fuel burn of the aircraft down to 10% of the original fuel burn of the aircraft. This improvement in aircraft fuel burn was applied to all aircraft in the fleet at the same level (i.e. all 12 aircraft received the same efficiency improvements). While this “magic wand” improvement to the fleet is unrealistic, the results indicate to what extent the fuel burn of the aircraft needs to improve to reduce CO₂ emissions to 2005 levels. In addition to making the aircraft more efficient, the study varied number of passengers served from 300% the 2015 demand down to 10% of the 2015 demand. By examining demand levels greater than 2015 levels, the study can determine how many more passengers can be accommodated if the aircraft become more fuel-efficient. By varying both of these factors at the same time, the study will be able to answer the following three questions: (1) If demand stays the same, how much more efficient do the aircraft have to be to meet 2005 CO₂ levels? (2) If the efficiency of the aircraft remains the same, how many fewer passengers must be severed to meet 2005 CO₂ levels? and (3) What combinations of passengers served and aircraft efficiency lead to CO₂ levels at or below 2005 levels?

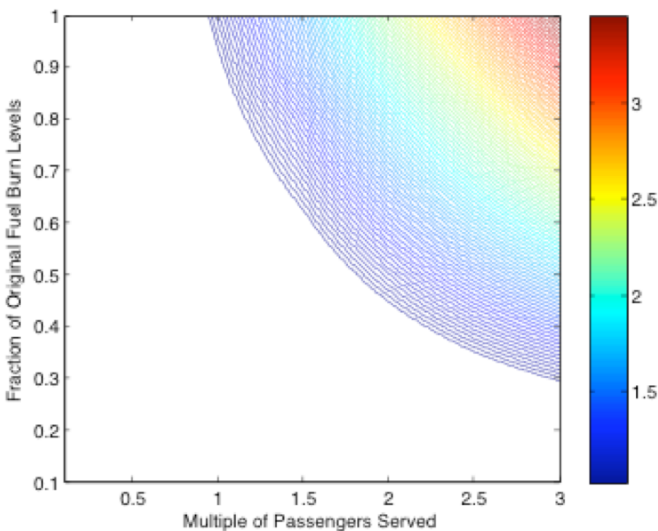


Figure 5: Contour Plot Showing Infeasible Passenger and Fuel Burn Combinations.

passengers served in 2015 must drop by approximately 7%. If fuel burn is reduced by 20%, the amount of passengers served increases by approximately 19%.

While improving the fuel burn of all current aircraft by 4% seems unrealistic, recent studies by Aviation Partners and Boeing estimate that fuel burn can be reduced by up to 6.5% by adding winglets to the Boeing 767-300ER.¹⁴ This is just one example of how current aircraft can become more efficient, and thus lower emissions. In addition, if

a new aircraft is introduced that reduces fuel burn by a large margin compared to a comparable existing aircraft, the possibility of that one aircraft being massively adopted and thus lowering the fleet's emissions is another possibility.

V. Future Work

This tool easily assesses fleet-level environmental metrics for various fleet mixes and scenarios; however, the allocation model used by this tool has several shortcomings because of the abstractions made to simplify the allocation. Using only 12 models for aircraft poorly represents the actual number of unique aircraft models used today. Additionally, the lack of multiple airlines minimizes the number of flights flown between cities, because no constraints exist to make sure the number of flights on each route reflects the number of airlines that actually fly that route. By making several improvements and additions to the allocation tool, the fidelity and realism of the allocation tool will increase. Such improvements include: better representation of airline profits through revenue modeling, decomposition of the allocation problem to allow for multiple airlines to be modeled, new studies involving future generation aircraft, simulation of aircraft retirement, dynamic demand modeling, and the ability to change available city pairs for operations. Another version of the allocation tool is currently being developed to incorporate super sonic transports (SST) into a larger international network. This international SST allocation tool contains productivity and mobility metrics to assess the impact of supersonic aircraft in the fleet. The addition of sensitivity and uncertainty bounds to help assess the allocation results are also being considered.

VI. Conclusions

The allocation tool presented here allocates aircraft amongst available routes to minimize DOC, CO₂ emissions, LTO NO_x emissions and other fleet-level metrics. By inserting new aircraft technology into the system and changing the performance of current aircraft through technology improvements, the tool allocates aircraft amongst the LMINET 102 airports and assesses how these future generations of aircraft and new technology impact fleet-level environmental metrics. This is a departure from current analyses, which consider the improvements and environmental impact of individual aircraft and/or technologies. The way in which an airline utilizes the aircraft can have a great impact on the ability of a new technology to achieve its predicted improvements and/or the fleet-level emission goals.

Through the allocation studies performed, the aircraft currently modeled and assumed to comprise the entire fleet of aircraft used by airlines cannot maintain 2005 emission levels in future years unless the number of passengers served decreases or the efficiency of the current aircraft improves. These results can help determine how much current aircraft need to improve in order to make strides towards satisfying the SFW goals. Additionally, this analysis can help to confirm whether or not the emission goals of the NASA SFW Project are realistic and can help to provide guidance in revising the SFW goals. Similarly, by enforcing the current SFW goals for emissions, the tool can help determine by what margins emissions of future aircraft and technology must be improved by to meet SFW goals.

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