

Evaluating Market and Environmental Impacts of an N+3 Supersonic Aircraft

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NASA’s Supersonics Project suggests that by 2035 an “N+3 generation” supersonic transport aircraft could be developed, produced and in operation. This study presented in this paper explored how a 100-passenger N+3 supersonic transport (SST) developed by Lockheed Martin Advanced Development Programs would interact with the existing subsonic fleet and how its operations would impact environmental emissions. Through an allocation tool representing a majority of commercial airline operations with at least one airport in the US, the studies integrated an N+3 SST into a subsonic fleet. Results indicate that when the allocation tool seeks to maximize time savings for passengers, the N+3 SST is best used on routes longer than 4,500 nmi, on average. However, if the allocation seeks to maximize fleet productivity, the N+3 SST operates on shorter routes with an average length of about 1,000 nmi. Environmentally, allocating an N+3 SST to minimize total fleet block hours leads to the lowest CO₂ emissions but the highest NO_x emissions, given reasonable estimates about the future fleet’s emissions. From an economic and market standpoint, minimizing total fleet block hours leads to the lowest direct operation costs (DOC) for the airline, whereas maximizing productivity leads to the highest DOC for the airline.

Nomenclature

BH_{ij}	Block Hours for Aircraft i on Route j
d_j	Demand on Route j
$d_{surplus}$	Maximum Amount of Demand Exceedance Allowed
κ	Scaling Factor
MH_{ij}	Maintenance Hours for Aircraft i on Route j
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 Supersonics Project¹ is pursuing research that could meet challenging technical goals that emphasize the importance of traveling faster and further, but also creating fuel efficient aircraft with minimal cruise emissions, specifically carbon dioxide (CO₂) and nitrogen oxide (NO_x) emissions. At the start of the studies described in this paper, the project envisioned three generations of supersonic aircraft.

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The N+1 generation supersonic aircraft hopes to see entry in service by 2015 with a capacity of six to 20 passengers and flight capabilities of Mach 1.6 to 1.8 and a range of 4,000 nmi. NASA states that the N+1 supersonic transport (SST) should be equivalent to subsonic aircraft for NO_x emissions and its fuel efficiency will serve as the baseline for future generations of supersonic aircraft. By 2030 to 2035, the N+3 generation of supersonic aircraft will enter into service. These aircraft, termed “Efficient Multi-Mach Aircraft” by NASA, hope to achieve cruise speeds of Mach 2.0 under unrestricted flight and Mach 1.6 to 2.0 for low boom flight over land. The N+3 SST hopes to achieve a longer range and carry more passengers, 6,000 nmi and 100 to 200 passengers, compared to the earlier N+1 and N+2 SST models. However, in addition to this enhanced performance, the N+3 SST will be the most fuel efficient of the generations and emit the least amount of NO_x . The NASA Supersonics Program believes that the N+3 SST can burn 25% less fuel ($\text{lb}_{fuel}/(\text{passenger-nmi})$) than the N+2 SST and have a NO_x emission index of less than 5 g NO_x per kg of fuel burned.¹

Whereas aircraft metrics evaluate the performance of a single aircraft model, a fleet-level metric captures the entire aircraft fleet – new and existing aircraft – and their use; a fleet-level metric also gives a high-level view of how the introduction of a new supersonic aircraft may impact the air transportation system. The environmental and economical impact of the supersonic aircraft is a function of both aircraft performance and the airlines’ use of the new supersonic aircraft with existing subsonic aircraft. To properly gauge the impact of the supersonic aircraft in the fleet, an allocation tool can incorporate not only the performance of the new aircraft, but also how airlines might use the new supersonic aircraft in concert with their existing subsonic aircraft.

With the development of a tool that calculates fleet-level passenger metrics – productivity, fleet block hours, or block hours saved – one can determine how the fleet, combining new supersonic aircraft and subsonic aircraft, will take advantage of the supersonic aircraft’s increased speed. By allocating aircraft to maximize the speed that passengers are flown, the total block hours saved, or to minimize block hours flown by the entire fleet, the supersonic aircraft will be optimally integrated into the existing subsonic fleet.

Whenever they enter service, these supersonic new aircraft will operate along with the rest of the fleet of aircraft, which are almost entirely subsonic aircraft. Even though the goals set forth by the NASA Supersonics Program promote greener aircraft, the environmental impact of these supersonic aircraft, using fleet-level measurements, compared to an all subsonic aircraft fleet is unknown. The tool measures fleet-level metrics of carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions to evaluate how the supersonic aircraft impact these fleet-level environmental metrics.

Resource allocation is a common problem in the operations research community and often takes the form of a large integer programming program. For airline operations, these tools take the form of maintenance scheduling, crew assignment, trip assignments, and fleet allocation. Typically, the objective is to minimize cost or maximize profit. Research efforts in this field have focused on the development of problem formulation strategies and algorithms to reduce the computation time and problem complexity;^{2–4} however, none of the referenced allocation models incorporate fleet-level passenger metrics, such as productivity or block hours saved, as the objective in the problem formulation. Additionally, environmental metrics, such as emissions, at the fleet level do not usually appear in the aircraft allocation or assignment problems.

This study leverages an allocation tool created to evaluate how new subsonic aircraft impact fleet-level metrics⁵ to assess the environmental and market impacts of a N+3 SST concept developed by Lockheed Martin Advanced Development Programs. The Lockheed Martin N+3 SST concept has a capacity of 100 passengers, a design range of 5,000 nmi, a cruise speed of Mach 1.6, and a cruise altitude of 38,000 to 52,000 feet.⁶ By using passenger-based fleet-level metrics to assess the advantages of supersonic aircraft and modifying the existing subsonic-based tool, the studies presented here help to illustrate how an N+3 supersonic transport might maximize productivity and total flight time saved, while also assessing other market and environmental metrics.

II. Method and Approach

To assess the fleet-level impact of the new supersonic aircraft, an aircraft allocation model needs to assign aircraft to demanded routes – as an airline would. The tool needs to allocate flights throughout the air transportation network, satisfy demand, and calculate the fleet-level passenger and environmental metrics based on the allocation results. This paper considers maximizing airline productivity by using various passenger-based metrics as allocation objectives.

A. Allocation Problem Formulation

The types of scheduling and fleet assignment problems solved by airlines are some of the most complex problems in the operations research field. Airlines must schedule thousands of flights per day using hundreds of different aircraft types. To reduce this complexity, this study makes several abstractions that facilitate the solution to the problem while retaining important features that reflect actual air transportation decisions. The tool assumes one benevolent, monopolistic airline meets all passenger demand, which eliminates the need to model multiple, competing agents within the allocation problem. Additionally, the tool assumes that the WWLMINET 257 airports⁷ make up the entire worldwide air transportation network. In 2005, the WWLMINET 257 airports captured 65% of all traffic and 80% of all passengers that had at least one origin or destination in the United States.⁸

The airlines currently serving the WWLMINET 257 airports use over 100 unique aircraft models. In this study, six aircraft describe all the subsonic aircraft in the fleet; Table 1 presents these aircraft. Each of these six aircraft represents a certain size of aircraft, based on seating capacity; these six aircraft are termed the new-in-class aircraft. The new-in-class aircraft are conceptual models believed to be in operation within each class by 2025 (the baseline year for these studies). Two models, the Bombardier CS100 and Boeing 787 are based on aircraft being designed and manufactured today. The remaining aircraft, labeled as N+2 aircraft,⁹ are conceptual aircraft that meet NASA’s Subsonic Fixed Wing Goals,¹ which are similar to NASA’s Supersonics Project Goals. A seventh aircraft type accounts for the supersonic aircraft. Because the N+3 SST carries 100 passengers, it falls in class 3.

Table 1. Aircraft Used as New-in-Class Representatives and SST Aircraft

Class	Seats	New-in-Class	Supersonic Aircraft
Class 1	20 - 50	N+2 Small Regional Jet	—
Class 2	51 - 99	N+2 Regional Jet	—
Class 3	100 - 149	Bombardier CS100	N+3 Supersonic Transport
Class 4	150 - 199	N+2 Single Aisle Transport	—
Class 5	200 - 299	Boeing 787	—
Class 6	300+	N+2 Large Twin Aisle Transport	—

While airlines would seek to maximize profit, the effort needed to develop an appropriate revenue model exceeded the scope of this study. By using three different metrics that focus on the passengers transported and the speed of the aircraft in the fleet, the resulting allocation indicates how the N+3 SST’s higher flight speed would factor into the airline’s operations to maximize one of the passenger-based performance metrics. These three metrics, while not immediately related to profit, all have aspects that represent the ability of the airline to attract passengers. In the aircraft allocation problem, the decision variables, x_{ij} , are the number of trips each aircraft type i performs on a specific route j in the network. With these abstractions, the aircraft allocation problem is an integer program (IP) formulated as:

$$\text{Maximize Fleet Productivity: } \sum_i \sum_j \left(x_{ij} \cdot p_i \cdot \frac{r_j}{BH_{ij}} \right) \quad (1a)$$

$$\text{– or – Block Hours Saved: } \left(\frac{\sum_i \sum_j BH_{ij, i=subsonic}}{\sum_1 i_{subsonic}} \right) - BH_{ij, i=SST} \quad (1b)$$

$$\text{– or – Minimize Fleet Block Hours: } \sum_i \sum_j (x_{ij} \cdot BH_{ij}) \quad (1c)$$

$$\begin{aligned} \text{Subject to } \quad & \sum_i x_{ij} \cdot p_i \geq d_j && \text{for all routes } j && (2) \\ & \sum_i x_{ij} \cdot p_i \leq d_j + d_{surplus} && \text{for all routes } j && (3) \\ & \sum_j x_{ij} \cdot (BH_{ij} + MH_{ij} + TH) \leq 12n_i && \text{for all aircraft } i && (4) \\ \text{Additionally } \quad & CO_2 \leq \kappa \cdot CO_{2,year} && \text{for total fleet } CO_2 && (5) \\ & DOC \leq \kappa \cdot DOC_{year} && \text{for total fleet } DOC && (6) \end{aligned}$$

The three different objectives, which are evaluated separately, use different metrics that emphasize passenger speed in various ways. Productivity is a common fleet metric for transport aircraft; it is defined (1a) as passengers \times block speed, which will increase as the airline transports more passengers at the same speed or as the airline transports the same passengers at a faster speed. The block hours saved (1b) calculation uses the average block hours flown by subsonic aircraft on a route less the block hours for the SST flying on the same route. Therefore, flying a supersonic aircraft on long routes, where the speed differential results in large time savings, the airline will maximize this metric. When this objective function is used to allocate the fleet, first the supersonic aircraft are allocated on routes, because only the supersonic aircraft change the value of this objective function. After the supersonic aircraft are allocated using block hours saved, the remaining passenger demand is allocated using subsonic aircraft and the objective function of maximizing productivity. Lastly, fleet block hours (1c) is the sum of all block hours flown by all aircraft. Because the metric of passengers / hour typically defines passenger throughput and this problem formulation ensures that the solution meets all passenger demand for travel, minimizing the total hours flown by all passengers has an impact similar to maximizing the throughput of the airline for the given demand level each year.

B. Aircraft Modeling for Allocation Problem Coefficients

NASA's FLight OPTimization System (FLOPS)¹⁰ simulates missions of each subsonic new-in-class aircraft with various ranges and passenger loads. The resulting mission output from FLOPS determines the direct operating cost (DOC), fuel burn, and NO_x emissions for each of the new-in-class aircraft. These FLOPS runs create different look-up tables for DOC, fuel burn, and NO_x that are interpolated to determine the DOC, fuel burn and NO_x for each of the six new-in-class aircraft on all of the possible routes. The ratio of fuel burned to CO₂ produced is 3.16 lbs of CO₂ per lb of fuel burn,¹¹ so fuel burn serves as a surrogate for CO₂ emissions.

Lockheed Martin performed mission analyses with combinations of ranges and passenger loads for the N+3 SST using their design tools and approach. Because of difficulty in obtaining an open-literature cost model for supersonic aircraft, this study predicted DOC costs for the Lockheed Martin N+3 SST using the approach presented in a NASA contractor report¹² for subsonic aircraft; this carries the assumption that this subsonic transport cost model is acceptable for the SST predictions. Based on these analyses, Lockheed Martin provided lookup tables for fuel burn, block hours, DOC, and NO_x in a format compatible with the allocation tool.

C. Allocation Problem Abstractions and Constraints

The constraints in (2) ensure that the allocation meets all passenger demand. The study assumes that each aircraft performs a roundtrip on its allocated route (i.e. the aircraft flies from City A to City B and then, after a turnaround to unload and load, etc, it flies back from City B to City A), which halves the number of decision variables. 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 on each route is based on the Bureau of Transportation Statistics (BTS) reported passengers for 2005.¹³ From 2005 onward, the total passenger demand on each route grew at an assumed rate of 2% annually. Because of the roundtrip assumption, the roundtrip demand is equal to the maximum demand of the two one-way segments between the two cities reported by that BTS database. Taking the maximum demand of each segment ensures that a roundtrip will meet the demand for each of the two one-way segments. Any aircraft model can serve the passenger demand of each route between a given city-pair, as long as the range of the route does not exceed the design range of the aircraft and the aircraft can land on the longest runway at both the

origin or destination airport. For example, a class 1 aircraft (a regional jet) cannot fly from Chicago (ORD) to London (HTR).

Because the objectives used in the study incorporate the maximization of passenger travel based metrics and this formulation does not address revenue, the allocation may assign more flights than necessary and capacity can exceed the passenger demand by large amounts. Therefore, (3) serves as an upper bound of passenger demand to ensure that the allocation does not include an excessive number of flights; this would correspond to flights with very low load factors. The parameter $d_{surplus}$ is set to 300 (i.e. each route can have a capacity of no more than 300 seats above the passenger demand), so at most the equivalent of one additional class 6 or six class 1 aircraft can be flown to meet passenger demand.

Lastly, because the number of aircraft available for allocation is finite, the allocation problem contains an aircraft flight hour limit (4), which serves to constrain the number of aircraft allocated to be at or below the number of aircraft available. 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 new-in-class aircraft on each route based on trip length and flight time. Additionally, Lockheed Martin provided block hour lookup tables for the N+3 SST. The average turn-around time for an aircraft at an airport is between 45 and 60 minutes,¹⁴ so these studies assume a turn-around time of one hour per roundtrip for all aircraft, regardless of type. 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,”¹⁵ so for every block hour flown, 3.5 hours of maintenance time is assumed. Therefore, MH_{ij} is equal to $3.5 \times BH_{ij}$. The constraints in (4) ensure that an aircraft is not utilized for more than 24 hours in a given day (represented as 12 hours in the constraint, because each aircraft makes a roundtrip). To determine a reasonable estimate of the aircraft available the MITRE Fleet Forecast,¹⁶ which lists the number of each aircraft owned by US Airlines in 2005, provides n_i . These values for each class of subsonic aircraft grow at an assumed rate of 2% annually to account for new aircraft acquisitions to meet the growing passenger demand.

(5) and (6) serve as additional constraints to limit DOC and CO₂. These constraints act as economic or policy decisions that enforce limits imposed on the airline to keep either DOC or CO₂ below certain levels. κ serves as a scaling factor relative to the DOC or CO₂ emissions of an indicated reference year. Studies presented here to examine the tradeoff between productivity vs. DOC and productivity vs. CO₂ use these constraints.

The software package GAMS¹⁷ (General Algebraic Modeling System) facilitates solution of this IP problem. GAMS provides an algebraically-based high-level language for the compact representation of large and complex models and uses the CPLEX¹⁸ solver to solve the IP problem via branch-and-cut.

III. Results

A. Maximizing Fleet Productivity and Minimizing Fleet Block Hours from 2025 to 2050

The first of three studies looks at two of the three objectives – maximizing fleet productivity and minimizing fleet block hours – while allocating aircraft for a representative day for each year over a 25-year period from 2025 to 2050. Each of the two objectives explores three different scenarios. In the first scenario, the tool only allocates subsonic aircraft. This scenario serves as the baseline to compare the results of the two other scenarios with the N+3 SST available. The other two scenarios involve different production rates for the N+3 SST. One scenario produces 25 SST per year from 2030 to 2050, and the other scenario produces 50 SST per year from 2030 to 2050. The 25 SST per year scenario is considered a “conservative” production rate, whereas the 50 SST per year is considered an “aggressive” production rate. During the years of the study, passenger demand grows at an assumed rate of 2% annually, which corresponds to 2005 demand doubling by 2040. Table 2 summarizes the three scenarios for each of the objectives studied.

Table 2. Summary of Scenarios for the First Study

Scenario	Years SST Available	SST Available per Year
Baseline	Not Available	0 per Year
Conservative	2030 to 2050	25 per Year
Aggressive	2030 to 2050	50 per Year

For this study, fleet-level CO_2 and total mission NO_x do not appear in the objective or constraint functions, the computation of fleet-level CO_2 and NO_x use the allocation results that maximizes productivity or minimizes fleet block hours and multiplies the number of flights on each route by the corresponding CO_2 or NO_x value.

Figures 1 through 3 show some of the results from maximizing productivity. Figure 1 shows the objective of fleet productivity. In 2030, the three scenarios begin to differ, because the airline has more SST available to increase the fleet's productivity. As expected, the aggressive scenario with 50 SST produced each year has the largest productivity, once the SST enters the fleet. Figures 2 and 3 show the environmental impact of adding the N+3 SST to the fleet.

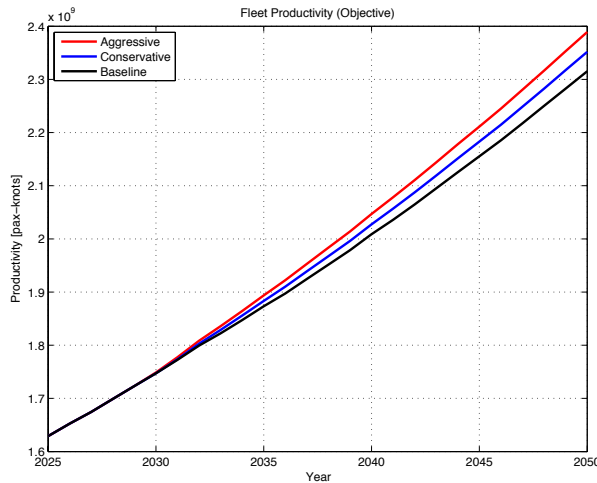


Figure 1. Fleet productivity when maximizing productivity.

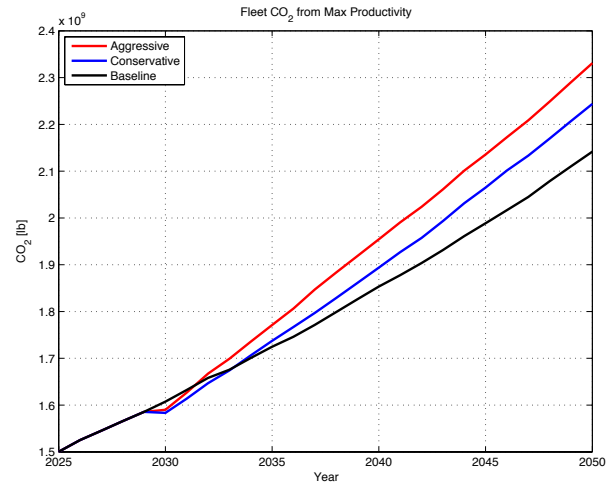


Figure 2. Fleet CO_2 emissions when maximizing productivity.

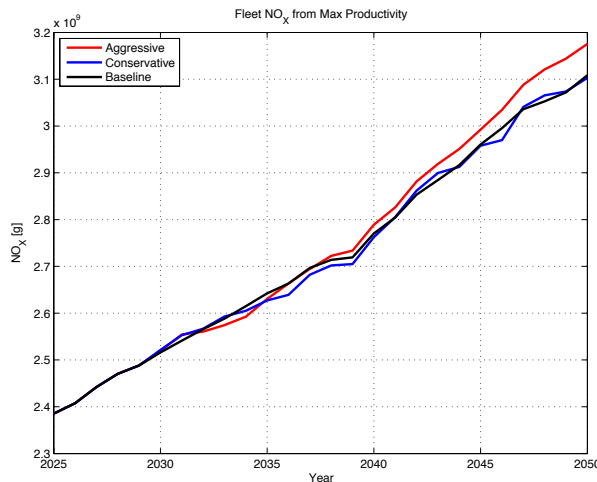


Figure 3. Fleet NO_x emissions when maximizing productivity.

As the allocation tool uses more SST to increase fleet productivity, the resulting CO_2 emissions increase; however, when SST are first introduced in 2030 there is a small decrease in CO_2 , but that decrease quickly disappears as the CO_2 grows at a faster rate in the presence of SST. One of the reasons for this decrease in the CO_2 initially is because of how the metric productivity is defined. Since many of the subsonic aircraft have a similar cruise speed, the productivity of one 300 passenger aircraft is essentially the same as three 100 passenger aircraft. However, the CO_2 emissions from one 300 passenger aircraft is less than the CO_2 emissions from three 100 passenger aircraft, which can lead to different fleet level CO_2 emissions. When the SST is introduced in 2030, the allocation tool allocates the subsonic fleet in a way that allows the CO_2 to be decreased. This tradeoff between productivity and CO_2 is examined in a later study. The NO_x emissions do not increase steadily as CO_2 emissions in the presence of SST. In fact, the NO_x emissions tend to remain fairly close to the baseline scenario, and in some years the SST allocation produces less NO_x than the baseline allocation.

The aggressive scenario tends to produce more NO_x than the baseline, which indicates that if the number of SST is larger, the impact on NO_x is greater.

Figures 4 through 6 show the results from minimizing fleet block hours for the representative day. As expected, when SST become available for allocation, the total fleet block hours decreases noticeably. However, the decrease in block hours when the number of SST is doubled is not as significant as the initial decrease, mostly because the allocation assigns the additional SST from the aggressive scenario to similar routes of

around 1,250 nmi. These shorter routes have a high amount of passenger demand, but the block hour savings from the SST are not as large as the block hour savings on longer routes.

Figures 5 and 6 show the environmental impact of the SST when minimizing fleet block hours. Similar to Figures 2 and 3 from maximizing fleet productivity, the impact of the SST becomes evident in 2030 when they are first available. However, compared to the baseline scenario, the fleet level CO₂ emissions appear to increase less than when maximizing productivity. Also, in contrast to the scenario of maximizing productivity, the NO_x emissions with the SST are always greater than the baseline scenario without SST. However, the increase in NO_x emissions from the SST is not as significant as the increase in CO₂ emissions.

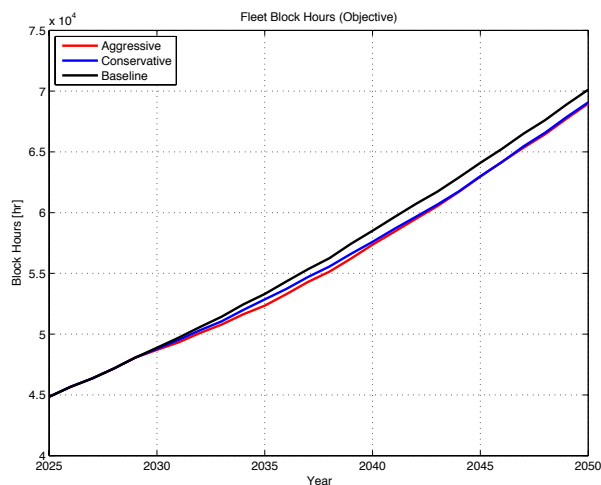


Figure 4. Fleet block hours when minimizing fleet block hours.

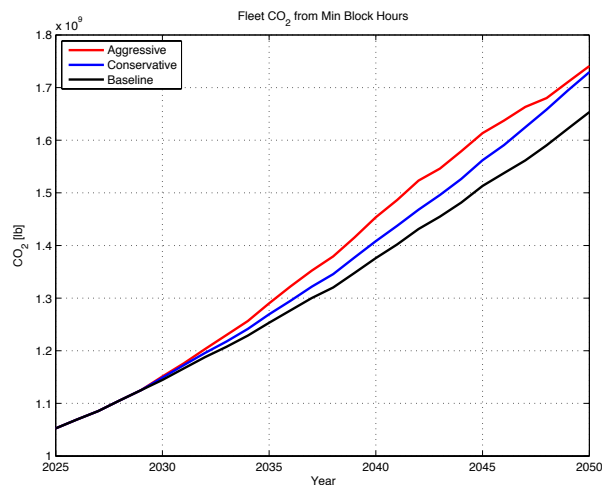


Figure 5. Fleet CO₂ emissions when minimizing fleet block hours.

Minimizing fleet block hours also has a large environmental benefit in terms of CO₂ emissions, which might be expected because lowering total flying time likely reduces fuel consumed. When minimizing fleet block hours, the CO₂ does increase when the SST are made available for allocation; however, the increase in CO₂ emissions from the baseline scenario is much smaller than the increase in CO₂ emissions from the baseline scenario when the objective of the airline is to maximize productivity. Furthermore, the total amount of CO₂ emissions when minimizing fleet block hours is significantly less than the total amount of CO₂ emissions when maximizing productivity.

In terms of NO_x emissions, the allocation to minimize fleet block hours initially produces lower NO_x emissions than the allocation to maximize productivity. However, as the allocations go forward from 2025, the rate of increase in NO_x emissions when minimizing block hours is much faster than the increase in NO_x from maximizing productivity. By 2050, minimizing block hours produces more NO_x than maximizing productivity in each of the three scenarios.

Figure 7 and 8 compare the environmental metrics from the two different objectives and highlight the different behaviors of CO₂ and NO_x.

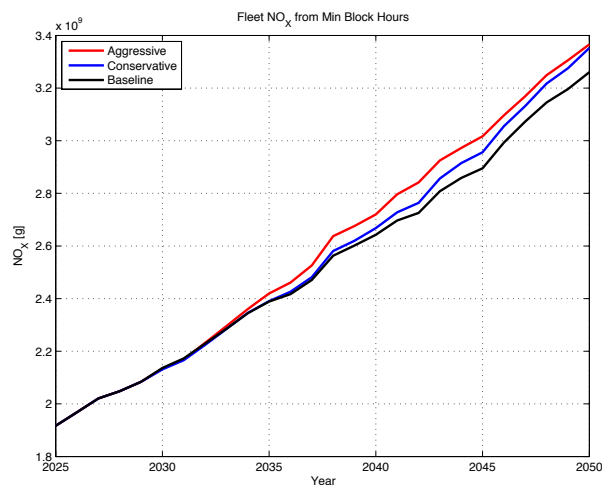


Figure 6. Fleet NO_x emissions when minimizing fleet block hours.

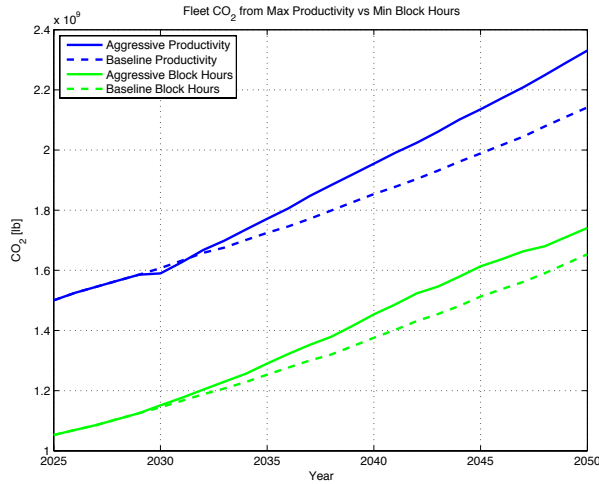


Figure 7. Fleet CO₂ emissions from maximizing productivity vs. minimizing fleet block hours.

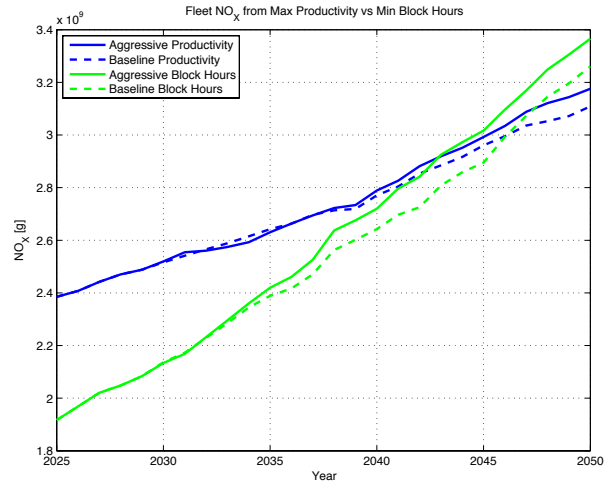


Figure 8. Fleet NO_x emissions from maximizing productivity vs. minimizing fleet block hours.

B. Comparison of the Three Objective Metrics

The results shown from the first study indicate that the two different metrics explored can lead to different results. To examine how the three different objective functions lead to different results, aircraft were allocated in 2050 in three different scenarios, one for each objective metric. Typically, in practice airlines would seek to maximize profit; however, developing a profit and revenue model was out of the scope of this project. In the absence of a revenue and profit model, the three objectives studied all represent different facets of improving passenger travel. Of these three objectives, productivity seems to most closely address the practices of an airline. This study uses the same assumptions regarding demand and fleet as the previous study. In addition, the assumed SST production rate was 50 SST per year from 2030 to 2050. After each separate allocation, the other two objective metrics that were not used in the objective function were calculated for comparison across all three allocations. Additionally, the number of roundtrips allocated to the SST and the average one-way distance of these SST roundtrips were also calculated. Lastly, each allocation corresponds to values of fleet CO₂ and NO_x emissions, along with fleet DOC. Table 3 presents the results of this study.

Table 3. Results of the Three Objectives Study for 2050 Passenger Demand

Objective	Fleet Productivity [pax-knots]	Block Hours Saved [hr]	Fleet Block Hours [hr]	SST Trips Allocated [roundtrips]
Productivity	2.389×10^9	3,982	1.353×10^5	1,560
Block Hours Saved	2.349×10^9	4,605	2.768×10^5	485
Block Hours	1.616×10^9	2,351	6.898×10^4	757
Objective	Avg Range for SST [nmi]	CO ₂ Emissions [billions of lb]	NO _x Emissions [billions of g]	DOC / Day [millions of USD]
Productivity	1,003	2.331	3.176	608
Block Hours Saved	4,604	2.397	3.236	599
Block Hours	1,330	1.741	3.366	436

When the objective is to maximize productivity, the allocation tool assigns the N+3 SST to a large number of trips with an average range (1,003 nmi) well below the design range of the SST (5,000 nmi). However, the maximum range route the SST is assigned to is near the design range at 4,939. When minimizing block hours, the allocation tool assigns the N+3 SST to half as many trips but with an average range close to that of maximizing productivity. Lastly, when maximizing block hours saved, the allocation tool assigns the N+3 SST to the fewest routes, but the average range of the SST is 4,604 nmi, much longer than the other two objectives. These apparent discrepancies are a result of the type and number of routes each objective

assigns to the SST. Figure 9 shows a scatter plot of the range of a route assigned to the SST and the number of SST round trips assigned to that route.

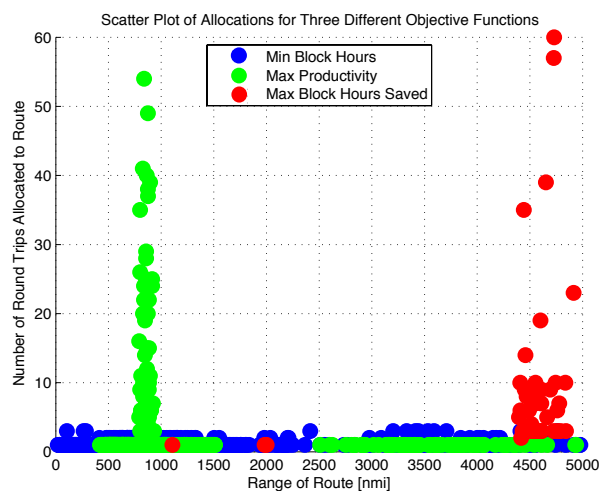


Figure 9. Scatter plot of SST route range vs. trip frequency.

nmi and another trip at 1,982 nmi. These two outliers result the SST not having enough time in the day to make a longer trip of 4,250+ nmi, thus two shorter trips were assigned to result in more block hours saved.

Lastly, when minimizing fleet block hours, the allocation tool assigns the SST to a wide variety of ranges and allocates the SST to at most 3 roundtrips per route. This allocation is likely the result of the allocation finding instances where it can serve most of the demand with a few trips of the SST, which will help reduce the total block hours of the entire fleet. Another possible explanation is the presence of many local minima existing for a minimum value of total fleet block hours, which results in a wide variety of SST allocations.

Even though the average ranges for maximizing productivity and minimizing fleet block hours are well below the 5,000 nmi design range of the SST, operating current subsonic aircraft on routes shorter their design range is common practice for most airlines. For example, the Boeing 737-700 and Boeing 737-800 have design ranges of 3,260 nmi and 2,940 nmi, respectively. However, according to 2005 BTS data, these aircraft flew an average range of 851 nmi and 922 nmi per trip, respectively.

In terms of environmental impact, allocating the fleet to minimize block hours results in the lowest CO₂ emissions. This results from the allocation tool choosing predominantly large aircraft, because flying larger aircraft at a lower frequency will result in a fewer fleet block hours than flying the same amount of passengers on smaller aircraft with a higher frequency. This “up-gauging” of the fleet to larger aircraft results in lower fuel burn and thus lower CO₂ emissions and lower DOC. However, this objective function also leads to the highest NO_x emissions. Maximizing productivity and block hours saved leads to similar results in terms of CO₂ and NO_x emissions, as well as DOC, but maximizing productivity appears to be slightly better in terms of CO₂ and NO_x emissions. We expect these results to be similar because of the approach taken to allocate the fleet when maximizing block hours saved is the objective. As mentioned previously, only the SST fleet can be allocated to maximize block hours saved; and after that allocation, the remaining passenger demand is allocated to maximize productivity. Because the vast majority of passengers will fly on subsonic aircraft under this allocation, the results at the fleet level should closely follow the results from maximizing productivity.

C. Tradeoffs Between Maximizing Productivity and CO₂ or DOC

The results in Table 3 show that the three different objectives can lead to different CO₂ emissions and DOC. Because of this tradeoff between the various objective functions, another study explored the tradeoff between one of the objective functions – maximizing productivity – and fleet-level CO₂ emissions and DOC. These studies make use of constraints (5) and (6) presented earlier when describing the formulation of the allocation IP problem. The fleet-level values of DOC and CO₂ from Table 3 provide the reference values in the right hand side of the constraints.

As seen in Figure 9, maximizing productivity allocates at least one SST roundtrip to a route as short as 420 nmi and as long as 4,940 nmi; however, a vast majority of the routes assigned to the SST are between 800 and 900 nmi. These routes have a very high passenger demand, so by performing a lot of trips on these routes, a high amount of passengers can take advantage of the speed of the N+3 SST; therefore, the allocation tool assigns more trips to these routes because of the capability to increase fleet productivity.

On the other hand, maximizing block hours saved has the opposite result. Longer routes have the most potential to save time with an SST instead of a subsonic aircraft. Because of this potential, the allocation tool assigns the SST to predominantly long routes of 4,250 nmi or greater. Because these longer routes require more block time, the total number of trips allocated is much lower than when the objective is to maximize productivity. Figure 9 shows two outliers for maximizing block hours saved – one trip at 1,107

As mentioned previously, since many of the subsonic aircraft have essentially the same cruise speed, the productivity of the fleet can remain close to the same with a completely different allocation. This occurs because the productivity of one aircraft with 300 passengers is fairly equivalent to the productivity of three aircraft with 100 passengers each. However, the CO₂ emissions and DOC for these two possibilities are not the same. Because of this situation, CO₂ and DOC can be reduced by fairly large margins while still allocating to maximize productivity, and in some cases the reallocation of different subsonic aircraft to meet demand and CO₂ emission and DOC constraints may allow the SST to operate in the same manner it did prior to DOC and CO₂ constraints.

In this study, subsequent allocation problems from those shown in Table 3 use a decreasing value of κ , from 1.0 in 0.025 increments from the 2050 fleet-level values for DOC and CO₂, until the allocation becomes infeasible (i.e. it is impossible to meet demand and meet either the limit on CO₂ or DOC). Two separate runs of allocations were performed, one to constrain CO₂ emissions and one to constrain DOC.

Figures 10 and 11 present the tradeoff between productivity vs. CO₂ emissions and productivity vs. DOC, respectively. As the results in Table 3 suggested, both CO₂ and DOC values change as productivity changes. The allocation tool was able to find a feasible allocation that maximized productivity at a restricted CO₂ value that was 60% below the value in Table 3 and at a restricted DOC value at 62.5% below the value in Table 3. Each data point in Figures 10 and 11 represent a feasible allocation that includes SST integrated into the subsonic fleet. As CO₂ and DOC become further constrained the amount of round trips allocated to the SST begins to decrease as more subsonic aircraft, which burn less fuel, take over routes flown by the SST. Eventually, the SST is only allocated to a handful of routes until eventually the number of SST allocated becomes zero or the allocation becomes infeasible.

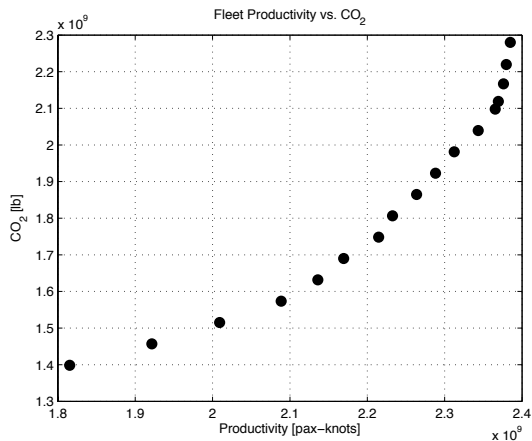


Figure 10. Feasible allocations with maximizing productivity with different epsilon constraints of CO₂.

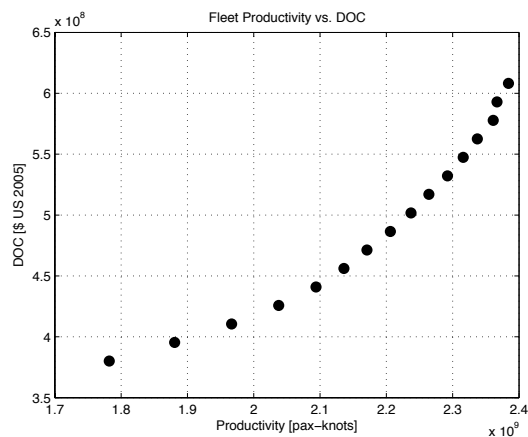


Figure 11. Feasible allocations with maximizing productivity with different epsilon constraints on DOC.

To examine how the subsonic aircraft and SST allocations change when constraining CO₂ and DOC, the total number of trips allocated to each class of subsonic aircraft and to the SST were calculated. The average nautical miles flown per trip provides a metric to examine how each allocation assigns these aircraft. Figures 12 - 14 plot the results when constraining CO₂, and Figures 15 - 17 plot the results when constraining DOC.

When maximizing productivity under constraints on CO₂, the class 4 subsonic aircraft is the predominately used aircraft. As seen in Figure 12, the number of trips for the class 4 subsonic aircraft is an order of magnitude higher than any other class of aircraft. This is mostly due to the fact that class 4 aircraft are the most popular aircraft for airlines, which gives them a much larger percentage of the fleet size. As expected, when trying to reduce CO₂ emissions, larger aircraft are used. This is evident in class 1 and class 2 aircraft, as they are allocated on fewer trips as the CO₂ is constrained to a lower value. However, class 5 aircraft are not used very often as the CO₂ is required to be lower, and in some instances, the class 3 aircraft receives more trips when CO₂ is constrained to be 75-65% of the original value.

The average miles flown per aircraft tend to remain fairly constant, indicating that each aircraft is allocated to similar routes. Many aircraft actually fly on shorter average routes as the CO₂ is constrained lower, notably, class 3 and class 5 aircraft.

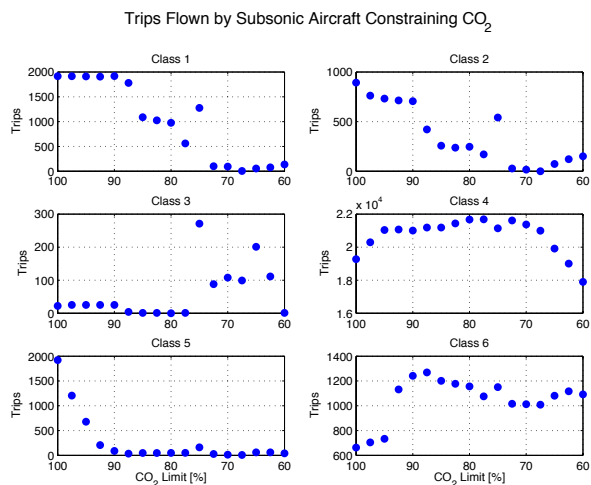


Figure 12. Trips flown by subsonic aircraft when constraining CO₂.

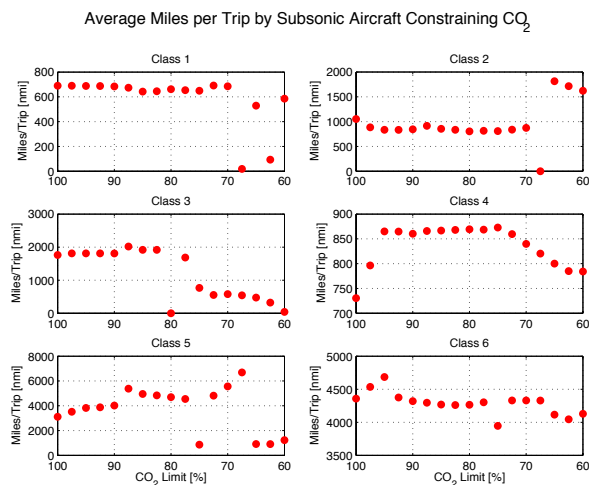


Figure 13. Miles per trip flown by subsonic aircraft when constraining CO₂.

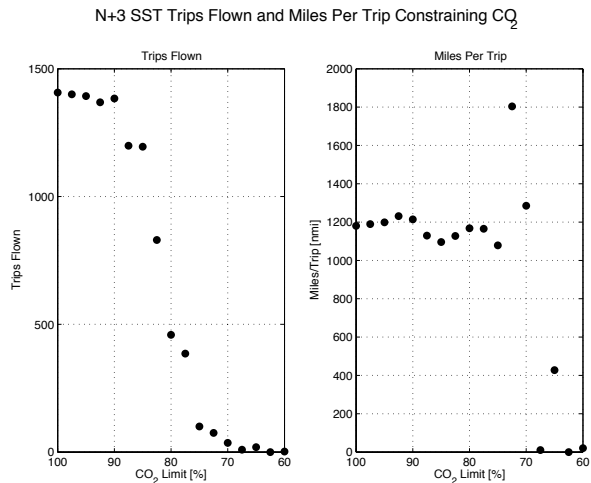


Figure 14. Trips and miles per trip flown by SST when constraining CO₂.

Figure 14 shows the trips flown and miles per trip flown for the SST when maximizing productivity under CO₂ constraints. As CO₂ is further constrained, the number of trips flown by the SST follows a backwards-S curve, where the trips stay about the same initially, then drop fairly quickly, and then maintain a constant low number. However, despite the decrease in trips flown by the SST, the average miles per trip remains rather constant until CO₂ is constrained to be below 70% of the original value. Interestingly, when CO₂ is constrained to be 72.5-70% less than the original value, the miles per trip for the SST increases quite a bit.

less than five trips every allocation, except the first one with no restrictions on DOC. Classes 4 through 6 aircraft all have similar allocations to the previous results. Similarly, the results in Figure 16, which show the average miles per trip when constraining DOC, mimic their counterparts in Figure 13 with only a few differences. The major differences when constraining DOC are that class 1 and class 2 aircraft are not used on longer routes for the highly constrained allocations, class 5 is used on shorter routes, and class 6 is used on longer routes.

Maximizing productivity while constraining DOC leads to similar results, but with some key differences. Figure 15 shows the trips allocated to the subsonic aircraft when constraining DOC. Similarly, many of the smaller aircraft are flown on fewer trips as the DOC is constrained further, but unlike the results in Figure 12, the class 3 aircraft is barely used at all –

The trips flown for the SST when maximizing productivity with constraints on DOC are slightly different than when CO₂ was constrained. Initially, there is an increase in the trips flown by the SST. However, with the increase in trips flown by the SST, there was a decrease in the miles per trip flown by the SST. Additionally, the trips flown by the SST decrease earlier as the constraints on DOC are increased, and the miles per trip do not remain nearly as constant as they did when constraining CO₂. There are a few allocations where the miles per trip increase to high levels (similar to the 72.5% constraint on CO₂).

Figure 18 compares the results from constraining CO₂ and constraining DOC by plotting both sets of results together. Generally speaking, the results are similar as they both follow a similar backwards-S curve in the case of trips flown. However, there are some noticeable differences. The first difference is that initially constraining DOC leads to more SST allocations, but as the DOC becomes more constrained, the SST

is allocated to fewer trips than when CO₂ is constrained by the same percentage. However, even though the SST is allocated to more trips when constraining DOC, the miles per trip for the SST is larger when constraining CO₂, except for a few allocations when DOC is constrained to be 85% to 75% of the original value. In those allocations, the miles per trip for the SST is larger when constraining DOC, and in fact the SST is allocated to its longest average trip length when DOC is constrained to be 77.5% of its original DOC.

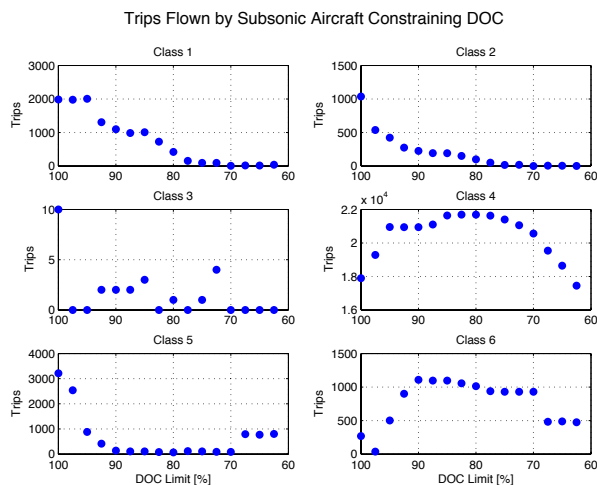


Figure 15. Trips flown by subsonic aircraft when constraining DOC.

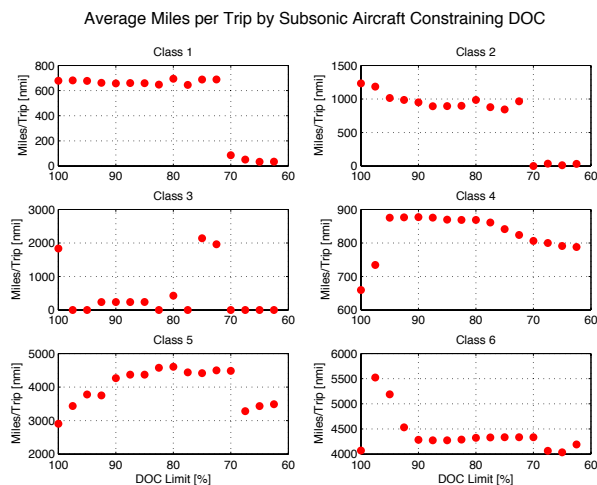


Figure 16. Miles per trip flown by subsonic aircraft when constraining DOC.

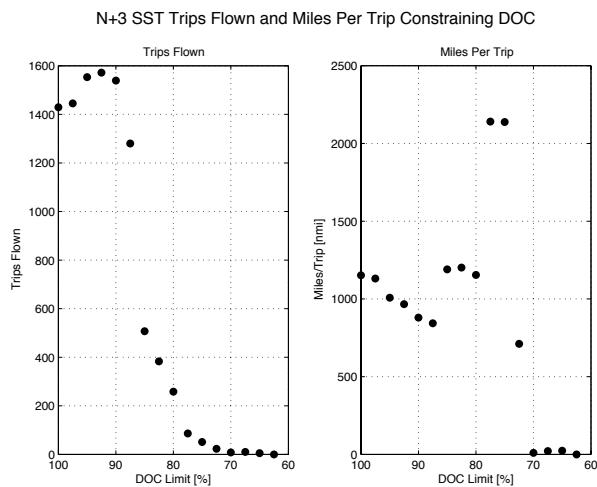


Figure 17. Trips and miles per trip flown by SST when constraining DOC.

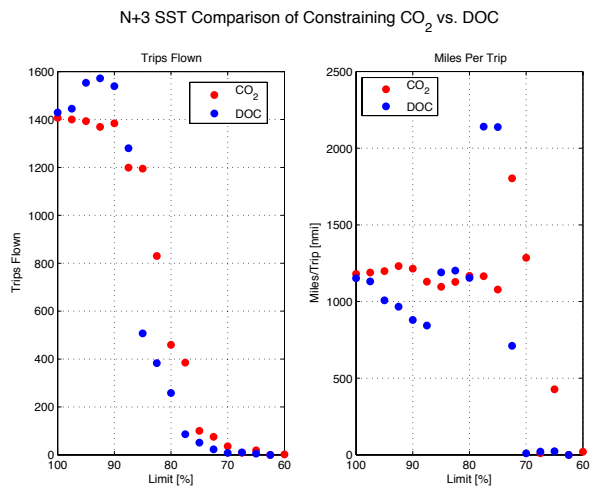


Figure 18. Comparison of SST trips flown and miles per trip when constraining CO₂ or DOC.

IV. Conclusions

The studies conducted in this work used three different objective functions in an allocation problem to assign aircraft to meet passenger demand. In the absence of an acceptable revenue and / or profit model, the three objectives addressed how passengers travel via the allocated fleet. As expected, the results reflect the modeling assumptions and allocation abstractions discussed above.

When using the objectives of maximizing airline productivity and minimizing total fleet block hours, the results indicate that the N+3 SST concept shows promise for operations on routes whose average range is notably shorter than the aircraft's design range. This result appears to be counter-intuitive, because the design range for the SST is 5,000 nmi, and the most time savings occur on longer routes. However, from

the perspective of moving more passengers at a faster speed (productivity) or moving passengers with fewer vehicle block hours (via minimizing fleet block hours), the N+3 SST has a larger impact on these shorter routes. Additionally, minimizing fleet block hours leads to the lowest CO₂ emissions and lowest DOC. When maximizing total time savings, the allocation places the N+3 SST on the longer distance routes where they save passengers much more time.

The studies demonstrated that tradeoffs exist between the fleet productivity objective and fleet-level CO₂ emissions and between fleet productivity and fleet DOC. In examining both of these tradeoffs while trying to meet projected passenger demand in 2050, modest decreases in CO₂ and DOC are available for small reductions in fleet productivity from the maximum possible value of productivity. However, these tradeoff curves show reducing CO₂ or DOC significantly begins to greatly reduce the productivity measure and decrease the number of SSTs allocated to routes.

The results also show that each of the three objectives lead to distinctive allocations and utilization of the N+3 SST. While each objective has its advantages and disadvantages for exploring the fleet-level metrics discussed here, an allocation problem that explicitly maximizes airline profit should provide more realistic results within the bounds of the three objectives and bounded with some DOC constraining. Nonetheless, the tool created for these studies enabled the investigation of each of these simple objectives, and the analyses shown, represent extreme cases of productivity without cost, cost without productivity, and hours saved without cost. But these cases were better to validate that the tool provides valid and understandable results. Hereafter, more sophisticated objectives that balance passenger value and associated revenue against fleet cost can be incorporated and should be capable of representative modeling of how airlines will use these vehicles and how cost and environmental constraints affect passenger productivity, vehicle selection and utilization, SST demand, and other model parameters.

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