Assessing National Airspace System Impact of Transonic Truss-Braced Wing Aircraft

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The Transonic Trussed-Braced Wing (TTBW) is a new highly fuel-efficient airplane concept designed to support narrowbody flights with a 3400NM range. This paper analyzes a day of high-volume traffic identifying aging midsize narrowbody passenger aircraft as early candidates for replacement with TTBW. Then NASA's National Airspace System Digital Twin is used to perform fast-time simulations to assess the fuel burn savings and encounter reductions impact. Replacing tails with TTBW supporting 4,954 flights out of 41,451 total, resulted in an average 39.08% fuel savings per flight among replaced tails (4.44% savings with respect to fuel burned by all flights) and a 30% reduction in pairwise aircraft encounters as proxy for airspace complexity (9% reduction with respect to all flights). TTBW aircraft also started decent 51.7 NM farther from the arrival airport. Overall, these results support TTBW as a promising aircraft concept for further study.

I. Nomenclature

A320	=	Airbus 320
B738	=	Boeing 737-800
BADA	=	Base of Aircraft Data
GASP	=	General Aviation Synthesis Program
IFF	=	Integrated Flight Format
NAS	=	National Airspace System
NOAA	=	National Oceanic and Atmospheric Administration
PMTG	=	Point Mass Trajectory Generator
TAS	=	True Air Speed
TOD	=	Top of Decent
TTBW	=	Transonic Truss-Braced Wing

II. Introduction

Toward achieving the U.S aviation climate action plan to Net-Zero greenhouse gas emissions [1], NASA is working with industry partners to verify and validate new aircraft concepts designed to improve efficiency and reduce carbon emissions. The Transonic Trussed-Braced Wing (TTBW) is a new concept with high aspect ratio wings braced to the fuselage to significantly increase lift over drag ratio and reduce fuel burn emissions [2]. NASA has developed TTBW aircraft models to verify and validate the performance of the aircraft concept for various flight range and aircraft design choices compared to an advanced Tube & Wing aircraft of similar technology level [3]. These studies

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help make design decisions and increase the range of beneficial mission profiles for the new aircraft concept. However, in operation, aircraft are utilized for a wide range of mission profiles depending on airline route networks and demand. To understand the fleet-wide impact of introducing TTBW into the National Airspace System (NAS), simulation of various NAS-wide aircraft replacement strategies is needed [4].

This paper presents an initial NAS-wide impact assessment, simulating TTBW replacement of midsize narrowbody aircraft types in current operation. Section III describes the development and analysis of a NAS-wide flight scenario used to inform TTBW modeling and experiment design decisions. Section IV describes the NAS Digital Twin simulation platform and TTBW model specifics. Metrics and results are described in Sections V and VI respectively. Finally, Section VII discusses conclusions and future work.

III. Flight Scenario

This study simulated and compared the results from two flight scenarios, a *baseline* scenario of a day of historic flight traffic in the U.S., and a *replacement* scenario which substitutes select narrowbody jet aircraft types with TTBW aircraft. This section describes the development of the *baseline* scenario from flight plan and track point data. Then the scenario is analyzed to inform TTBW model design decisions and select aircraft types to replace.

A. Baseline Flight Scenario Development

The baseline flight scenario consists of a high volume, low weather-impact day (7/11/2024) of NAS-wide flights departing within 24 hours starting at 0:00 UTC. Each flight in the scenario must include origin and destination airport, aircraft type, cruise altitude and True Air Speed (TAS), a sequence of latitude/longitude waypoints constituting a route, and a departure time relative to the start of the simulation. These and other data facilitating processing and filtering were extracted from Integrated Flight Format (IFF) data from NASA's Sherlock Data Warehouse [5]. IFF files contain raw flight plan and track point data for the entire U.S. merged from individual facilities (center, terminal area, surface). Starting with 52,326 unique flights extracted from the 7/11/2024 IFF file, Figure 1 summarizes the numbers of flights that were removed or added for various reasons to produce the final 41,451 flight baseline scenario.

First, a route parser converted IFF route strings into a sequence of identified named waypoints with latitude/longitude. The flight was removed if the first or last waypoint (origin or destination airport), was unidentified. Furthermore, if the first and last waypoint referred to the same airport, the flight was removed. Occasionally, portions of the route string outside US airspace refer to unknown waypoints with the same name as known US waypoints, causing erratic jumps in the parsed route. Potential route errors were identified by comparing great circle distance between origin and destination to the path length distance of the route. When the path length to great circle ratio exceeded 1.5, an algorithm systematically attempted to remove up to three waypoints to reduce the ratio below 1.2. Otherwise, if the ratio still exceeded 3.0 or difference exceeded 500 NM, the flight was removed for unresolved route errors.

The IFF aircraft type was then reconciled to a known set of Base of Aircraft Data (BADA) 3.8 [6] aircraft propulsion and aero models utilized in simulation (discussed further in Section IV). If the aircraft type could not be reconciled, the flight was removed. A flight's cruise altitude was assigned as the greater of IFF cruise altitude and maximum track point altitude observed, not to exceed BADA maximum altitude for the aircraft type. BADA performance tables were then used to assign the appropriate cruise TAS for the assigned cruise altitude. Occasionally, when IFF cruise altitude is erroneous and track points are available for only the beginning or end of the flight, the assigned cruise altitude will result in an unreasonably low cruise TAS for the route distance. A rough estimate of flight time was calculated as path distance divided by cruise TAS. For any flight exceeding 8 hours flight time, its cruise altitude was modified to maximum BADA altitude if this would increase the cruise TAS. If flight time exceeded 20 hours, a route error was assumed, and the flight was removed.

IFF flight track points do not always start at the origin airport and so the departure time may be earlier than the first track point timestamp. Therefore, departure time is assigned as first track point time minus the distance between first track point and origin airport divided by the cruise TAS. Then any flight with departure time outside the 24-hour time range for the day (e.g. 7/11/2024 0:00 UTC - 7/12/2024 0:00 UTC) was removed.

The flights were then analyzed by tail number and adjusted to maintain reasonable route network connectivity. As part of this process, flights with the same tail number and origin-destination that departed too close to one another to support a connecting flight in between were identified as duplicates and removed. Similarly, missing flights were added when gaps in route network connectivity were large enough to support a connecting flight. This was most common when both the origin and destination of the missing connecting flight were international airports.

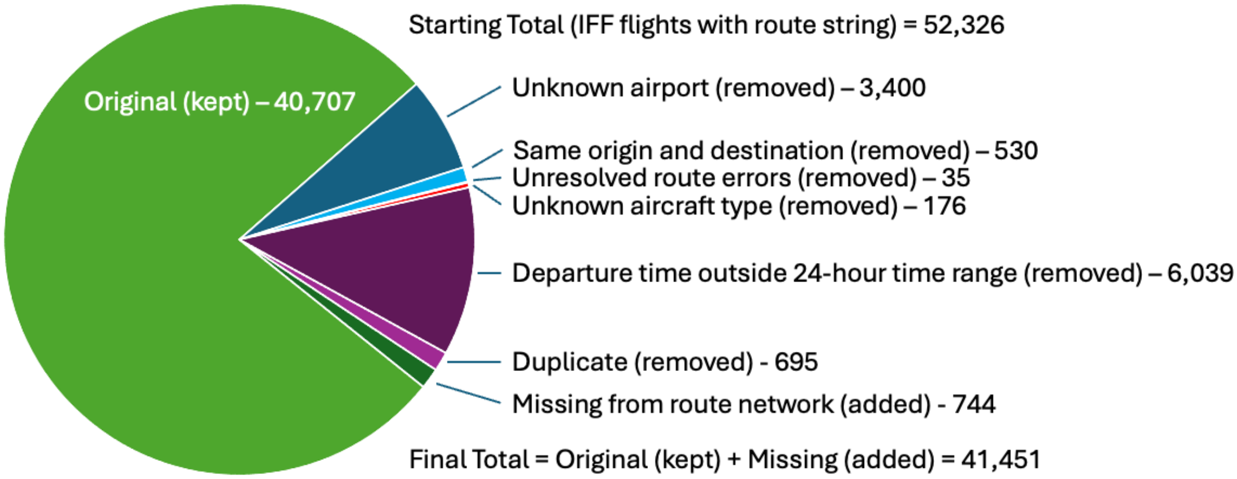

Figure 1. IFF Flight Filtering for 7/11/2024 Baseline Flight Scenario

B. Flight Scenario Analysis

Figure 2 shows the breakdown of the baseline scenario by engine type and jet size category. Tail counts are the number of unique tail numbers performing the flights shown. Most flights in the baseline scenario are narrowbody mainline airliner jets. Narrowbodies are single-aisle jets with ~100-250 seats, which encompasses the target mission identified for the TTBW. As seen in Figure 2, by comparing number of flights with number of tails, each narrowbody jet performs more than 3 flights per day on average. Although narrowbody jets comprise only 28% of the tails, they perform 40% of the flights.

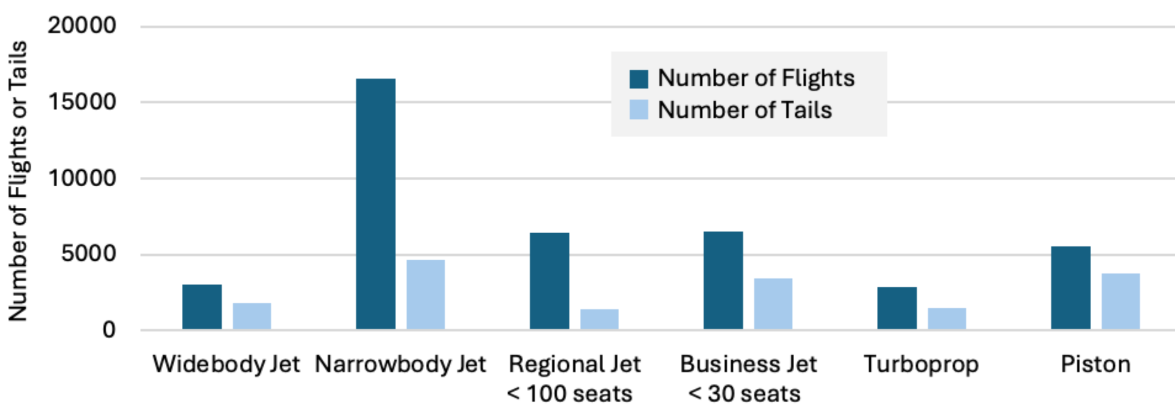

Figure 2. Breakdown of aircraft categories in baseline scenario

Figure 3 shows numbers of flights and tails transporting passengers and cargo for each narrowbody jet aircraft type in the baseline scenario with 10 or more tails. Aircraft types along the x-axis appear from left to right ordered by increasing maximum payload weight. A passenger vs. cargo designation for each flight was determined based on whether the airline referred to by its callsign was a passenger or cargo airline. It is evident that narrowbodies primarily transport passengers, with only the B752 and B738 performing 186 and 27 cargo flights, respectively. On this day, air cargo was transported mostly by widebody and regional aircraft not shown in Figure 3. The B738 has the most flights and tails of all narrowbodies. As seen in Figure 3, newer Boeing MAX8 (B38M) and MAX9 (B39M), and Airbus 320neo (A20N) and 321neo (A21N) aircraft are being introduced into the fleet. However, older generation aircraft (B738, B739, A320, A321) still outnumber the new generation roughly two to one. Overall, B738 and similarly sized B38M, A320, and A20N aircraft comprise 44% of the narrowbody fleet, over 2000 tails, providing an attractive target niche for TTBW. The older generation passenger carrying midsize narrowbodies (B738 and A320) were selected as target flights for replacement with TTBW in this study for two reasons: First, these aircraft are likely to retire and require replacement earlier than B38M and A20N. Second, detailed aircraft models for B38M and A20N were not available, to be explained further in the next section.

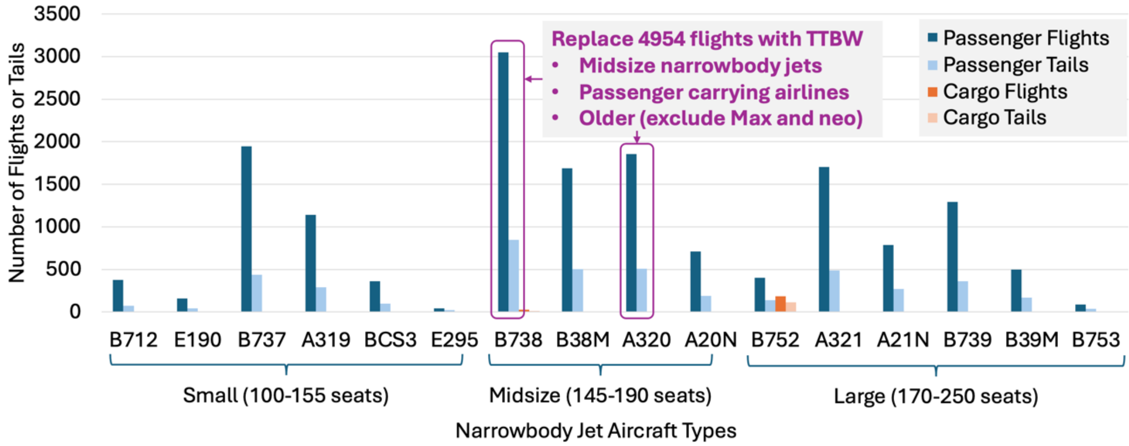

Figure 3. Numbers of passenger and cargo flights and tails per aircraft type in baseline scenario

Figure 4 shows an analysis of seat count vs flight range for the 4954 flights with B738 and A320 aircraft types replaced with TTBW, henceforth referred to as target flights. Seat counts are based on airline published cabin seat counts for each aircraft type [7, 8], whereas flight ranges are the path distances along filed routes. Gradient shading reveals an expected pattern of decreasing flight range as the seat count increases. The average seat count is 164 seats and the average flight range is 910 NM. These averages fall within the most common bin combination of 500-1000 NM flight range and 160-169 seats, cell (500,160). All but one flight is within the TTBW target flight range of 3400 NM.

seat count bin \ flight range bin (NM)	0	500	1000	1500	2000	2500	3000	3500
140	1	11	8	5	0	0	0	0
150	270	618	366	170	77	3	0	1
160	286	710	451	120	20	0	0	0
170	315	640	265	102	15	0	0	0
180	87	251	116	35	11	0	0	0

Figure 4. Numbers of target flights (B738 and A320) within seat count and flight range bins

IV. Modeling and Simulation

NASA's National Airspace System (NAS) Digital Twin is a simulation platform for creating realistic simulations of aircraft and airspace systems [9]. NAS Digital Twin's Point Mass Trajectory Generator (PMTG) uses physics-based aircraft models to generate high fidelity trajectories and fuel burn estimations.

This study utilized two sources of aircraft models, BADA and Gascon. BADA 3.8 from Eurocontrol [6], providing over 115 aircraft performance models that map to over 400 aircraft types in current operation, was used to model all baseline aircraft types. However, BADA 3.8 does not provide models for more recent aircraft types developed since 2010, including BCS3, E295, B38M, A20N, A21N, and B39M narrowbody jets. Any aircraft type not included in BADA 3.8 was mapped to the closest matching BADA model (BCS3 and E295:A319, B38M:B738, A20N:A320, A21N:A321, and B39M:B739). As such, only midsize narrowbodies with BADA 3.8 models (B738 and A320) are replaced with the TTBW for this study.

As a conceptual aircraft not yet in operation, the TTBW required another method of performance modeling. NASA's Gascon [10], an advanced Python implementation of the legacy aircraft modeling tool General Aviation Synthesis Program (GASP) [11], was used to model a midsize narrowbody TTBW with advanced technologies consistent with a 2035 entry into service [3]. The TTBW fuselage was sized to carry 190 passengers. However, the average seat count for the target flights in Figure 4 is 164 and the average 2024 passenger load factor of ~83% [12] reduces the average load below 150 passengers. Therefore, the TTBW model was optimized for a design payload of 33,750 lbs (150 passengers at 225 lbs per passenger). Table 1 summarizes the TTBW design assumptions and requirements and lists the resulting GASP model parameters.

Table 1. TTBW design assumptions and requirements (left) and model parameters (right)

Assumptions and Requirements
33,750 lbs Payload (150 pax – 225 lbs)
3,400 NM Design Mission
Design Mach 0.8
2035 Aero Technology [13]
Advanced Direct Drive Turbofan 1.50
Body tanks allowed

Model Parameters	
Gross Takeoff Weight (lb)	132,843
Empty Weight (lb)	67,586
Wingspan (ft)	155.2
Wing Area (ft^2)	1,231.2
Aspect Ratio	19.57
Cruise Altitude (ft)	42,750
Start of Cruise Lift/Drag	22.8
Engine Sea Level Static Thrust (lb)	20,810
3400 NM Fuel Burn	21,929
900 NM Fuel Burn	6,793

Because fuel burn estimation is dependent on aircraft weight, a new NAS Digital Twin capability was implemented to estimate the takeoff weight [14] for each flight based on its payload weight and flight plan (route, cruise altitude, cruise TAS). This ensures that each flight caries the appropriate fuel weight required for its mission and enables fair comparison of fuel burn between different aircraft types performing the same mission (e.g. TTBW and the baseline aircraft it replaced). For this study, all baseline flights were assigned a payload weight of $s_{a,t} \times 0.83 \times 225$ lb, where $s_{a,t}$ is the seat count airline a uses for aircraft type t, 0.83 implements a 83% passenger load factor, and 225 lb is the assumed weight per passenger including luggage. For replacement scenarios, TTBWs were assigned the exact same payload weight as the baseline aircraft replaced. All other aircraft in each scenario were allowed to default to the BADA reference takeoff weight (roughly 60% between empty and maximum takeoff weight).

As previously described in Section II.A, baseline flights are assigned a cruise altitude and TAS based on flight plan and track point data and BADA performance tables. All flights with replacement TTBWs are assigned a cruise altitude of 43,000 ft and cruise TAS of 460 kts.

Rapid Refresh data from the National Oceanic and Atmospheric Administration (NOAA) [15] provides NAS Digital Twin with wind data impacting aircraft trajectories. NOAA provides data on a 13-km square grid and interpolation is used to estimate values through the entire grid area.

NAS Digital Twin was configured to collect Aircraft State Messages for each flight every 1 minute, including position (latitude, longitude, and altitude) and weight as the flight progressed along its route and burned fuel. These data were used to compute impact metrics described in the next section.

Two 41,451-fllight scenarios were run using NAS Digital Twin: the *baseline* scenario described in Section III, and the *replaced* scenario replacing the aircraft type of 4,954 target flights with TTBW.

V. Impact Metrics

Three metrics comprised of fuel burn savings, encounter savings, and top-of-decent distance from arrival airport, were selected to investigate the NAS-wide impact of TTBW performance differences. Figure 5 shows fuel burn rate (left) and altitude (right) vs simulation time for a B738, A230, and TTBW performing the same 500NM sample route. The B738 and A230 were assigned the most common cruise altitude observed for those aircraft types in the *baseline* scenario, 41,000 ft and 39,000 ft, respectively.

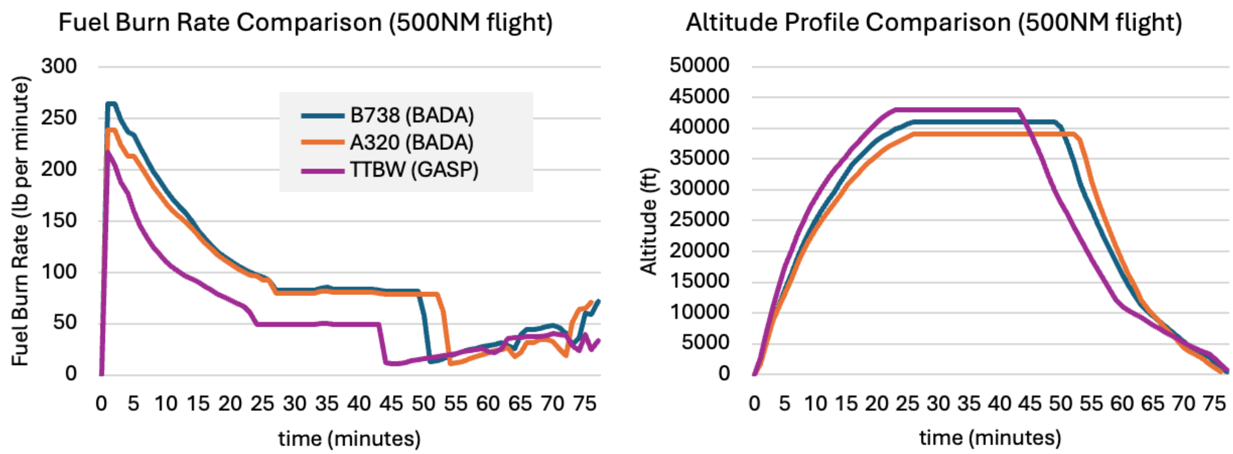

Figure 5. Comparison of fuel burn rate (left) and altitude profile (right) between B738, A320, and TTBW

As seen in Figure 5 (left), whereas the fuel burn rates are similar between B738 and A320, TTBW fuel burn rates are much lower in climb and cruise phases of flight suggesting that replacing B738 and A320 with TTBW should result in substantial fuel savings. Fuel savings is calculated on a per-flight basis for target flights only (B738 and A320 replaced with TTBW) as total or percent fuel burn difference between *baseline* and *replaced* simulations using the weight (lbs) from the first and last Aircraft State Messages of each flight as follows.

$$Total\_Fuel\_Burn_{f,s} = First\_Weight_{f,s} - Last\_Weight_{f,s} \tag{1}$$

$$Fuel\_Burn\_Savings_{f} = Total\_Fuel\_Burn_{f,baseline} - Total\_Fuel\_Burn_{f,replaced} \tag{2}$$

$$Percent\_Fuel\_Burn\_Savings_{f} = 1 - (Total\_Fuel\_Burn_{f,replaced} / Total\_Fuel\_Burn_{f,baseline}) \tag{3}$$

where f represents a given target flight and s represents a given simulation (*baseline* or *replaced*).

As seen in Figure 5 (right), TTBW not only flies at a higher cruise altitude than B738 and A320, but it has a steeper, shorter climb and more gradual, longer descent. These differences are expected to impact where and when flights come close enough to one another to require controller attention. Aircraft State Message position (latitude, longitude, altitude) is used to calculate and count pairwise encounters as a proxy for airspace complexity and controller attention required. An encounter occurs when a flight pair comes within 10 NM and 2000 ft at the same simulation time. The same flight pair may have multiple encounters only if they come back within range after being out of range for at least 5 minutes.

TTBW's shallower longer descent is expected to impact the Top of Decent (TOD) point calculated as the last Aircraft State Message position in cruise before beginning the decent phase of flight. The TOD distance to arrival airport (or time to landing) is calculated to capture changes in traffic patterns that may be of consideration for airspace design or controller training.

VI. Results

A. Fuel Savings Analysis

Figure 6 compares sum total fuel burn between the *baseline* and *replaced* target flights, as well as individual percent fuel burn savings per flight. Overall, replacing the 4,954 flights with TTBW resulted in 22.65 million pounds of fuel savings, which is 39.08% fuel savings with respect to just target flights or 4.44% fuel savings with respect to all flights. Looking closer at individual flight savings (Figure 6 right), there appears to be a logarithmic relationship between flight range and fuel savings, reinforcing the expectation that longer flights achieve greater benefit from TTBW replacement.

Figure 6

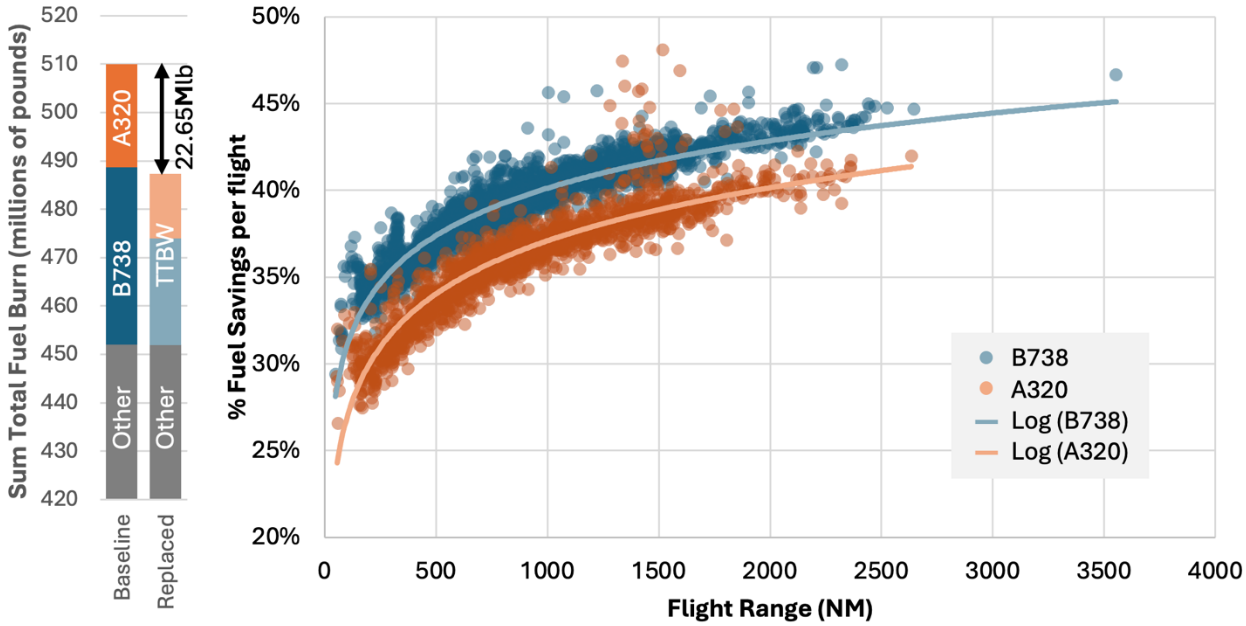

Figure 6. Fuel savings from replacing B738 and A320 with TTBW

As the replacement of the current aging fleet with new aircraft will not be instantaneous, two replacement prioritization schemes are explored to see if early benefits can be boosted. Figure 6 suggests that replacing longer range flights should be prioritized to maximize early benefits. However, each flight is part of a network of up to seven flights performed by a single aircraft tail in a day, and so it is the replacement of the 1,352 tails performing the 4,954 flights that must be prioritized. A minimum and sum flight range prioritization scheme (referred to as minDist and sumDist) are defined as follows. First flights are grouped by tail and the tail is assigned a minDist and sumDist value equal to the minimum flight range and sum of all flight ranges of the flights within its network, respectively. Then tails are replaced in order of decreasing minDist or sumDist. Figure 7 and Figure 8 show histograms of tails with respect to minDist and sumDist, respectively, segregated by the number of flights within a single tail's network for the day (labeled as Flights/Tail across the top). Tails are replaced sequentially from top to bottom. Note how the minDist is higher for lower Flights/Tail ratios, whereas sumDist is higher for higher Flights/Tail ratios. This is because the longer the minimum range flight a tail performs, the fewer of these flights it can perform within a single day. The sum of many shorter range flights tends to exceed the sum of few longer range flights.

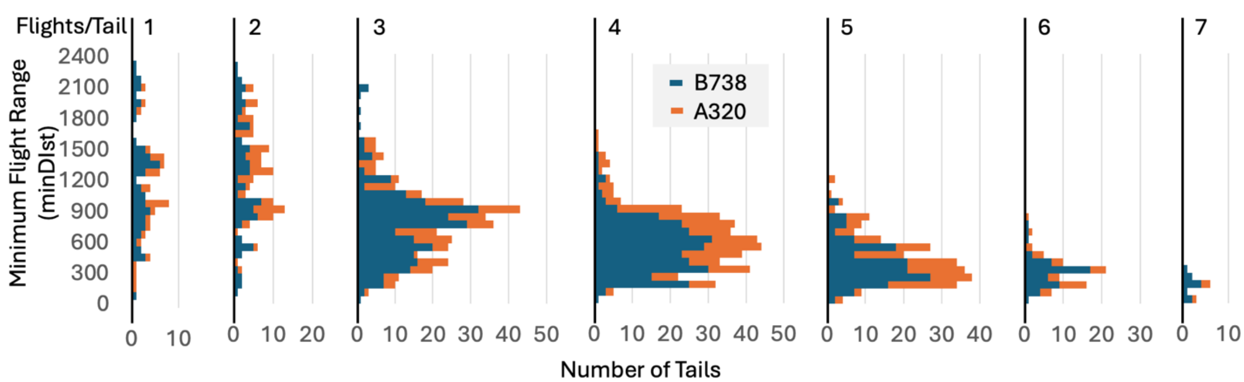

Figure 7. Minimum Flight Range (minDist) tail replacement prioritization scheme

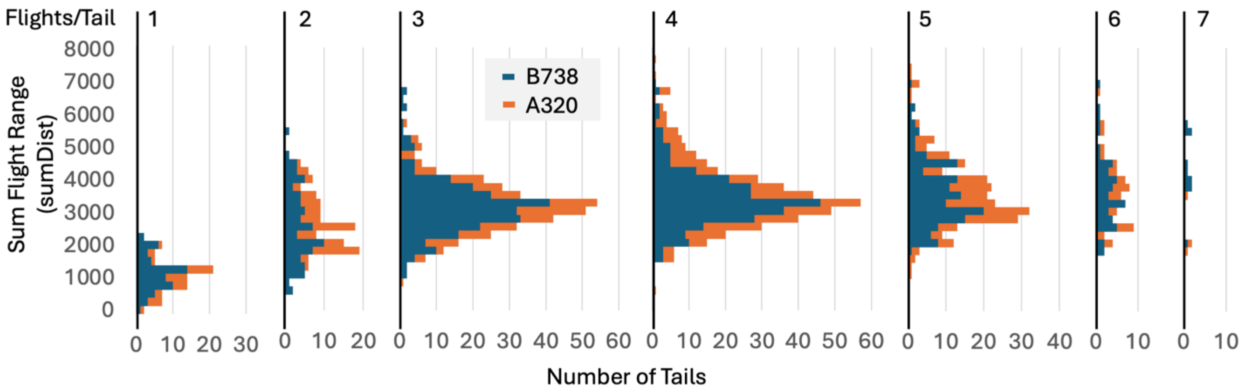

Figure 8. Sum Flight Range (sumDist) tail replacement prioritization scheme

Figure 9 shows cumulative number of flights with a replacement (left), sum total fuel savings (middle) and percent fuel savings (right) as tails are replaced according to minDist and sumDist prioritization schemes, as well as random replacement of tails. Random replacement results in linear increases in number of flights and sum fuel savings and quickly converges to the overall percent fuel savings of 39%. The cumulative increase in number of flights replaced using minDist and sumDist is slower and faster than random, respectively, due to the respective tendency of minDist and sumDist to prioritize lower and higher flight/tail ratios as seen in Figure 7 and Figure 8. Both prioritization schemes improve early sum total and percent fuel savings over random. However, whereas minDist is more successful at maximizing early percent fuel savings, sumDist is more successful at maximizing early sum total fuel savings. Whereas early individual flight benefits are maximized with minDist, early systemic benefits of saving more fuel are maximized with sumDist.

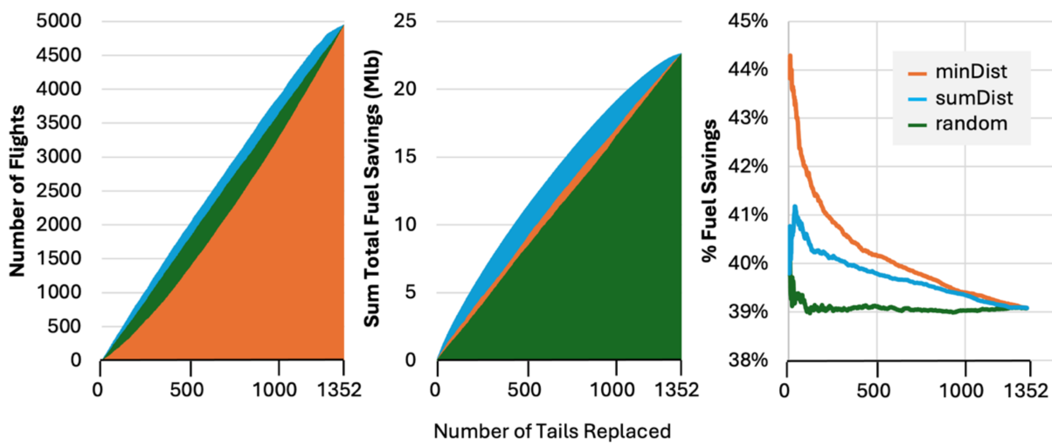

Figure 9. Comparison of cumulative fuel savings across tail replacement prioritization schemes

B. Encounters Analysis

Figure 10 compares encounter counts between the baseline and replaced simulations. The left shows all encounters between two other flights (other vs other), between two target flights (target vs target), and between one of each (target vs other). Other vs other encounters do not change between *baseline* and *replaced* simulations because the flight performance is unchanged. The largest difference in encounters is between target and other flights. The *replaced* simulation reduced encounters by 16,805 which is a 30% reduction of encounters involving a target aircraft or a 9% reduction of all encounters. The right decomposes just target involved encounters by phase of flight (upper) and by altitude (lower). Target encounters by phase of flight shows that the largest difference in encounters is a reduction of 12,996 between two flights in cruise, followed by more modest reductions in cruise vs climb and climb vs decent flights. Target encounters by altitude shows that although most encounters occur at altitudes below 10,000 ft and above 37,000 ft, most of the difference in encounters between *baseline* and *replaced* simulations occurs above 37,000 ft. A peak in *baseline* target encounters is seen between 38,000 and 41,000 ft where B738 and A320 aircraft most commonly cruise, and a peak in *replaced* target encounters is seen at TTBW's cruising altitude of 43,000 ft. The results suggest that the TTBW's higher cruising altitude shifted target flights away from the more popular cruising altitudes below thus reducing their encounters with other flights.

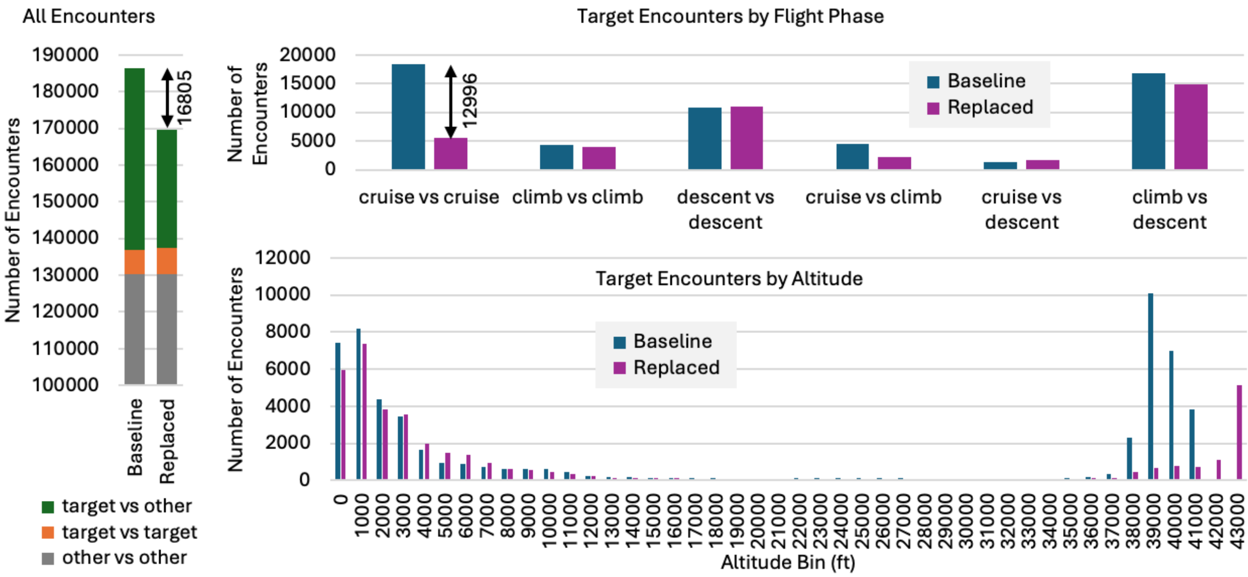

Figure 10. All encounter results (left) and target encounters by phase of flight (upper right) and by altitude (lower right)

C. Top of Decent Analysis

Figure 11 compares target flight TOD distance from arrival airport (left) and time from landing (right) between *baseline* and *replaced* simulations. Due to the TTBW's longer shallower decent seen in Figure 5, on average the *replaced* target flights begin decent 51.7NM farther from the arrival airport and 8.24 min earlier from landing than the *baseline*. This shift in traffic pattern may be a consideration for possibly updating airspace design and controller training if large numbers of TTBW aircraft are integrated into the NAS.

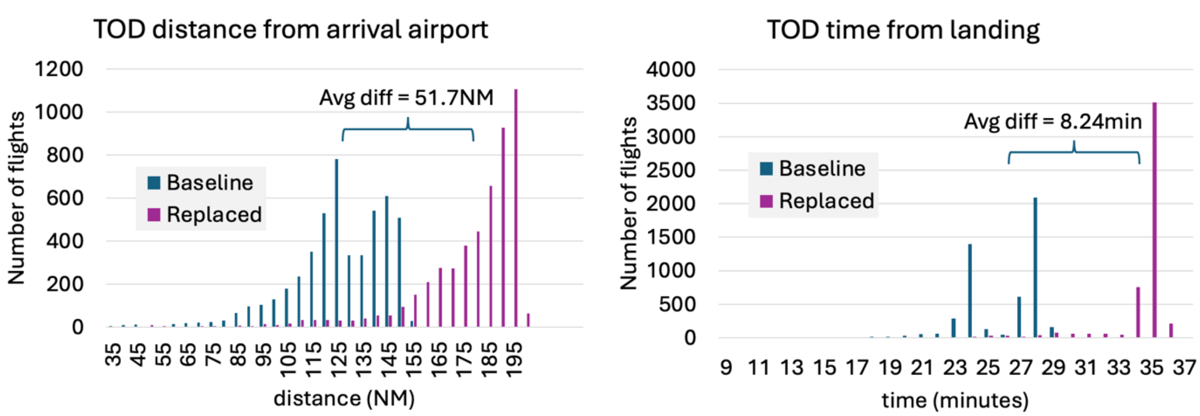

Figure 11. Target flight TOD distance from arrival airport (left) and time from landing (right)

VII. Conclusion

NAS Digital Twin fast-time simulations were used to assess the NAS-wide impact of replacing 4,954 aging midsize narrowbody passenger aircraft flights from a single day of historical traffic with a TTBW model designed for a comparable mission. The TTBW replacement resulted in fuel savings of 22.65 million pounds on this typical high volume day (39.08% savings with respect to the flights replaced or 4.44% savings with respect to all flights). These savings may appear optimistic because TTBW is replacing only older aircraft models available in BADA 3.8, excluding comparably sized state-of-the-art midsize narrowbody models, which should be included in future studies. Because fuel savings per flight tended to increase logarithmically with flight range, replacement prioritization schemes maximizing either the minimum or sum flight range of all flights within a single tail's flight network for the day were explored. Although both prioritization schemes succeeded in boosting fuel savings early in a potential TTBW implementation rollout, the prioritization based on sum flight range yielded the highest early total fuel savings.

The TTBW replacement also resulted in a 16,805 reduction in pairwise encounters (30% reduction with respect to the flights replaced or 9% reduction with respect to all flights), primarily while in cruise at altitudes above 37,000ft (due to TTBW flying at a higher cruise altitude better segregating these flights from other traffic). TTBW flights also started decent an average of 51.7NM and 8.24min farther from the arrival airport than the baseline flights owing to TTBW's longer, shallower decent. Future studies may dig deeper into the impact of these deviations in behavior on sector loading.

Overall, the TTBW shows potential for saving fuel and reducing encounters. Future NAS impact studies should not only include state-of-the-art aircraft models, but also explore other TTBW replacement strategies including competing advanced aircraft concepts such as advanced Tube & Wing and Blended Wing Body, as well as cascading replacement strategies repurposing current aircraft displaced by more advanced aircraft.

Acknowledgments

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References

[1] Federal Aviation Administration, "United States 2021 Aviation Climate Action Plan," 2021. [Online]. Available: https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf.

[2] M. Bradley, C. Droney and T. Allen, "Subsonic Ultra Green Aircraft Research: Phase II - Volume I - Truss Brased Wing Design Exploration," NASA/CR-2015-218704/Volume I, Boeing Research and Technology, Huntington Beach, California, April 2015.

[3] C. J. Recine, N. S. Listgarten, M. J. Schuh and K. D. James, "Quantification of the Impact Requirements have on the Relative Performance Improvement of a Transonic Truss Braced Wing when Compared to an Advanced Tube and Wing Aircraft of a Similar Technology Level," in *AIAA SciTech Forum*, Orlando, Florida, 2025.

[4] R. Fong, K. James, A. Meade, K. Palopo, G. Zilliac, C. Recine, D. Pham, T. Lauderdale, R. Windhorst, A. Kiak, A. E. Washburn and B. Sridhar, "Framework for National Airspace System (NAS) Level Sustainability Assessment of New Aircraft," in *AIAA Aviation Forum and Ascend*, Las Vegas, Nevada, 2024.

[5] NASA Sherlock Data Warehouse, "Integrated Flight Format (IFF)," 2024. [Online]. Available: https://sherlock.datawarehouse.arc.nasa.gov/browse/docs/#/products/IFF.

[6] Eurocontrol, "Aynonym Aircraft Report for the Base of Aircraft Data (BADA) - Revision 3.8," 2010. [Online]. Available: https://www.eurocontrol.int/publication/synonym-aircraft-report-base-aircraft-data-bada-revision-38.

[7] Tripadvisor, "SeatGuru - Browse Airlines," [Online]. Available: https://www.seatguru.com/browseairlines/browseairlines.php. [Accessed 2024].

[8] SeatMaps, "Find your flight seat map," [Online]. Available: seatmaps.com. [Accessed 2024].

[9] T. A. Lauderdale, R. D. Windhorst, R. A. Coopernbarger, D. P. Thipphavong and H. Erzberger, "Overview of the National Aispace System (NAS) Digital Twin Simulation Environment," in *AIAA Aviation Forum and Ascend*, Las Vegas, Nevada, 2024.

[10] B. W. L. Margolis, K. R. Lyons, J. A. Garcia, D. D. V. Pham, N. S. Listgarten, C. A. Natividad, J. V. Bowles, E. Chang and N. Bridges, "General Aviation Synthesis Program Advancements with Symbolic Computations, Optimization, and Decoupled Numerical Methods," in *AIAA Aviation Forum*, Las Vegas, NV, 2024.

[11] D. Hague, "GASP - General Aviation Synthesis Program. Volume 1: Main Program. Part 1: Theoretical Development," NASA-CR-152303-VOL-1-PT-1, National Aeronautics and Space Administration, Jan. 1978.

[12] United States Department of Transportation, "Bureau of Transportation Statistics - Load Factor," [Online]. Available: https://www.transtats.bts.gov/Data_Elements.aspx?Data=5. [Accessed 2024].

[13] C. J. Recine, D. D. V. Pham, J. V. Bowles, K. R. Lyons, B. W. L. Margolis and J. A. Garcia, "Analysis and Optimization of Baseline Single Aisle Aircraft for Future Electrified Powertrain Flight Demonstration Comparisons," in *AIAA Aviation Forum*, San Diego, CA, 2023.

[14] H.-T. Lee and G. B. Chatterji, "Closed-Form Takeoff Weight Estimation Model for Air Transportation Simulation," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, Texas, 2010.

[15] National Oceanic and Atmospheric Administration (NOAA) Global Systems Laboratory, "Rapid Refresh (RAP)," 2024. [Online]. Available: https://rapidrefresh.noaa.gov/.