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Alaska Airlines TASAR Operational Evaluation: Achieved Benefits

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Executive Summary

The NASA Traffic Aware Strategic Aircrew Requests (TASAR) concept offers onboard automation that advises the pilot of traffic compatible route modifications that would be beneficial to the flight. The Traffic Aware Planner (TAP) is the onboard automation component of TASAR. TAP was installed on three Alaska Airlines 737-900ER aircraft and used to conduct an operational evaluation of TASAR between July 24, 2018 and April 30, 2019.

TAP-recorded data onboard Alaska Airlines revenue flights was the primary data source to estimate the achieved benefits of TAP. The data recorded by TAP and used during the estimation included ownship state and ownship route received from aircraft systems. TAP ownship trajectory predictions and TAP advisories that were displayed were also recorded in flight and used during benefit estimation. TAP trajectory predictions and Alaska Airlines flight plans were used to estimate cost had the TAP-inspired route modifications not been made. A spreadsheet, referred to as the TAP Logbook, was populated by the TAP operator and used as a supplemental source to confirm which TAP advisories were approved and executed.

Benefits were quantified as the cost difference between flights with TAP being used and baseline flights without TAP-inspired requests. Publicly available Bureau of Transportation Statistics databases were used to estimate Alaska Airlines direct operating costs to convert fuel savings ($2.28/gallon) and time savings ($1,710/hour excluding fuel) into cost savings.

During baseline flights, TAP generated and recorded route modification advisories but did not display the advisories to pilots and therefore these advisories were not requested of ATC or flown. The difference between predicted costs and flown costs were used to quantify non-TAP effects during baseline flights. During TAP flights, TAP-computed advisories were displayed to pilots and were used to make TAP-inspired route modification requests to ATC. The difference between predicted costs and flown costs during TAP flights were used to quantify the combined TAP cost savings and non-TAP effects. Aggregate TAP cost savings were isolated by subtracting the estimate of baseline flights non-TAP effects from TAP flights containing both TAP cost savings and non-TAP effects.

For TAP flights, it was assumed that TAP impacted the flown trajectory along a defined segment. The segment began at the location of execution of the first executed TAP advisory and ended where the aircraft rejoined the pre-departure flight plan route after completing the final executed advisory. The predicted cost of the flight plan route between the start and end of the segment was used to select a corresponding baseline flight. The baseline flight with the same flight duration range (< 2 hours, 2 to 4 hours, or > 4 hours) as the TAP flight and occurring closest in calendar date (to mitigate seasonal variations) to the TAP flight was matched to the TAP flight.

The conduct of the Alaska TASAR operational evaluation created conditions that may not be representative of TAP use in regular operations in the future. For example, a goal of the operational evaluation was to have TAP be used by the Alaska pilots flying the aircraft. However, TAP operators were restricted to a limited group for cost reasons. The TAP operators consisted of four Alaska pilot interns, two NASA researchers, and four Alaska technical pilots. The pilot interns and NASA researchers, seated in the jump seat, offered TAP-inspired route modifications to the flight crew. Alaska technical pilots operated TAP from either the jump seat or front seats, depending on the flight. Alaska pilots may use TAP differently when they are responsible for its use as compared to taking input from TAP operators located in the jump seat.

Of the 119 Alaska revenue flights sampled as TAP flights, 29 flights experienced technical issues or other characteristics preventing the flight from being analyzed for benefits. Of the remaining 90 flights deemed valid for benefits analysis, 59 flights (65%) had TAP-inspired requests approved by ATC and 31 flights did not have TAP-inspired requests approved by ATC. It was not determined for these flights whether TAP-inspired requests were not made or whether they were made but not approved by ATC.

Benefits were estimated to be about $100/flight corresponding to a savings of about one minute and 30 gallons of fuel, though there is uncertainty surrounding these estimates due to the variability in the estimated benefits. The benefit estimation depended on the selection of baseline flights intended to represent

conditions if TAP-inspired advisories were not requested during TAP flights. TAP benefits ranged from about $90/flight to $110/flight depending on the flights selected to represent the baseline.

Prior to the operational evaluation the expectation was that using TAP during longer transcontinental flights would produce higher benefits. Results were consistent with this expectation since flights greater than 4 hours long had the highest estimated achieved benefits of about $180/flight as compared to achieved benefits of about $80/flight corresponding to flights between 2 and 4 hours. There was no measured benefit to using TAP on flights less than 2 hours during the operational evaluation.

Another factor that impacted benefits was the TAP operator. TAP was intended to be used by TAP-trained airline pilots from the front seat. However, during the operational evaluation, this only occurred during 22 flights. These 22 flights had an estimated benefit ($200/flight) that was about double the estimated benefit for all flights ($100/flight). This indicates that the $100/flight overall benefit may underestimate the benefits of deploying TAP to all Alaska pilots in the future if Alaska pilots were to consistently use TAP during most flights.

Prior to the operational evaluation, a fast-time simulation model was used to estimate the benefits of deploying TAP to 109 Alaska Airlines aircraft at $5.53M/year. This estimate was made before Alaska Airlines merged with Virgin America. The estimated cost savings from the operational evaluation was leveraged to estimate a cost savings of $14.97M/year if deploying to the expanded fleet of assumed 180 Alaska Airlines candidate aircraft. The updated annual benefit estimate is roughly consistent with the results from the previous fast-time simulation-based method. Two conditions may cause benefits to be higher or lower than this estimate. Higher annual benefits representing approximately double the values in the table can be obtained if it is assumed that the technical pilot $200/flight cost savings shown can be sustained if TAP is deployed for use by all pilots. Alternatively, if pilots do not consistently use TAP, or TAP is not deployed to the number of candidate aircraft assumed in the report, then the annual benefits will be lower than $14.97M/year.

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1. Introduction

The NASA Traffic Aware Strategic Aircrew Requests (TASAR) concept offers onboard automation that advises the pilot of traffic compatible route modifications that would be beneficial to the flight[1,2]. The Traffic Aware Planner (TAP) is the onboard automation component of TASAR[3]. TAP is an optimization software application hosted on an Electronic Flight Bag (EFB) that leverages Automatic Dependent Surveillance Broadcast (ADS-B) surveillance information and other external data to filter the solutions that would be conflicted, for an increased likelihood of Air Traffic Control (ATC) approval of pilot-initiated route modification requests, thereby increasing the portion of the flight flown on or near a desired business trajectory.

NASA partnered with Alaska Airlines to conduct an operational evaluation of TASAR in airline revenue-service operations. TAP was installed on three Alaska Airlines 737-900ER aircraft (N267AK, N270AK, and N272AK) and was used where appropriate to request route modifications during Alaska revenue flights[4,5]. Alaska technical pilots, Alaska pilot interns and, on certain flights, NASA researchers coordinated with Alaska pilots to make TAP-inspired requests to ATC between July 24, 2018 and April 30, 2019. These requests were intended to save fuel and time relative to the aircraft's current active route. TAP was also recording data during baseline flights where pilots were making typical requests to ATC without the benefit of TAP. The purpose of this report is to quantify the benefit of TAP-inspired route modification requests relative to baseline flights where pilots were not using TAP. Route modification requests consisted of lateral, vertical, or combination lateral/vertical (combo) route changes.

This report is organized as follows. Section 2 describes the data sources that were used to calculate benefits. The method used to compute benefits is presented in Section 3 followed by limitations of the method and operational evaluation in Section 4. The method was applied to generate the aggregate benefits and summary statistics in Section 5. Section 6 concludes the benefits assessment. The appendices contain: (A) supplemental analysis that supports the benefits assessment, (B) example flight plots corresponding to categories of benefits, (C) instructions to use the Python analysis scripts that quantified the benefits contained in this report, (D) TAP benefit opportunities estimated from in-flight TAP advisories, (E) a study of flight plan and TAP fuel and time prediction accuracy, (F) estimated annualized aggregate benefits of equipping domestic airlines' aircraft with TAP, and (G) a proposed TAP benefit estimation methodology.

2. Data used during Benefits Estimation

TAP-recorded data from Alaska Airlines revenue flights was the primary benefits estimation data source. This data source and supporting data sources are described in this section. Leveraging these data sources as inputs to the Python analysis scripts is described in Appendix C.

2.1. TAP-recorded Data

Table 1 contains a description of the TAP-recorded data that was analyzed post-flight and their use in the benefits assessment. The various files (left column) were extracted from the TAP-recorded files ending in .dat using the TAP data_translator.exe utility. The TAP display log listed in the last row of Table 1 did not need to be processed before being analyzed by the Python analysis scripts.

2.2. Flight Plans

The benefits assessment used company-generated, pre-departure flight plans to acquire predicted fuel burn and flight time between waypoints. These predictions provided one of two methods for estimating the flight segment cost that would have been incurred had the TAP-inspired route modification not been made. The other method used TAP predictions in place of flight plan predictions and is described in Section 3. Section 3 also describes the process to interpolate fuel burned and flight time in the cases where the aircraft deviated from its pre-departure flight plan.

Table 1. Description of TAP-recorded data used during benefits assessment.

TAP-Recorded Data Files	Description	Use in Benefits Assessment
AopOwnshipStateDataRecord	Ownship state (position, time, speed, weight, etc.) recorded at one second intervals.	Data source for flown fuel, time, lateral path, and altitude. Also used to detect altitude changes.
AopRouteDataRecord	Latitude, longitude, and identifier of ownship active route waypoints are recorded when they change. Target cruise altitude and cost index are also recorded.	Successive routes were used to identify lateral route changes. Also used to identify location that approved TAP advisories rejoin the pre-request active route.
AopOwnshipTrajectoryDataRecord	TAP-predicted fuel and time along the active route to the destination airport. Predictions were generated and recorded at regular (about ten second) intervals.	Used to estimate what would have happened if TAP advisory had not been requested and approved. This was an alternative to using flight plan predictions.
TapAdvisoryRefreshDataRecord	Characteristics of advisories generated by TAP.	Used to identify TAP advisories that were displayed and selected.
TapAdvisoryRouteDataRecord	Complete route along advisory lateral path to the destination airport.	Used to identify waypoint where TAP advisory route rejoins the original route.
TapSystemEventDataRecord	TAP system-level events.	Used to identify if TAP shut down prematurely prior to auto-shutdown location.
TAPDisplayEventLog	Record of all pilot interactions (e.g., button presses) with TAP Display.	Used to identify when pilot clicked “ATC Approved” after TAP-inspired request to ATC.

2.3. FlightAware Flight Schedules

The origin airport, destination airport, flown departure time, and flown arrival time were obtained from the FlightAware website for each flight conducted by the N267AK, N270AK, and N272AK aircraft. These data were downloaded because TAP does not record the origin airport and may not have been running and recording data at the times of departure and arrival. The downloaded data were then used to create a file (referred to as the TAP_Flights_* file) containing all flights where TAP was launched.

TAP-recorded data was used as a basis to determine whether TAP was launched during a flight. Every time that TAP was launched, which may have occurred several times per flight, a separate set of TAP-recorded data files were created representing a TAP instance. The characteristics of these instances, which included the location of TAP-recorded data and whether any TAP-recorded data files were missing, were recorded in a file (referred to as the TAP_Instances_* file) and used as an input to the Python analysis scripts described in Appendix C.

Though recorded TAP data for all TAP flights were listed in the TAP_Instances_* file, only the TAP flights meeting the selection criteria defined in either Section 3.2 or Section 3.5 were incorporated into the benefit calculations. Generally, the criteria ensured that the flights occurred within TAP’s valid geographic domain, TAP was used operationally, and sufficient data was collected and retrieved for analysis.

2.4. TAP Logbook

TAP did not have the capability to upload approved requests to the aircraft flight management system (FMS) so TAP-recorded data was not always definitive regarding whether a specific TAP advisory was requested and approved. The TAP logbook was a spreadsheet of flight information and TAP-specific information hand-recorded by the TAP operator during each TAP flight to supplement TAP-recorded data. The TAP-specific information in the TAP logbook included how many TAP advisories were reviewed by the pilots, how many TAP advisories were requested, and how many of those requests were approved by ATC. This information, and the TAP operator comments in the logbook, were used to confirm that the Python analysis scripts were correctly identifying approved and executed TAP advisories.

2.5. Aircraft Operating Costs

Alaska Airlines aircraft operating costs were estimated from air carrier quarterly financial reports published by the Bureau of Transportation Statistics (BTS), a part of the Department of Transportation and the preeminent source of statistics on commercial aviation [6]. These aircraft operating costs were used to convert fuel and time savings to U.S. dollar ($) cost savings.

Typically, airlines use an hourly direct operating cost (DOC) parameter, which includes fuel cost, to convert time savings to cost savings. However, since TAP-inspired altitude changes traded off between fuel and time, the analysis separated the time-related and fuel-related components of hourly direct operating costs. Alaska's hourly DOC ($1,710/hour excluding fuel) and fuel costs ($2.28/gallon) correspond to Alaska Airlines' reported 737-900ER financials for domestic third quarter of 2018. Values in Equations (1) and (2), corresponding to DOC and fuel costs respectively, are defined in Table 2.

$$DOC\ excluding\ fuel\ \left(\frac{\$}{hour}\right) = \left[\frac{TotalAirOpExpenses - FuelFlyOp}{TotalAirHours}\right] = \left[\frac{\$265{,}649 - \$145{,}182}{70.42\ hours}\right] = \frac{\$1{,}710}{\text{hour}} \tag{1}$$

$$Fuel\ cost\ \left(\frac{\$}{gallon}\right) = \left[\frac{FuelFlyOp}{AirFuelIssued}\right] = \left[\frac{\$145.182}{63.787\ gallons}\right] = \frac{\$2.28}{\text{gallon}} \tag{2}$$

Table 2. Field descriptions from BTS Form 41, Schedule P5.2 (Reference 6) for calculating aircraft operating costs.

Field	Description
TotalAirOpExpenses	Total aircraft direct operating expense (thousands of dollars)
FuelFlyOp	Total spent on aircraft fuel (thousands of dollars)
TotalAirHours	Total wheels-off to wheels-on airborne hours (thousands of hours)
AirFuelIssued	Total aircraft fuel issued for revenue and non-revenue flights (thousands of gallons)

3. Benefit Method

During the TASAR operational evaluation there were multiple stages of system testing and data collection[7]. During Stage 1 flights, TAP computed and recorded route modification advisories but did not display them to pilots on the TAP Display and therefore these advisories were not requested of ATC or flown. During Stage 2 flights, the TAP-computed advisories were displayed to pilots and were used to make TAP-inspired route modification requests to ATC. Stage 2 flights were conducted from July 24th, 2018 to September 20th, 2018. A second set of flights with TAP fully operational was conducted from January 23rd, 2019 to April 30th, 2019 and are referred to as Stage 3. Between Stage 2 and Stage 3, minor updates were made to the TAP Display software to enhance system stability, but no changes were made to the route optimization algorithms. Therefore for the benefits analysis, Stage 2 flights and Stage 3 flights were collapsed into a single dataset referred to as TAP flights. Stage 1 flights were used as a non-TAP baseline since pilots did not use TAP to make requests during Stage 1 flights.

The TAP benefit during the operational evaluation was defined to be the as-flown cost savings on the set of TAP (Stage 2 and 3) flights relative to a comparable set of baseline (Stage 1) flights. The method to compute these cost-savings benefits is described in this section.

3.1. Benefit Equation

The goal of the benefits analysis, represented by Equation (3), was to quantify the change in operating cost of flights with TAP (left summation term) relative to baseline flights operated without TAP (right summation term). A negative total cost change indicates a benefit to using TAP while a positive total cost change indicates an additional cost to using TAP. During TAP flights, pilots had access to TAP automation when negotiating with ATC to meet their objectives. During baseline flights pilots did not have access to TAP automation when negotiating with ATC. So the expected lower flown cost (C^{flown}) on TAP flights as compared to baseline flights should be the benefit of the TAP automation.

$$Total\ Cost\ Change = \sum_{TAP\ flights}(C^{flown} - C^{predicted}) - \sum_{baseline\ flights}(C^{flown} - C^{predicted}) \qquad (3)$$

One factor complicating the analysis was that in an operational setting, unlike in a simulated setting, the same flight cannot be flown twice, once with TAP and once as a baseline without TAP. The selection of an appropriate baseline flight to pair with the TAP flight is discussed later in this section. However, regardless of the non-TAP baseline flight chosen for a given TAP flight, the flight conditions between the baseline and TAP flights will be different.

The unimpeded predicted cost ($C^{predicted}$) was subtracted from the flown cost (C^{flown}) on both TAP and baseline flights to partially mitigate route and atmospheric differences between the flights. The unimpeded predicted cost is the flight segment predicted cost had the aircraft remained on the planned route rather than flown the TAP-inspired route. Two prediction methods were available: (1) the flight plan prediction and (2) TAP's own predictions. Flown costs are incorporated into the equation (rather than using predicted costs along the TAP-inspired route) since unpredictable events may occur after TAP-inspired requests that can only be accounted for by using aircraft state data. These events may include pilot and ATC actions required to meet their objectives as well as changing atmospheric conditions.

Section 5 reports results using both flight plan predictions and TAP predictions since there are advantages and disadvantages to using either prediction method. Flight plans predict step climbs and are used operationally at Alaska for flight efficiency analysis. However, aircraft may be off their pre-departure flight plan at the time a TAP advisory is approved, which complicates the analysis. Unlike the flight plan, TAP predictions reflect updated route and wind information received post-departure that is the primary basis for its route modification recommendations. However, TAP does not predict step climbs which are included in flight plans. Therefore, benefit estimates are presented using both prediction methods. Section 4 contains a list of other study and method limitations.

3.2. TAP Flight Sampling

During TAP flights pilots made route modification requests based on TAP advisories (i.e., TAP-inspired) that resulted in the aircraft flying a modified route. However on certain flights, the use of TAP was limited due to certain technical integration issues and limitations associated with the operational evaluation (e.g., navigation database limited to U.S. airspace). For this reason validation criteria in Table 3 were used to exclude flights during which pilots did not use TAP within the Continental US (CONUS) for a sufficient period of time or for which adequate data was not received. Benefits were calculated for all flights meeting the validation criteria regardless of other flight characteristics.

Note that Table 3 references a TAP "advisory generation state." This advisory generation state, which is referred to as "OPERATE" in TAP documentation, refers to TAP actively computing and displaying route modification advisories to the pilot. This TAP mode occurs after the pilot completes the TAP startup checklist, the aircraft climbs above 10,000 feet, the aircraft autoflight system is fully engaged in lateral and vertical navigation modes, and TAP receives sufficient input data, most notably winds, to be able to calculate advisories. TAP records when it is in an advisory generation state.

Table 3. Validation criteria that TAP flights needed to meet to be included in quantitative benefits estimate.

Validation Criteria
Departure airport is within CONUS
Arrival airport is within CONUS
Flight time above Flight Level (FL) 180 within CONUS must be at least 75 percent of total flight time from wheels-off to wheels-on
At least one pilot interaction with the TAP Display (i.e., button press) occurred while TAP was in an advisory generation state
TAP receives sufficient data to be able to calculate advisories and at least one of the following criteria was met: 1) Pilots made a TAP-inspired request to ATC 2) Cumulative 30 minutes in advisory generation state 3) 50 percent of the flight time above FL180 in advisory generation state
TAP-recorded data for the flight was retrieved from the aircraft

3.3. Identify TAP Start Point (TSP) and TAP Finish Point (TFP)

To quantify the impact of TAP on a flight, the flown segment altered by TAP-inspired route modification requests was identified. The start of the segment is referred to as the TAP Start Point (TSP) which was the location of execution of the first executed TAP advisory. The end of the segment is referred to as the TAP Finish Point (TFP) which was the location where the aircraft rejoins the pre-departure flight plan route after completing the final executed TAP advisory. Multiple TAP-inspired route modifications may occur between the TSP and TFP. The TFP defaults to Top-of-Descent (TOD) if the altitude or route of the as-flown TAP flight did not rejoin the flight plan altitude or route prior to TOD. For analysis purposes, it was assumed that the portions of the flight before the TSP and after the TFP were not affected by TAP and are therefore excluded from the computation of benefits. Figure 1 illustrates the location of the TSP and TFP for a notional TAP flight. Note that the aircraft may be off its pre-departure flight plan at the TSP and/or TFP.

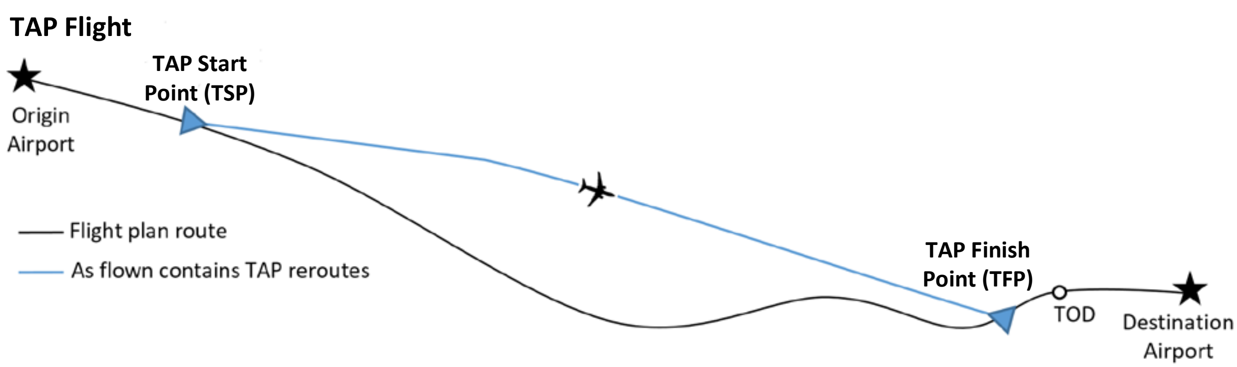

Figure 1. TSP to TFP segment impacted by TAP-inspired requests.

Table 4 shows the steps to calculate the TSP and TFP. TSP will be the same whether the flight plan or TAP was used to calculate the unimpeded predicted cost, $C^{predicted}$. TFP may or may not be the same location if the flight plan or TAP was used to calculate $C^{predicted}$ depending on whether there was an altitude change.

If there was a TAP-inspired altitude change then the distance from TSP to TFP will be longer for TAP predictions as compared to flight plan predictions. This was due to the TFP defaulting to the TOD since TAP does not predict step climbs and therefore the flown altitude will not rejoin the altitude predicted by TAP. Longer predictions should increase benefit estimation uncertainty since certain flight conditions, such as convective weather, may occur between the earlier TFP corresponding to flight plan predictions and the later TFP corresponding to TAP predictions. The quantitative impact of selecting a different TFP location was not studied. However, using a baseline flight with a predicted cost similar to TSP to TFP, which will be described in Section 3.6, is expected to minimize this effect.

Table 4. Steps to calculate TSP and TFP.

Step	Description
1	Identify route and altitude changes, using TAP-recorded data. Only altitude changes and route changes with a maximum of two off-route waypoints (TAP's maximum) are captured. Route and altitude changes are not yet attributed to TAP in Step 1.
2	Identify TAP advisories that were displayed. Use TAP-recorded data to identify which TAP advisories were selected by the aircrew for review. Also use TAP-recorded data to identify TAP advisories in the selected state while the TAP operator touched the button indicating ATC approved the request.
3	Match changes from Step 1 to advisories from Step 2 according to four classifications. Classification 1: advisory matches change and TAP operator touched the button indicating ATC approved the request at the time of the advisory. Classification 2: advisory matches change and TAP operator selected the advisory. Classification 3: advisory matches change but TAP operator did not interact with TAP Display. Classification 4: advisory partially matches change and that partial match may have been the result of an ATC route amendment.
4	Use the results of Step 3, comments in TAP logbook, and analyst judgment to determine whether a route or altitude change was the result of TAP usage. Assign ownship state at the time of the first match as the TSP. Two characteristics are used during Steps 5 and 6 next to determine TFP. Characteristic 1: The location that the last approved lateral or combo TAP advisory was predicted to rejoin to the ownship active route. In the case of one approved lateral request (the typical case) this location corresponds to the second blue triangle in Figure 1. Characteristic 2: The altitude corresponding to the last approved altitude or combo TAP-inspired request.
5	If using flight plan predictions for $C^{predicted}$ then TFP is determined as follows: i. If there are only lateral changes then the Characteristic 1 location is used as the TFP. ii. If there are only altitude changes then TFP is the first flight plan predicted waypoint location for which the planned altitude matches Characteristic 2, i.e., TFP will be at the flight plan waypoint location. If there is no match then the flown top-of-descent location is used as the TFP. iii. If there are both altitude and lateral changes then the first flight plan predicted waypoint after the Characteristic 1 location with altitude matching Characteristic 2 will be the location of TFP. If there is no match then the flown top-of-descent location is used as the TFP.
6	If using TAP predictions for $C^{predicted}$ then TFP is determined as follows: i. If there are only lateral changes then the Characteristic 1 location is used as the TFP. ii. If there are only altitude changes or if there are both altitude and lateral changes then the flown top-of-descent location is used as the TFP. TAP does not predict step climbs so the altitude change will not match the TAP-predicted altitude prior to top-of-descent.

3.4. Estimate Cost Difference from TSP to TFP

The steps to calculate ($C^{flown} - C^{predicted}$) from Equation (3) in Section 3.1 corresponding to TAP flights is described in Table 5. The steps are similar, but not identical, when using flight plan or TAP predictions which is why they are shown as separate columns. The steps are illustrated in Figure 2 after Table 5.

Table 5. Steps to calculate cost difference from TSP to TFP.

Step	Flight Plan $C^{predicted}$	TAP $C^{predicted}$
1	Obtain ownship state at TSP.	Obtain ownship state at TSP.
2	Find the closest point on the flight plan route to TSP. This point will generally not be a waypoint. The point is found by converting TSP and flight plan waypoint locations from geodetic (latitude, longitude, altitude) coordinates to Earth-Centered, Earth-Fixed (ECEF) X, Y, Z Cartesian coordinates and then applying standard geometry techniques to find the point.	The ownship trajectory prediction immediately prior to the TSP may be impacted by transitory conditions such as turns and altitude changes. TAP is generally robust to these conditions but small fuel and time prediction variance may occur for a short period of time. For this reason a candidate set of ownship trajectory predictions are obtained up to 10 minutes prior to the TSP. During the next step a representative prediction is selected out of this candidate set to minimize the impact of transitory conditions.
3	Calculate predicted aircraft weight and time at each waypoint in the flight plan downstream of TSP. Weight and time to first waypoint is interpolated by distance.	To exclude any ownship trajectory predictions with transitory effects, use the ownship trajectory prediction with median predicted ownship fuel at destination airport.
4	Obtain ownship state at TFP.	Obtain ownship state at TFP.
5	Find the closest point on the flight plan route to TFP. Interpolate by distance to obtain the predicted weight and time at this point. Apply the method described in Steps 2 and 3 to perform this calculation.	Find the closest point on the TAP ownship trajectory prediction to TFP. Interpolate by distance to obtain the predicted weight and time at this point. Apply the method described in Flight Plan (left column) Steps 2 and 3 to perform this calculation.
6	Calculate time component of ($C^{flown} - C^{predicted}$) by subtracting the predicted time at TFP obtained in Step 5 from the ownship state time at TFP and then multiplying by DOC (excluding fuel cost) from Section 2.5.	Calculate time component of ($C^{flown} - C^{predicted}$) by subtracting the predicted time at TFP obtained in Step 5 from the ownship state time at TFP and then multiplying by DOC (excluding fuel cost) from Section 2.5.
7	Calculate fuel component of ($C^{flown} - C^{predicted}$) by subtracting (-1 * predicted weight) obtained in Step 5 from (-1 * ownship state weight) at TFP, converting to gallons using 6.8 lbs per gallon, and then multiplying by the fuel cost from Section 2.5.	Calculate fuel component of ($C^{flown} - C^{predicted}$) by subtracting (-1 * predicted weight) obtained in Step 5 from (-1 * ownship state weight) at TFP, converting to gallons using 6.8 lbs per gallon, and then multiplying by the fuel cost from Section 2.5.
8	Calculate ($C^{flown} - C^{predicted}$) by adding results from Steps 6 and 7.	Calculate ($C^{flown} - C^{predicted}$) by adding results from Steps 6 and 7.

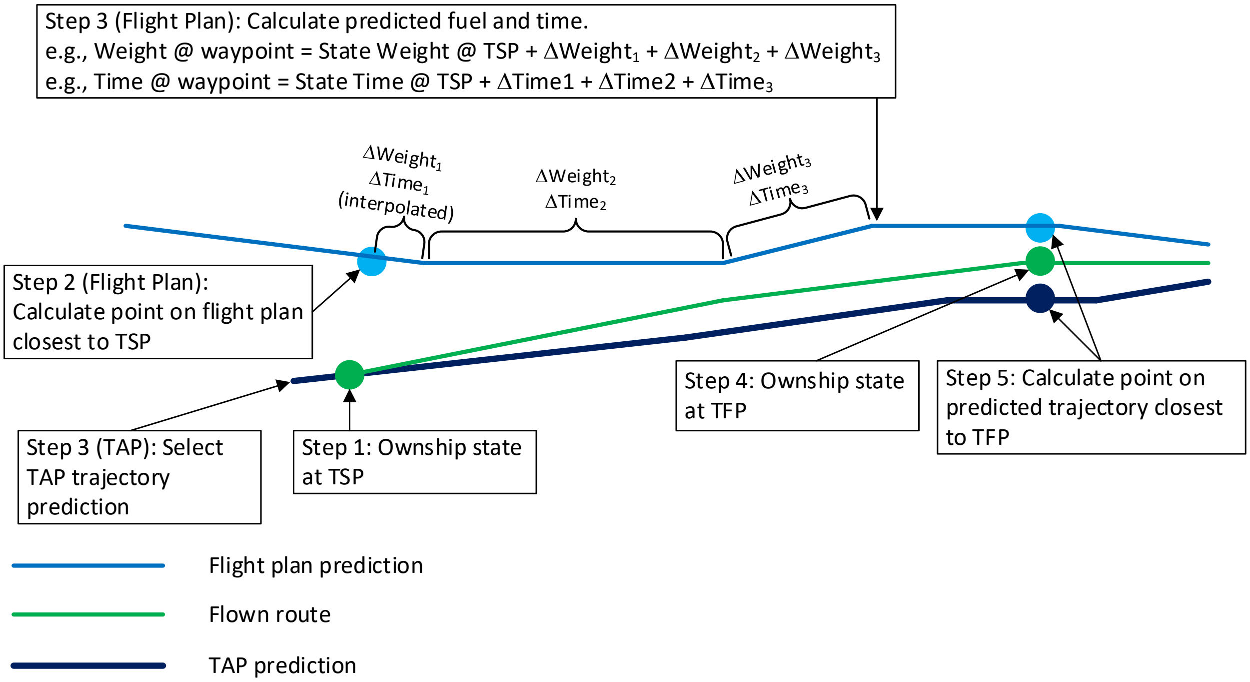

Figure 2. Illustration of certain steps to calculate predicted and flown costs from TSP to TFP.

3.5. Baseline Flight Sampling

For each valid TAP flight defined in Section 3.2 a corresponding baseline flight was selected as follows, with one exception: valid TAP flights without an approved TAP-inspired request were included in the results as zero benefit and therefore did not require a corresponding baseline flight. Valid TAP flights with an approved TAP-inspired request were ordered by date. Starting with the first valid TAP flight, the set of baseline flights meeting the criteria in Table 6 were used as candidates to be paired with a TAP flight. The candidate baseline flight that occurred closest in calendar date to the TAP flight (to mitigate seasonal variations) was paired with the TAP flight and removed as a pairing candidate for other TAP flights. This proceeded sequentially until all valid TAP flights with an approved TAP-inspired route modification request had a corresponding baseline flight.

Table 6. Criteria for flights to be a candidate baseline flight corresponding to a TAP flight.

Candidate Criteria
Departure airport is within CONUS
Arrival airport is within CONUS
Flown flight duration is within the same range as TAP flight: 1) 0 to 2 hours 2) 2 to 4 hours 3) More than 4 hours e.g., if TAP flown flight duration is 3 hours then baseline flight must have been 2 to 4 hours long.
TAP on the baseline flight was making ownship predictions and recording ownship state for at least the predicted time duration from TSP to TFP corresponding to the TAP flight. i.e., exclude baseline flights that were not recording data for a sufficient period of time.

3.6. Calculate Baseline Start Point (BSP) and Baseline Finish Point (BFP)

After the TSP and TFP were identified on the TAP flight, they served as benchmark locations for the corresponding baseline flight. A corresponding Baseline Start Point (BSP) and Baseline Finish Point (BFP) along the predicted path of the baseline flight were selected as follows. To simplify the analysis, the BFP was selected to be at the flown TOD since the TFP was generally at or near the TOD. The TFP was at the TOD 64% of the time when using flights plans to compute $C^{predicted}$. The TFP was at the TOD 100% of the time when using TAP to compute $C^{predicted}$. Figure 3 depicts the BSP and BFP. Note that the aircraft may be off its pre-departure flight plan at the BSP and/or BFP. The steps to calculate the BSP and the cost difference between the BSP and BFP are in Table 7.

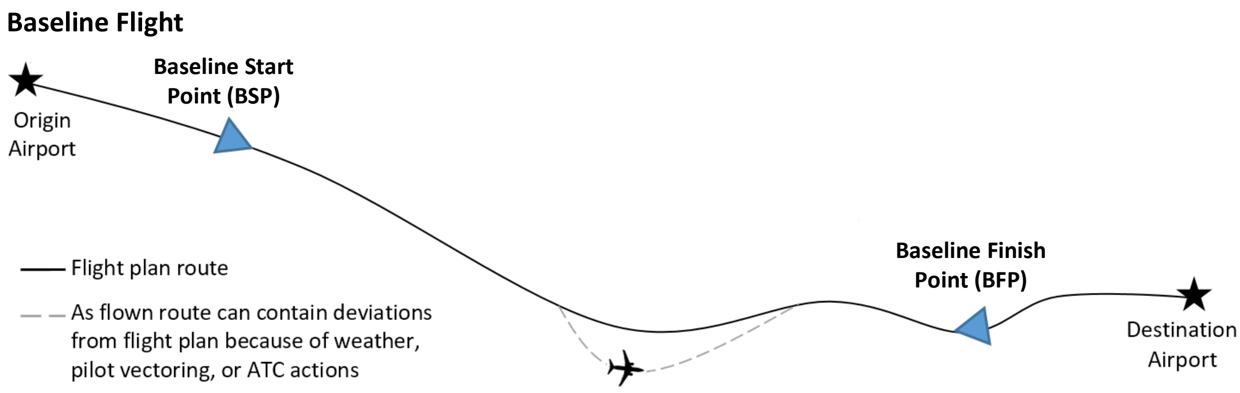

Figure 3. BSP to BFP baseline segment.

Table 7. Steps to calculate BSP and the cost difference from BSP to BFP.

Step	Description
1	Obtain $C^{predicted}$ from TSP to TFP as an output from the Table 5 steps in Section 3.4.
2	For each baseline flight TAP ownship trajectory prediction, obtain predicted aircraft weight and time at BFP (i.e., flown TOD) by applying Steps 2 and 3 from Table 5 in Section 3.4. Do the same for flight plan predictions by assuming the BSP occurs at the beginning of each TAP ownship trajectory prediction. Note that TAP is generating ownship trajectory predictions at an interval of about ten seconds or less, so this process results in many candidate ownship trajectory predictions with corresponding candidate BSPs. A specific TAP ownship trajectory prediction will be selected from this candidate set of ownship trajectory predictions next in Step 3. Similarly, a specific interpolated flight plan prediction will be selected from a candidate set of flight plan predictions interpolated at different candidate BSPs next in Step 3.
3	For the baseline flight, select the TAP ownship trajectory prediction with predicted operating cost ($C^{predicted}$ from BSP to BFP) that is closest in magnitude to the predicted operating cost on the TAP flight ($C^{predicted}$ from TSP to TFP). Repeat using the flight plan prediction. This step results in two BSPs, one for the TAP prediction and one for the flight plan prediction.
4	Calculate C^{flown} by applying aircraft operating costs listed in Section 2.5 to ownship state time and fuel differences between BSP and BFP.
5	Subtract $C^{predicted}$ from C^{flown} to obtain ($C^{flown} - C^{predicted}$) for baseline flights.

4. Operational Evaluation and Method Limitations

The conduct of the Alaska TASAR operational evaluation created conditions that may not be representative of TAP use in regular operations in the future. The characteristics of the benefit method may also limit its applicability. These and other limitations are described in Table 8.

Table 8. Description of limitations and their effect on achieved benefits.

Limitation	Description	Effect
TAP operator	A goal of the operational evaluation was to have TAP be used by the Alaska pilots flying the aircraft. However, TAP operators were restricted to a limited group for cost reasons. The TAP operators consisted of four Alaska pilot interns, two NASA researchers, and four Alaska technical pilots. The pilot interns and NASA researchers, seated in the jump seat, offered TAP-inspired route modifications to the flight crew. Alaska technical pilots operated TAP from either the jump seat or front seats, depending on the flight.	The benefits calculated may not be representative of benefits in regular operational use by Alaska pilots since only 24% of the valid flights had TAP operated from the front seat as intended. Alaska pilots may use TAP differently when they are responsible for its use as compared to taking input from TAP operators located in the jump seat.
TAP intermittent availability	TAP was designed to generate advisories when the aircraft is above 10,000 ft. However, connectivity was not always available between hardware devices hosting TAP components. For this reason TAP advisories may not have been generated for some or all of the flight.	This temporary condition unique to the TAP evaluation aircraft is expected to reduce the number of requests per flight and benefits. The validation criteria in Table 3 was developed and applied as a partial mitigation to this limitation.
Quantity of data collected	TAP benefits were expected to be of similar magnitude to normal flight-by-flight variability of fuel burned and flight time. For this reason evaluating the benefits of TAP across a larger sample of Alaska revenue flights would have increased confidence in the quantitative benefit results. Also, flights departing Seattle in the afternoon or returning to Seattle in the morning were generally not sampled. The data collection period for the operational evaluation was curtailed for programmatic reasons.	The reduced quantity of data resulted in larger margins of error. Results may also not be representative of routes not flown by Alaska during the evaluation period. The methodology in Appendix G is intended to mitigate this issue.
Seasonal data collection	Data was collected during two time periods: (1) July to September and (2) January to April. There was no TAP-inspired requests during the remaining months.	This prevented the study of TAP benefits across certain times of the year and certain weather patterns.
Measurement granularity effects	TAP benefits were expected to be about the same order of magnitude as TAP and flight plan data precision. For example, flight plan predictions to route waypoints were available to the nearest one minute and 100 lbs. of fuel.	These measurement effects represented uncertainty when calculating benefits for any particular flight though they were expected to average out when calculating benefits across a relatively large number of flights.

Limitation	Description	Effect
Identifying executed TAP advisories (TSP/TFP positive identification)	TAP was not integrated with the aircraft FMS. This required Alaska pilots to separately enter any approved TAP-inspired requests into the FMS for execution. Without an electronic record of the route modification entry, it could not be known with 100% certainty whether or not a route or altitude change executed in the FMS was TAP-inspired. Pilot interactions with the TAP Display (advisory selection, touching "ATC approved"), the TAP operator logbook, and analyst judgment were used to ascertain whether specific route and altitude changes were TAP-inspired.	The process for identifying TAP-inspired route modifications had potential for error, resulting in possible misidentification of route changes as TAP-inspired or not.
Evaluating non-TAP maneuvers	TAP was used during the operational evaluation to decide whether it was still beneficial to climb according to the step climb listed in the flight plan. TAP could similarly be used to evaluate ATC-offered directs. The benefits of not executing a potentially detrimental maneuver was not incorporated into the benefit methodology. In addition to modifying the method, additional data collection would likely be required to identify these cases.	Not including these cases has the effect of making the benefit estimation more conservative.
Baseline flight selection	It is not possible to fly the same flight twice, once with TAP and once without TAP, to definitively quantify TAP's benefit. Baseline flights were used as an approximation for what would have happened without TAP. However, baseline flights were different from TAP flights in that they likely experienced different weather, ATC actions, and unplanned pilot maneuvers. For this reason, a single baseline flight may be less representative than using a larger sample of baseline flights. Limited TAP data collection prevented the application of a larger set of baseline flights.	Benefits for individual flights may have substantial error, though benefits averaged over many flights should partially mitigate this error.

5. Benefit Results and Usage Summary

This section presents the quantitative TAP benefits estimated from the Alaska Airlines operational evaluation. Appendix A contains TAP request and flight characteristic statistics to complement the benefit results.

5.1. Valid Flights

Between July 24, 2018 and April 30, 2019 a total of 119 Alaska revenue flights were reviewed for analysis, including seventy flights between July 24 and September 20, 2018 and an additional 49 flights between January 23 and April 30, 2019. Ninety of those flights were determined to be valid TAP flights according to the criteria in Table 3. Of those 90 valid flights, 59 (66%) were determined to have had at least one approved TAP-inspired request during the flight.

5.2. Benefits

Recall from Equation (3), the total cost change equation in Section 3.1, that either flight plan predictions or TAP predictions could be used to calculate the $C^{predicted}$ term. Both sets of results are presented for the sake of completeness and to illustrate that a wide range of benefit estimates are possible using a small sample size.

Table 9 summarizes benefits aggregated for all operational evaluation TAP flights. The first row shows the summation of the flown cost minus the predicted cost across all valid TAP flights. On average, flown cost was higher than predicted cost since both the flight plan predictions (middle column) and TAP predictions (rightmost column) are unimpeded predictions, and unplanned deviations were common on most flights (e.g. ATC vectors, maneuvering for weather). The second row similarly shows this summation for baseline flights. The cost change is shown in the third row, which is calculated as the first row minus the second row. Since there was a reduction in cost attributed to TAP, the cost change is multiplied by -1 to provide the benefit attributed to TAP in row 4. Row 4 is divided by the number of valid flights (90) to obtain the average cost saving per flight calculated using flight plan predictions ($97.00/flight) and TAP predictions ($96.93/flight). The standard deviation of the benefit is also shown to indicate the spread of flight-by-flight benefits. The Margin of Error (MoE), defined as half the width of the confidence intervals corresponding to 80% and 95% confidence levels (CL), is shown below the standard deviation. The time and fuel benefit estimation are then shown in the final two rows.

Table 9. Aggregate benefit results corresponding to 90 valid flights.

Item	Flight Plan $C^{predicted}$	TAP $C^{predicted}$
$\sum_{TAP\ flights}\left(C^{flown} - C^{predicted}\right)$	$570.88	$2,056.25
$\sum_{baseline\ flights}\left(C^{flown} - C^{predicted}\right)$	$9,300.56	$10,780.19
Total cost change due to TAP ($)	-$8,729.68	-$8,723.93
Total TAP benefit ($)	$8,729.68	$8,723.93
Benefit per valid flight ($/flight)	$97.00/flight std dev=$274.28 MoE=$37.05, CL 80% MoE=$56.67, CL 95%	$96.93/flight std dev=$269.30 MoE=$36.38, CL 80% MoE=$55.64, CL 95%
Benefit per valid flight (minutes/flight)	0.84 minutes/flight std dev=3.84 minutes MoE=0.52 minutes, CL 80% MoE=0.79 minutes, CL 95%	0.58 minutes/flight std dev=4.56 minutes MoE=0.62 minutes, CL 80% MoE=0.94 minutes, CL 95%
Benefit per valid flight (gallons/flight)	32.1 gallons/flight std dev=89.6 gal MoE=12.10 gal, CL 80% MoE=18.51 gal, CL 95%	35.2 gallons/flight std dev=81.4 gal MoE=11.00 gal, CL 80% MoE=16.82 gal, CL 95%

The approximately $270 standard deviation indicates a relatively large spread of cost savings around the $97/flight average. Cost savings due to TAP were estimated to range from about -$500 to about $1,200 as shown in Figure 4. Any flight could be impacted by events unrelated to TAP-inspired requests that increase or decrease cost savings. Flights with negative cost savings had (1) a non-TAP event that negatively impacted the TAP flight, (2) a non-TAP event that positively impacted the baseline flight, or (3) a combination of positive and negative events that impacted both the TAP and baseline flights. Similarly, it would be difficult to distinguish the cost savings from noise for flights with savings between about -$500 to about $500 with the exception of $0 cost savings that correspond to flights that did not experience a TAP-inspired request. Flights further to the right on the plot experienced clear benefits though the exact value of that benefit is unknown due to uncertainties caused by the baseline flight selection. The figure also shows that there is no significant difference in the benefit distribution when using flight plan for predicted costs ($C^{predicted}$) as compared to using TAP for predicted costs.

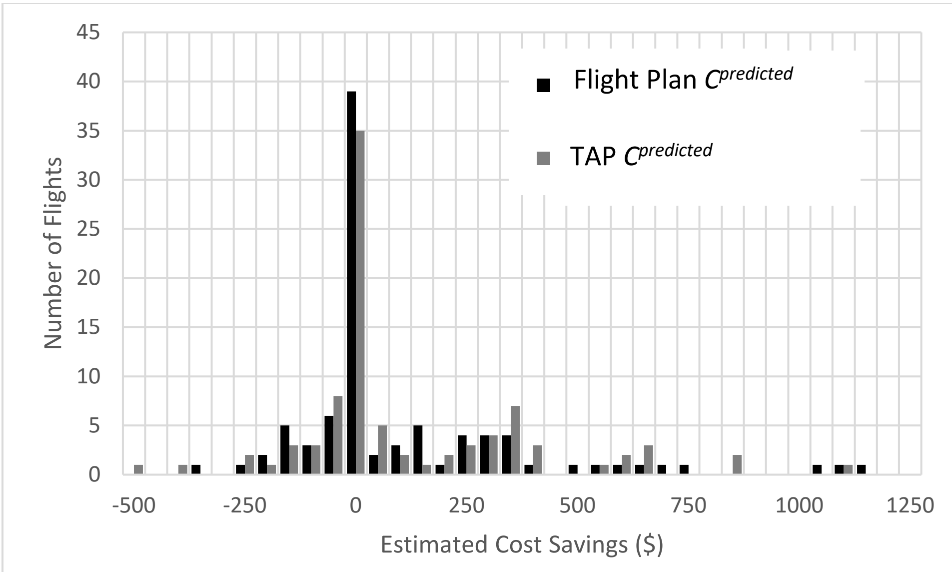

Figure 4. Distribution of estimated cost savings for each of the 90 valid flights.

Table 10 summarizes benefits by flown flight length (wheels-off to wheels-on) for reference even though the sample size is generally too small to definitively estimate benefits. The trend across flown flight lengths was as expected with the largest benefit per flight corresponding to flights exceeding 4 hours ($185.49/flight) and the lowest benefit corresponding to flights less than 2 hours (-$25.59/flight). Benefits corresponding to flights from 2 to 4 hours came in-between ($78.99/flight). The majority of benefits were concentrated to a few flights with estimated benefits exceeding $400/flight. On flights between 2 to 4 hours 85% of the benefits were attributed to 4 of the 51 flights. Similarly, on flights exceeding 4 hours 70% of the benefits were attributed to 5 of the 27 flights.

Table 10. Aggregate benefit results by flight length. Flight plan exclusively used to calculate $C^{predicted}$.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
Total valid flights With approved request Without approved request	12 5 (42%) 7 (58%)	51 31 (61%) 20 (39%)	27 23 (85%) 4 (15%)
$\sum_{TAP\ flights}(C^{flown} - C^{predicted})$	$236.71	$743.47	-$409.30
$\sum_{baseline\ flights}(C^{flown} - C^{predicted})$	-$70.35	$4,772.06	$4,598.85
Total cost change due to TAP ($)	$307.07	-$4,028.59	-$5,008.15
Total benefit ($)	-$307.07	$4,028.59	$5,008.15
Benefit per valid flight ($/flight)	-$25.59/flight (std dev=$59.83)	$78.99/flight (std dev=$275.34)	$185.49/flight (std dev=$307.41)
Benefit per valid flight (minutes/flight)	0.10 min/flight (std dev=0.35 min)	0.43 min/flight (std dev=3.46 min)	1.94 min/flight (std dev=5.06 min)
Benefit per valid flight (gallons/flight)	-12.44 gal/flight (std dev=29.57 gal)	29.29 gal/flight (std dev=93.78 gal)	57.07 gal/flight (std dev=92.76 gal)

TAP is intended to be used by the aircrew from the front seat. However in the operational evaluation, TAP was used by an Alaska tech pilot from the front seat during only 22 of the 90 valid flights. An additional 12 flights had either an Alaska tech pilot or NASA researcher in the jump seat but a pilot with no TAP experience in the front seat. The remaining 56 flights had non-airline pilot interns operating TAP from the jump seat.

Table 11 summarizes benefits by type of TAP operator and position in the cockpit. The highest achieved benefits occurred when Alaska tech pilots operated TAP from the front seat ($204.79/flight). These achieved benefits were higher than when TAP was operated from the jump seat by a tech pilot or NASA ($143.35/flight) or by a non-airline pilot intern ($44.71/flight). The benefit of about $200/flight when TAP was operated from the front seat indicates that the overall estimated benefit of $97/flight may underestimate future benefits if TAP is exclusive used by trained pilots from the front seat, as it was designed and intended to be used.

Table 11. Aggregate benefit results by TAP operator. Flight plan exclusively used to calculate $C^{predicted}$.

Item	TAP Operator		
	Alaska Tech Pilot from Front Seat	**Tech Pilot or NASA from Jump Seat**	**Non-Airline Pilot Intern from Jump Seat**
Total valid flights	22	12	56
With approved request	13	8	38
Without approved request	9	4	18
Flown flight length			
0 to 2 hours	3	4	5
2 to 4 hours	17	2	32
4+ hours	2	6	19
Mean flown flight length	3.05 hours	3.47 hours	3.61 hours
$\sum_{TAP\ flights}(C^{flown} - C^{predicted})$	-$1,369.39	-$165.36	$2,105.62
$\sum_{baseline\ flights}(C^{flown} - C^{predicted})$	$3,136.03	$1,554.87	$4,609.66
Total cost change due to TAP ($)	-$4,505.42	-$1,720.22	-$2,504.04
Total benefit ($)	$4,505.42	$1,720.22	$2,504.04
Benefit per valid flight ($/flight)	$204.79/flight (std dev=$419.16)	$143.35/flight (std dev=$221.06)	$44.71/flight (std dev=$192.29)
Benefit per valid flight (minutes/flight)	2.34 min/flight (std dev=5.23 min)	1.47 min/flight (std dev=2.72 min)	0.11 min/flight (std dev=3.23 min)
Benefit per valid flight (gallons/flight)	60.56 gal/flight (std dev=132.9 gal)	44.45 gal/flight (std dev=83.65 gal)	18.21 gal/flight (std dev=65.51 gal)

5.3. Alternative Baselines

Baseline flights represent, as close as possible, conditions if TAP-inspired advisories were not requested during TAP flights. Baseline flights include all of the non-TAP variables that affect the flown cost relative to the unimpeded predicted cost (e.g., ATC vectors, pilot-inspired short cuts, maneuvering for weather) and thereby allow the effects of TAP-inspired route modifications to be quantified. Baseline flights were successfully conducted during the July 24 to September 20, 2018 time period and therefore had similar conditions as the TAP flights. However, technical issues prevented the baseline flight data collection during January 23 to April 30, 2019. In a conservative approach, the TAP flights during this time period instead were paired with baseline flights from winter 2018-19 (September 2018 to January 2019) to estimate the benefits that were shown in Tables 9, 10, and Table 11.

To characterize the sensitivity of benefit estimation to the selection of the baseline, benefits were calculated using several alternative baseline assignments for the January 23 to April 30, 2019 dataset. Benefits quantified using baseline flight data from spring 2018 (January to July) and summer 2018 (July to October) were calculated using both the flight plan and TAP prediction methods and are summarized in Table 12. Also summarized in Table 12 are benefits calculated using baseline data collected in the March to May 2019 period from Alaska's Flight Operations Quality Assurance (FOQA) state data. FOQA was a data source independent from TAP containing ownship state data and was only available for select flights of the TAP-equipped aircraft in the March to May 2019 period.

As noted previously, the baseline from winter 2018-19 was selected to estimate benefits. One desirable characteristic of this baseline is that the benefits based on both flight plan predictions ($97.00/flight) and TAP predictions ($96.93/flight) fall within the range of all baselines ($92.12/flight to $111.13/flight). The narrow benefit range across baselines indicates that results for different baselines are generally consistent and benefit results are robust to selection of alternative baselines. Another desirable characteristic of the winter 2018-19 baseline is that it is one of two baselines that have results corresponding to both the flight plan and TAP predictions. The baseline leveraging data from summer 2018 also has results corresponding to flight plan and TAP predictions. However, the benefit results corresponding to the summer 2018 baseline at about $110/flight benefit is less conservative than the winter 2018-19 baseline at about $97/flight benefit.

Table 12. Aggregate benefit results corresponding to different baselines.

Item	Flight Plan $C^{predicted}$	TAP $C^{predicted}$
Baseline 1: Winter 2018-19 (September 2018 to January 2019)		
Benefit per valid flight ($/flight)	$97.00/flight	$96.93/flight
Benefit per valid flight (minutes/flight)	0.84 minutes/flight	0.58 minutes/flight
Benefit per valid flight (gallons/flight)	32.1 gallons/flight	35.2 gallons/flight
Baseline 2: Spring 2018 (January 2018 to July 2018), flight plans unavailable		
Benefit per valid flight ($/flight)	Unavailable	$109.10/flight
Benefit per valid flight (minutes/flight)		1.10 minutes/flight
Benefit per valid flight (gallons/flight)		34.1 gallons/flight
Baseline 3: Summer 2018 (July 2018 to October 2018)		
Benefit per valid flight ($/flight)	$109.08/flight	$111.13/flight
Benefit per valid flight (minutes/flight)	0.96 minutes/flight	0.85 minutes/flight
Benefit per valid flight (gallons/flight)	35.9 gallons/flight	38.1 gallons/flight
Baseline 4: Spring 2019 (March 2019 to May 2019), FOQA data only, TAP predictions unavailable		
Benefit per valid flight ($/flight)	$92.12/flight	Unavailable
Benefit per valid flight (minutes/flight)	0.66 minutes/flight	
Benefit per valid flight (gallons/flight)	32.2 gallons/flight	

5.4. Comparison to Benefits Predicted by Fast-Time Simulation

Prior to the Alaska TASAR operational evaluation, a fast-time simulation analysis was performed to estimate the benefits of using TAP on Alaska aircraft[8]. That study examined the potential for benefits by use case and aircraft type. The use cases were (1) lateral change after an ATC-initiated reroute has ended, (2) lateral change to optimize in the presence of convective weather, and (3) change to a more wind optimal trajectory. The study was conducted using data from the summer of 2012 when there were fewer high impact convective weather events than typical. For this reason, use cases (1) and (2) did not occur frequently and did not have a significant impact on the predicted benefits. In excess of 90% of the benefits were attributed to use case (3) which was switching to a more wind optimal trajectory.

Table 13 shows an estimate that 99% of the fuel benefit (10,465 gal out of 10,567 gal) and 99% of the time benefit (1,164 min out of 1,169 min) was due to the wind use case predicted for 737-900 aircraft.

Though benefits were estimated for the 737-900ER, 737-900, 737-800, and 737-700 aircraft, the simulation benefits corresponding to the 737-900 are shown here because the airport pairs shown in the left two columns more closely represent those flown during the Alaska TASAR operational evaluation than the 737-900ER simulation results that included transcontinental flights to Newark, Boston, and Orlando. Average fuel and time benefits can be obtained by weighting the "Per Operation Benefit" middle columns by the "Ops per 737-900" column to obtain an average savings of 25 gallons/flight and 2.8 minutes/flight, which when applied to Alaska's DOC and fuel costs correspond to a fast-time simulation estimated cost savings of $136.05/flight. The results in Table 9 show an achieved savings of 32.1 gallons/flight and 0.84 minutes/flight during the operational evaluation representing a lower estimated cost savings of $97.00/flight. However, there is still the caveat of large uncertainty in these estimates due to the small operational evaluation sample size.

Table 13. Fast-time simulation predicted benefits corresponding to 737-900 routes.

Airport 1	**Airport 2**	**Per Operation Benefit**		**Annual Benefit**		
		Fuel (gal)	**Time (min)**	**Ops per 737-900**	**Fuel (gal)**	**Time (min)**
Chicago (ORD)	Seattle (SEA)	41.7	5.7	77	3,012	414
Los Angeles (LAX)	Seattle (SEA)	14.8	1.4	133	1,968	191
Dallas (DFW)	Seattle (SEA)	45.1	6.0	39	1,761	234
Las Vegas (LAS)	Seattle (SEA)	16.6	1.4	83	1,375	113
Denver (DEN)	Seattle (SEA)	26.5	1.8	19	489	34
Phoenix (PHX)	Seattle (SEA)	14.5	1.3	33	477	44
Minneapolis (MSP)	Seattle (SEA)	53.2	3.5	11	168	31
Total Annual Benefit (Wind Use Case)				466	10,465	1,164
Total Annual Benefit (Wind, Convective Wx, and expired TMI)				466	10,567	1,169

The use cases exercised during the Alaska TASAR operational evaluation were different than the dominant wind optimal use case exercised during the fast-time simulation study. During the operational evaluation the dominant beneficial use cases seemed to be (1) climb to a more fuel-efficient altitude and (2) lateral change in the presence of convective weather. It is possible that additional benefits were available if TAP had generated, and pilots had selected, more advisories to follow a more wind optimal trajectory, but this behavior was not frequently observed. This could be due to the post-departure wind direction and magnitude shifts relative to the pre-departure flight plan route during the operational evaluation being less conducive to lateral wind optimization than was predicted by fast-time simulation. It is also possible that the lower fidelity fast-time simulation identified wind cases that the higher fidelity TAP automation correctly identified as being non-beneficial.

A significant factor was likely also the TAP operator. Of the 90 flights, 56 were conducted by non-airline pilot interns. Their junior position relative to the flight crew may have reduced the likelihood of executing lateral path changes that occurred frequently in the fast-time simulation model, favoring instead altitude changes which a flight crew unfamiliar with TAP might more easily accept as a recommendation. There were an estimated 12 lateral or combination lateral-vertical TAP-inspired route modifications during the 56 flights conducted with a non-airline pilot intern TAP operator. By comparison, there were 16 lateral or combination lateral-vertical TAP inspired route modifications during the remaining 34 flights representing a much higher rate of non-altitude TAP-inspired route modifications when either an Alaska tech pilot or NASA researcher operated TAP.

The output from the fast-time simulation model was also used to estimate an annual TAP benefit of approximately $5.15M/year across 109 aircraft equipped with TAP. This simulation-based estimate can be updated to $5.53M/year using the aircraft operating costs from Section 2.5. A corresponding estimate can be made using the operational evaluation results so far. The estimate will have a high degree of uncertainty due to the relatively small sample size of valid TAP flights given the large variation of benefits.

Annual TAP benefits were estimated for the top 10 domestic US airlines using cost savings by flight length shown in Table 10. The top 10 airlines were selected using the number of annual domestic CONUS operations. Table 12 summarizes estimated benefits for these airlines with further details provided in Appendix F. The number of aircraft that are candidates to be equipped with TAP were estimated and shown in the middle column. Generally, modern mainline jets were considered candidates. Regional jets and older aircraft were assumed to not be candidates for TAP for the purpose of this calculation. Also, the fleet size should be considered approximate since new aircraft regularly enter airline fleets and older aircraft are retired. Benefits for aircraft types that have recently been introduced by an airline are not quantified due to insufficient historical cost and flight frequency data.

Table 14. Estimated annual TAP cost savings benefits.

Airline	Estimated Aircraft that are Candidates to be Equipped with TAP	Estimated Cost Savings due to TAP
Alaska Airlines (AS)	180	$14.97M/year
Allegiant Air (G4)	37	$1.41M/year
American Airlines (AA)	831	$52.29M/year
Delta Airlines (DL)	466	$23.61M/year
Frontier Airlines (F9)	62	$4.38M/year
JetBlue Airways (B6)	63	$6.69M/year
Southwest Airlines (WN)	754	$36.47M/year
Spirit Airlines (NK)	61	$4.86M/year
Sun Country (SY)	30	$1.41M/year
United Airlines (UA)	562	$23.26M/year

Alaska Airlines has a larger fleet in 2019 than when the simulation-based estimate was conducted in 2015 due to a merger between Alaska Airlines and Virgin America. The merger is one reason why the $14.97M/year benefit estimate shown in Table 12 is higher than the simulation-based estimate of $5.53M/year, which was based on a smaller fleet of 109 aircraft. Another reason is that Table 12 includes benefits for all routes more than 2 hours planned duration while not all Alaska Airlines route were simulated in 2015. The estimates in Table 12 are based on a combination of Alaska technical pilot and non-pilot intern TAP operator results. Higher annual benefits representing approximately double the values in the table can be obtained if it is assumed that the technical pilot $200/flight cost savings shown in Table 11 can be sustained if TAP is deployed for use by all pilots. Alternatively, if pilots do not consistently use TAP then the annual benefits will be lower than those shown in Table 12.

5.5. Lateral, Altitude, and Combo Request Usage

TAP-recorded data was used to estimate how many lateral, altitude, and combo requests were approved. Since TAP was not integrated into the aircraft FMS the value of these statistics cannot be known with certainty. However, the statistics are useful in determining the relative quantity of each type of TAP-inspired requests that were approved and executed. TAP-inspired requests to change altitude were the most common TAP-inspired request, representing 107 of 138 (78%) of approved requests during the operational evaluation. As shown in Table 15, this was significantly higher than was predicted by the fast-time simulation study (1%). Note that the fast-time simulation pilot model always selected the TAP advisory with the highest predicted benefit to request to ATC.

Lateral (15% of approved requests) and combo (7% of approved requests) were also less frequently requested and approved than was predicted by the fast-time simulation study (67% and 32%, respectively). The use of lateral and combo requests are expected to increase as pilots gain experience and confidence using TAP. With the exception of a few Alaska technical pilots, none of the pilots on the TAP flights had any previous experience or training with TAP. In the cases where pilots had no TAP experience, TAP-inspired requests were made possible by the use of trained interns operating TAP from the jump seat. Their junior status relative to the flight crews may have impacted the number of lateral and combo requests that the flight crews were willing to make.

Table 15. Request type statistics based on TAP-recorded data. Results from fast-time simulation study are shown in *italics* for reference.

Item	Request Type		
	Lateral	Altitude	Combo
Flight with at least one approved request of listed type	18	48	7
Total approved requests	19	107	9
Approved requests per valid flight			
Operational evaluation	0.2	1.2	0.1
Fast-time simulation study	*1.4*	*<0.1*	*0.7*
% of approved requests			
Operational evaluation	15%	78%	7%
Fast-time simulation study	*67%*	*1%*	*32%*

6. Conclusions

This report quantified the benefits of TAP-inspired lateral and/or altitude route modification requests made to ATC during Alaska Airlines revenue flights selected for the operational evaluation of TASAR. During these flights onboard three TAP-equipped aircraft, TAP was operated by Alaska technical pilots in the front seats or by Alaska interns or NASA researchers in the jump seats. Of the 119 Alaska revenue flights sampled, 29 flights experienced technical issues or other characteristics preventing the flight from being analyzed for benefits. Of the remaining 90 flights deemed valid for benefits analysis, 59 flights (65%) had TAP-inspired requests approved by ATC and 31 flights did not have TAP-inspired requests approved by ATC. It was not determined for these flights whether TAP-inspired requests were not made or whether they were made but not approved by ATC.

The 90 valid flights were conducted across two data collection time periods: (1) July 24 to September 20, 2018 and (2) January 23 to April 30, 2019. This prevented the study of TAP benefits across other times of the year and certain weather conditions.

Benefits were estimated to be about \$100/flight corresponding to a savings of about one minute and 30 gallons of fuel, though there is uncertainty surrounding these estimates due to the variability in benefits from flight to flight. The benefit estimation depended on the selection of baseline flights intended to represent conditions if TAP-inspired advisories were not requested during TAP flights. TAP benefits ranged from about \$90/flight to \$110/flight depending on the flights selected to represent the baseline.

Time savings were lower and fuel savings higher than a previous fast-time simulation method estimated. Changing to a more efficient altitude represented 78% of approved requests during the operational evaluation. This was a different use case than the fast-time simulation study that experienced a relatively high number of lateral (67%) and combination lateral-altitude (32%) approved TAP-inspired requests to change to a more wind-optimal trajectory.

Prior to the operational evaluation the expectation was that using TAP during longer transcontinental flights would produce higher benefits. Results were consistent with this expectation since flights greater than 4 hours long had the highest estimated achieved benefits of about $180/flight as compared to achieved benefits of about $80/flight corresponding to flights between 2 and 4 hours. There was no measured benefit to using TAP on flights less than 2 hours during the operational evaluation.

Another factor that impacted benefits was the TAP operator. TAP was intended to be used by TAP-trained airline pilots from the front seat. However, during the operational evaluation, this only occurred during 22 flights. These 22 flights had an estimated benefit ($200/flight) that was about double the estimated benefit for all flights ($100/flight). This indicates that the $100/flight overall benefit may underestimate the benefits of deploying TAP to all Alaska pilots in the future if Alaska pilots were to consistently use TAP during most flights.

7. References

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Appendix A: Supplemental Analysis

Additional analysis of data collected during the operational evaluation to complement the achieved benefits analysis is presented in this appendix.

A.1. Valid Flights by Origin and Destination Airport

The number of inbound flights to and outbound flights from each airport sampled by the 90 valid flights is summarized in Table 16. The left column is the total number of flights either inbound to or outbound from the airport. The division by inbound and outbound flights is shown in the right two columns. All flights begin or end at Seattle except for four flights: (1) Boston to Portland, (2) Dallas to Portland, (3) Orlando to Portland, and (4) Portland to Dallas.

Table 16. Origin and destination airports corresponding to 90 valid flights.

Total Flights	Airport	Inbound Flights	Outbound Flights
86	Seattle (SEA)	46	40
9	Dallas (DFW)	5	4
8	Chicago (ORD)	5	3
7	Kansas City (MCI)	3	4
6	San Antonio (SAT)	2	4
6	Oakland (OAK)	3	3
5	Omaha (OMA)	1	4
5	Nashville (BNA)	3	2
4	Phoenix (PHX)	1	3
4	Minneapolis (MSP)	2	2
4	Tampa (TPA)	2	2
4	Portland (PDX)	3	1
3	Indianapolis (IND)	1	2
3	Raleigh-Durham (RDU)	1	2
2	Atlanta (ATL)	1	1
2	Austin (AUS)	1	1
2	Boston (BOS)	1	1
2	Washington (IAD)	1	1
2	Orlando (MCO)	1	1
2	New Orleans (MSY)	1	1
2	Palm Springs (PSP)	1	1
2	Salt Lake City (SLC)	1	1
2	Tucson (TUS)	1	1
2	San Jose (SJC)	1	1
2	Sacramento (SMF)	1	1
1	Baltimore (BWI)	0	1
1	Denver (DEN)	0	1
1	Ontario (ONT)	0	1
1	Philadelphia (PHL)	1	0

A.2. Predicted cost from Start Point (TSP/BSP) to Finish Point (TFP/BFP)

The predicted cost from the start point to the finish point ($C^{predicted}$) is the segment that TAP-inspired requests altered the flight path. The average of this metric, which is summarized in Table 17, is intended to demonstrate that both the TAP (TSP to TFP) and baseline flights (BSP to BFP) were measured along similar segment lengths. TAP predictions had later rejoins than flight plan predictions since TAP predictions did not contain step climbs and rejoined the original route at the top-of-descent if any altitude changes were approved. This is the reason why the bottom set of numbers corresponding to TAP predictions being used for $C^{predicted}$ are higher than the top set of numbers corresponding to flight plan predictions being used for $C^{predicted}$.

The BSP to BFP length in the right column was slightly shorter than the TSP to TFP length since TAP was not launched sufficiently early on certain baseline flights to obtain a prediction with look-ahead at or longer than the TSP to TFP look-ahead. These baseline flights met the criteria in Table 6. An additional baseline flight selection criteria was not added since there were insufficient candidate baseline flights available to further restrict the baseline flight sampling.

Table 17. Start Point (TSP/BSP) to Finish Point (TFP/BFP) $C^{predicted}$ statistics.

Prediction	Item	TSP to TFP	BSP to BFP
Flight Plan	Sample size	59	59
	Average predicted start to finish cost ($)	$6,901	$6,800
	Average predicted start to finish time (min)	114 min	114 min
	Average predicted start to finish fuel (gal)	1,603 gal	1,558 gal
TAP	Sample size	59	59
	Average predicted start to finish cost ($)	$8,275	$7,842
	Average predicted start to finish time (min)	138 min	132 min
	Average predicted start to finish fuel (gal)	1,906 gal	1,790 gal

A.3. Flight Length

The flight length statistics in Table 18 show that TAP and baseline flights had similar flight lengths. Recall that only TAP flights with approved requests are matched to baseline flights since TAP benefits are zero if there were not any approved requests. Generally a baseline flight of a given interval (e.g., 0 to 2 hours) was matched to a TAP flight of the same interval. However, due to limited sample size, two flights between 2 to 4 hours were used as baseline flights for two TAP flights greater than 4 hours. Similarly, one flight greater than 4 hours was used as a baseline flight for one TAP flight between 2 to 4 hours flight length. These substitutions were not expected to have a significant impact on the quantitative benefit results.

Table 18. TAP and baseline flight lengths. Characteristics of winter 2018-19 (September 2018 to January 2019) baseline shown in bottom two rows.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
Total valid TAP flights	12	51	27
With approved request	5	31	23
Without approved request	7	20	4
Average TAP flight lengths	1.60 hours	3.19 hours	4.79 hours
With approved request	1.63 hours	3.25 hours	4.84 hours
Without approved request	1.56 hours	2.95 hours	4.48 hours
Total baseline flights	5	32	22
Average baseline flight lengths	1.66 hours	3.01 hours	4.98 hours

A.4. TAP-Inspired Requests and Approvals

TAP has no reliable way of identifying and recording the TAP advisories that were actually requested. For this reason the TAP logbook was used as the source of TAP-inspired requests and approval rate. The TAP logbook indicated that 123 TAP-inspired requests were made to ATC. Of these 123 requests, 109 were approved by ATC and executed, corresponding to an 89% approval rate. This approval rate was higher than expected. The high approval rate may be due to the large percentage of altitude TAP-inspired requests which may be easier for ATC to approve than lateral requests.

The number of approved TAP-inspired requests in the TAP logbook is lower than the approved TAP-inspired requests based on TAP-recorded data. This potentially indicates underreporting in the logbook, which was typically filled out well after the flight completed. The first TAP-inspired request on each of the 59 valid TAP flights containing requests was manually reviewed using TAP logbook comments. This manual review was intended to minimize the likelihood of categorizing non-TAP changes as TAP-inspired.

Appendix B: Example Results Corresponding to Each Benefit Category

Four benefit categories are described in this appendix to illustrate the typical TAP-inspired changes experienced during the operational evaluation.

B.1. Benefit Category 1: Altitude changes only

TAP-inspired altitude changes were the only change type during 37 of the 59 valid TAP flights with approved TAP-inspired requests. One or more approved altitude change may occur during the flight.

Figure 5 and Figure 6 show an example where the pilot requested a climb to a higher altitude earlier than the step climb called for in flight plan, but made no lateral changes to the flight path. Flight plan predicted altitude at waypoints are shown as blue squares. Flight plan altitude is shown as zero during predicted descent since the flight plan did not report specific altitudes during predicted descent.

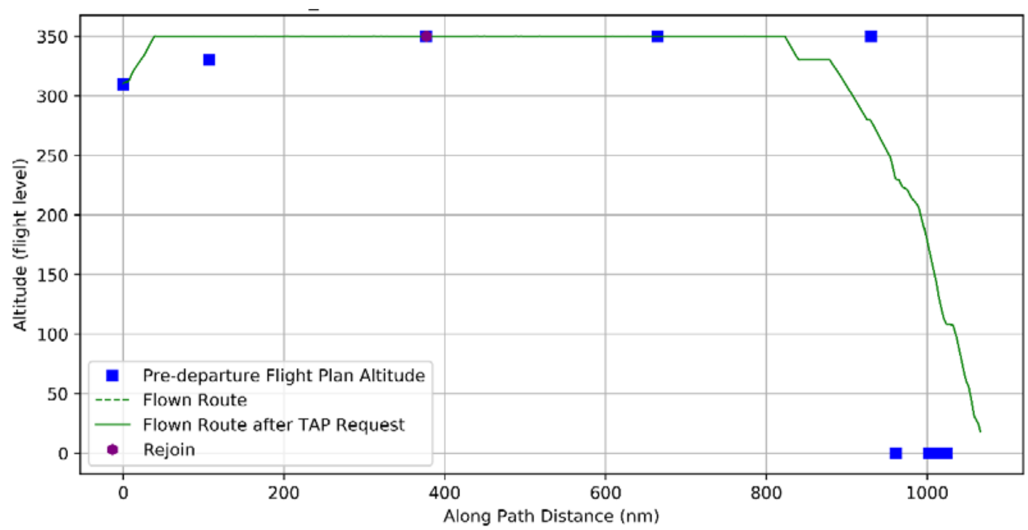

Figure 5. Example altitude profile for a flight that experienced only altitude TAP-inspired approved requests.

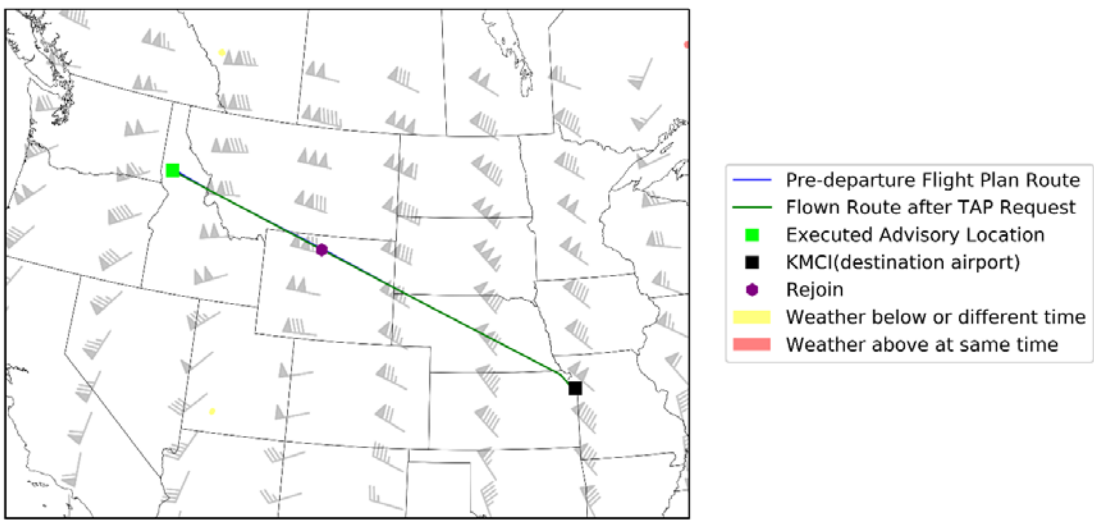

Figure 6. Example lateral path for a flight that experienced only altitude TAP-inspired approved requests.

B.2. Benefit Category 2: Lateral change in the presence of convective weather

Figure 7 and Figure 8 show an example where the pilot made a TAP-inspired combination lateral altitude change request during initial climb in the presence of convective weather. This request was intended to save fuel and time rather than avoid weather since the ownship active route avoided existing convective weather at the time of the TAP-inspired lateral change. Vectoring was used to avoid convective weather after the TAP-inspired request was approved and executed. In Figure 8, flight plan predicted altitude at waypoints are shown as blue squares. Flight plan altitude is shown as zero during predicted climb and descent since the flight plan did not report specific altitudes during predicted climb and descent.

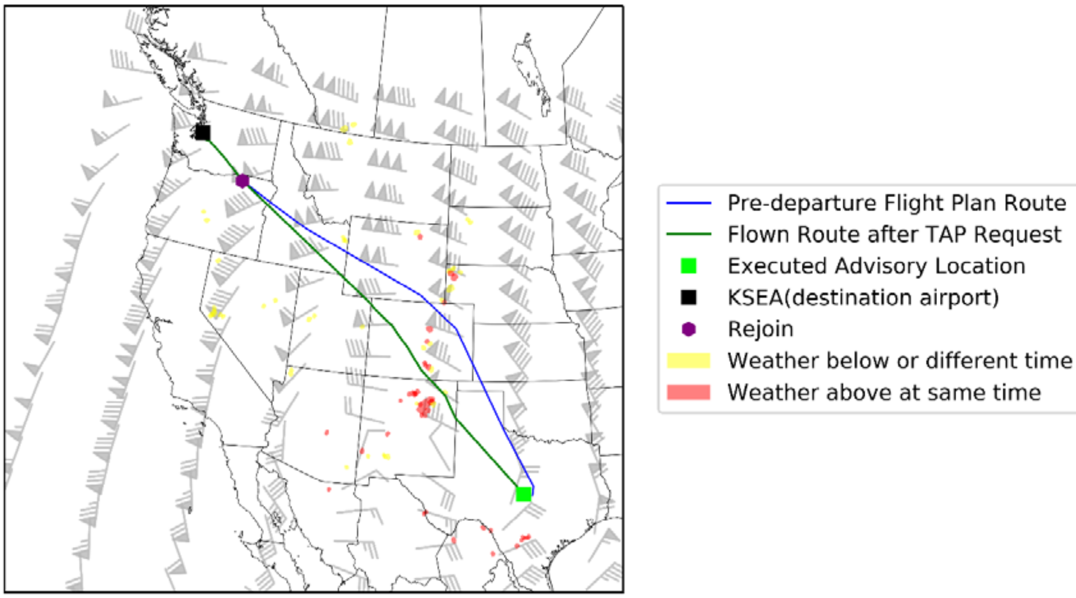

Figure 7. Example lateral path for a flight that had a TAP-inspired lateral change in the presence of convective weather.

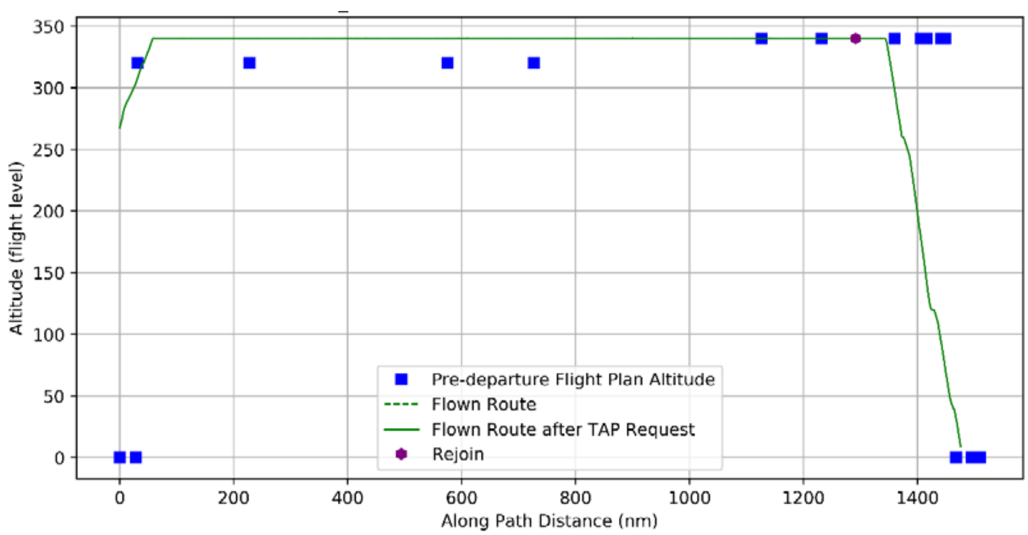

Figure 8. Example altitude profile for a flight that had a TAP-inspired lateral change in the presence of convective weather.

B.3. Benefit Category 3: Direct to downstream waypoint

Figure 9 and Figure 10 show an example where the pilot made a TAP-inspired request corresponding to direct to a downstream waypoint. Convective weather was not projected to impact the pre-departure flight plan route or TAP-inspired route in this example. Direct to a downstream waypoint was more common corresponding to about 24 out of 31 lateral or combination lateral/altitude changes than requesting one or two off-route waypoints followed by rejoining the route. This example had a step climb later in the flight which was typical of flights with TAP-inspired directs to a downstream waypoint. Target altitude was FL350 at time of lateral change during initial climb. Flight plan predicted altitude at waypoints are shown as blue squares. Flight plan altitude is shown as zero during predicted descent since the flight plan did not report specific altitudes during predicted descent.

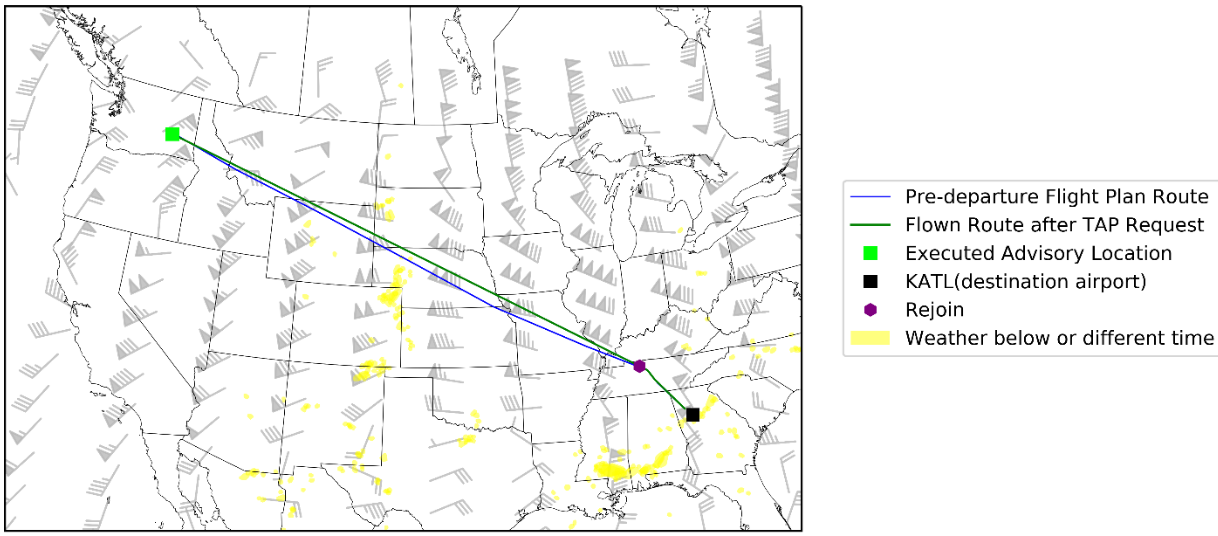

Figure 9. Example lateral path corresponding to a TAP-inspired direct to a downstream waypoint. Downstream waypoint is depicted as a purple hexagon.

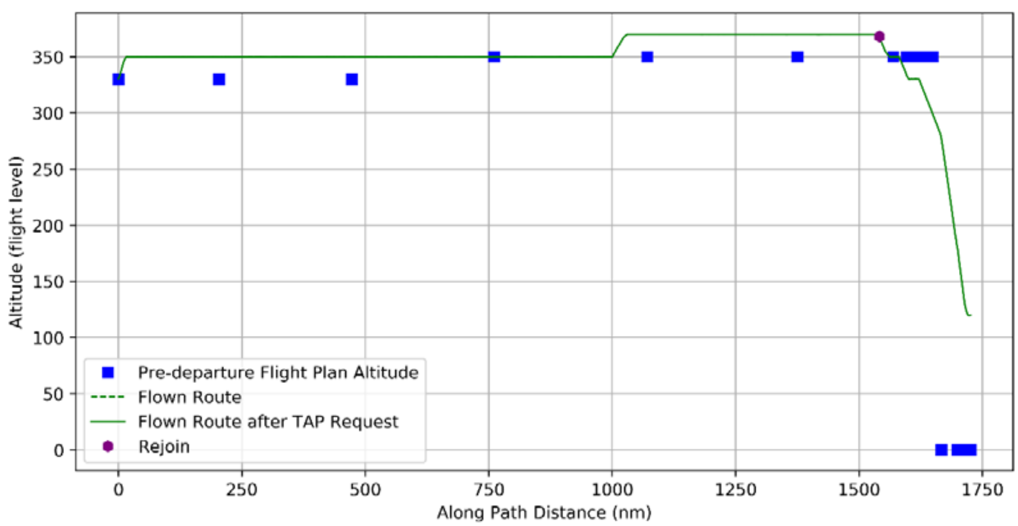

Figure 10. Example altitude profile corresponding to a TAP-inspired direct to a downstream waypoint.

B.4. Benefit Category 4: Off route waypoint(s)

Figure 11 and Figure 12 show an example show an example where the pilot made a TAP-inspired combination lateral altitude change request during initial climb. The lateral component had one off-route waypoint prior to rejoining to the original route. Off route waypoint is shown as a green star. Downstream waypoint is depicted as a purple hexagon. Flight plan predicted altitude at waypoints are shown as blue squares. Flight plan altitude is shown as zero during predicted descent since the flight plan did not report specific altitudes during predicted descent. This was not a typical case, as was mentioned in the previous paragraph, but an off-route waypoint example is included for the sake of completeness. A non-TAP-inspired direct to a downstream waypoint to avoid convective weather later modified the route.

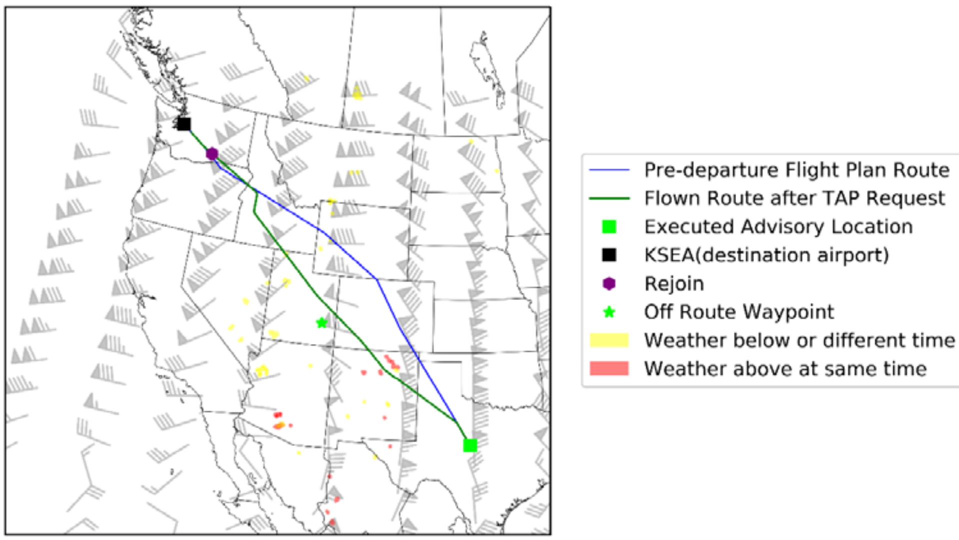

Figure 11. Example lateral path corresponding to a TAP-inspired direct to an off route waypoint followed by rejoining the route at a downstream waypoint.

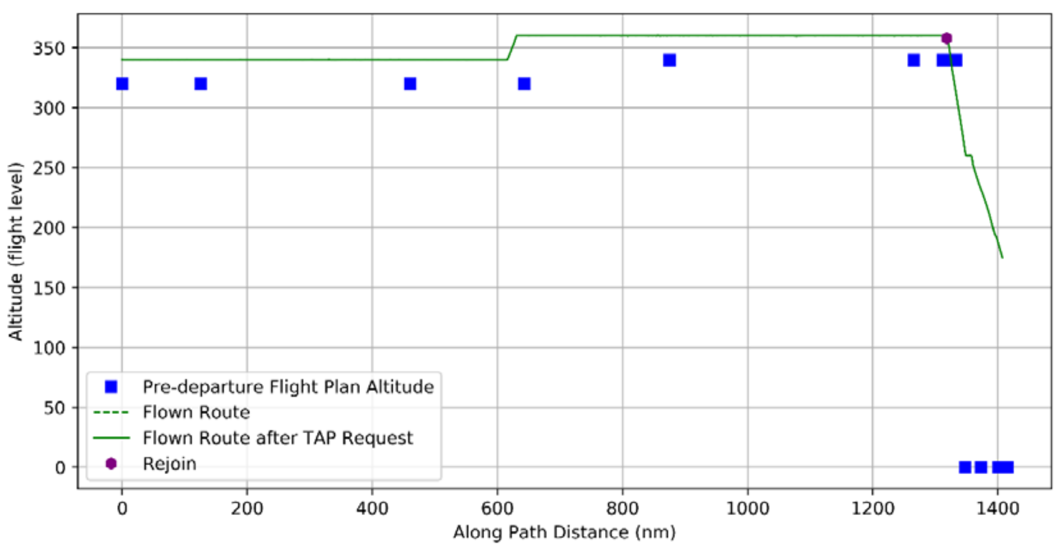

Figure 12. Example altitude profile corresponding to a TAP-inspired direct to an off route waypoint followed by rejoining the route at a downstream waypoint.

Appendix C: Python Benefit Scripts

A set of scripts written in Python were used to analyze TAP-recorded data and Alaska flight plans to generate the quantitative results in Section 5 and flight-by-flight plots in Appendix B. These command line scripts read in a file containing analysis parameters and the location of data within the file system. The scripts then write results and plots corresponding to each flight.

The run_single_flight.py script contains the entry point to the analysis scripts. A configuration file (benefit_assessment_multi.xml) was used as a command line argument. The following Interactive Python (IPython) command statement was used to launch the scripts. Other Python launch commands are also possible but not described.

```
>%run run_single_flight.py benefit_assessment_multi.xml
```

There are data pre-processing steps that need to be performed prior to executing the above command. These steps are summarized in Table 19.

Table 19. Python benefit scripts data pre-processing steps.

Step	Description
1	Identify characteristics of flights (i.e., tail number, date, flight number) that will be analyzed for benefits. Flight characteristics entered into the TAP flight logbook were used during this study.
2	Identify non-overlapping TAP-recorded data corresponding to the flights from Step 1. There may have been overlapping TAP-recorded data if two instances of TAP were running simultaneously on the same flight. All of the following TAP data is required by the Python benefit scripts: • TapDisplayEventLog • AopOwnshipStateDataRecord • AopOwnshipTrajectoryDataRecord • AopRouteDataRecord • TapAdvisoryRefreshDataRecord • TapAdvisoryRouteDataRecord • TapSystemEventDataRecord
3	The Python benefit scripts are only able to analyze one TAP instance per flight. If there were multiple TAP instances per flight then they were combined using the following command: `>%run run_single_flight.py combine_instances.xml` The fields in the combine_instances.xml configuration file are described in Table 20.
4	Create a CSV file that describes each flight. Table 21 describes each of the required columns in this flight CSV file. Also, create a CSV file that lists the location of the merged files created from Step 3 above. Table 22 similarly describes each of the required columns in this CSV file.
5	Set the configuration parameters in benefit_assessment_multi.xml including the location of the CSV file created during Step 4. Table 23 describes the parameters in benefit_assessment_multi.xml.

Table 20. Parameters in combine_instances.xml.

Parameter name	Description
dat_csv_files	Lists the TAP-recorded data to be combined. Does not need to be updated.
instance1_folder, instance2_folder, …, instance*n*_folder	Fully qualified location of folder containing TAP data record .csv files. These files are named *DataRecord.csv and are listed in the dat_csv_files parameter. These files are created when extracted from TAP_OWNSHIP_*.dat files.
aoproute1_remove_lines, aoproute2_remove_lines, …, aoproute*n*_remove_lines	Remove line or lines in AopRouteDataRecord. E.g., [100, 101, 102] removes lines 100, 101, and 102 from AopRouteDataRecord. The Python scripts do not have the capability to detect abeam waypoints. These optional parameters are used to remove lines in AopRouteDataRecord.csv containing abeam waypoints so that route changes can be matched to TAP advisories. These parameters are only required if the Python scripts are unable to detect TAP-inspired route changes. The aoproute1_remove_lines parameter corresponds to AopRouteDataRecord.csv in the instance1_folder and similarly for the aoproute2_remove_lines to aoproute*n*_remove_lines parameters.
flightaware_track	Optional parameter that specifies the location of a FlightAware track file. This file has the following columns: • timestamp – Unix epoch timestamp (e.g., 1532633918) • latitude – Latitude in units of decimal degrees (e.g., 47.4212) • longitude – Longitude in units of decimal degrees (e.g., -122.3106) • groundspeed_kts – not used • altitude_ft – Altitude in units of feet (e.g., 33000) • altitude_status – not used • update_type – not used • altitude_change – not used FlightAware track data can be used to plot lateral path and altitude to the destination airport when TAP is shut down early. However, the plots in Appendix B did not use this data.
output_folder	Location of the folder that will contain the combined files output.
instance1_dsp_event, instance2_dsp_event, …, instance*n*_dsp_event	Fully qualified location of TapDisplayEventLog file corresponding to instance1_folder, instance2_folder, …, instance*n*_folder.

Table 21. Parameters in flights CSV file. Additional columns included after these columns are ignored. Each column must contain data but the data marked "Not used" is not used by the Python scripts.

Parameter column names	Description
Unique_flight_id	Unique identifier that must match the Unique_flight_id column in the instances CSV file described in Table 22.
Alaska_dataset	Not used
Stage	Not used
Flight_number	Not used
Tail_number	Not used
Takeoff_datetime	Not used
Origin_airport	Not used

Parameter column names	Description
Landing_datetime	Not used
Destination_airport	Not used
Flight_outside_CONUS	Not used
Flight_Plan_Path	Fully qualified filename of a flight plan corresponding to a single Alaska flight.
Takeoff_to_Landing_sec	Not used
Origin_airport_zone	Not used
Destination_airport_zone	Not used

Table 22. Parameters in instances CSV file. Additional columns included after these columns are ignored. Each column must contain data but the data marked "Not used" is not used by the Python scripts.

Parameter column names	Description
Instance_tag	The tag from the TAP Engine .dat file is used as a unique identifier. e.g., L_N270AK-CAPTAIN_8A7115062CD8C372_20180120_230513_20180120_230513
Alaska_dataset	Not used
Stage	Not used
Unique_flight_id	Unique identifier that must match the Unique_flight_id column in the flights CSV file described in Table 21.
Missing_required_files_Y_N	Not used
TAPDisplayEventLog	Fully qualified filename of the TAP Display event log. This will be in the output folder created when running the combine_instances.xml file with parameters specified in Table 20.
DataRecord_csv_folder	Fully qualified path to the folder containing CSV files extracted from TAP Engine .dat file. This will be in the output folder created when running the combine_instances.xml file with parameters specified in Table 20.
Seat_(L/R)	Not used
EngineStart_datetime	Not used
DisplayStart_datetime	Not used
Provenance	Not used
Playback_Instance	Not used
Operate_to_end_sec	Not used

Table 23. Parameters in benefit_assessment_multi.xml that may need to be updated. Unlisted parameters do not need to be modified.

Parameter name	Description
tap_flights_filename	Fully qualified filename of file created during Step 4 in Table 19 with fields described in Table 21.
tap_instances_filename	Fully qualified filename of file created during Step 4 in Table 19 with fields described in Table 22.
top_level_folder (file_list_identifier = tap_wind_files)	The top_level_folder parameter appears multiple times in benefit_assessment_multi.xml. This specific parameter is referring to the case where the file_list_identifier is set to tap_wind_files.

Parameter name	Description
	Fully qualified folder to look for EDS-generated wind files to create the wind barbs shown in the plots in Appendix B.
top_level_folder (file_list_identifier = csv_polygon_files)	The top_level_folder parameter appears multiple times in benefit_assessment_multi.xml. This specific parameter is referring to the case where the file_list_identifier is set to csv_polygon_files.
use_flight_plan	If set to “True” then the flight plan is used for $C^{predicted}$, otherwise TAP is used for $C^{predicted}$.
benefits_output_folder	Fully qualified location of output folder. All files, including plots, generated by the Python analysis scripts will be created in this folder. Table 24 lists the files that will be created in the output folder.
benefits_template_filename	Fully qualified location of the benefit_assessment_template.xml configuration file. Generally, this file will be located in the ..\tap_analysis_tools\misc\xml folder.
top_level_folder (file_list_identifier = savings_stats_files)	Set to the value of the benefits_output_folder parameter.
combined_filename	Fully qualified filename for combined CSV results.

Table 24. Output files created by the Python benefit scripts.

Filename	Description
Advisory_flown_alt_[*MatchType*]_[*Unique_flight_id*].png	Altitude profile of flown trajectory and planned altitude (either flight plan or TAP). Examples are shown in Figures 5, 8, and 10.
Advisory_flown_map_[*MatchType*]_[*Unique_flight_id*].png	Lateral path of flown trajectory and planned route (either flight plan or TAP) plotted on a geographic map. Examples are shown in Figures 6, 7, and 9.
advisory_info_[*Unique_flight_id*].csv	Contains information regarding specific advisories. Generally, the TapAdvisoryRefreshDataRecord.csv is a better source for this information.
benefits_log_[*Unique_flight_id*].txt	Low-level information that was used to debug the Python scripts. The most useful information may be in the “Module: analysis.benefits.match” section which shows TAP advisories that were matched to ownship route changes.
events_[*Unique_flight_id*].csv	Lists ownship route and altitude changes that may or may not have been TAP inspired. Ownship state at the time of the change is also listed. This information was also used to debut the Python scripts.
[*Unique_flight_id*].xml	Temporary file created by Python scripts. This file can be used to determine the specific parameters for a given flight. Can be deleted and will be recreated if the Python benefit scripts are re-run.
savings_stats_[*Unique_flight_id*].csv	Quantitative benefit results for each flight. Table 25 contains the column descriptions for this file. [All files of this type are concatenated to create the combined results specified by the combined_filename parameter in Table 23.]

Table 25. Parameters in savings_stats CSV file.

Parameter column names	Description
FlightIdentifier	Unique identifier corresponding to the Unique_flight_id columns in the flights and instances CSV files described in Tables 21 and 22 respectively.
AutoShutDownProximity	Equals “1” if TAP automatically shut down due to proximity to the destination airport or altitude. Equals “0” otherwise. This parameter was used to identify flights that did not reach the auto shutdown location but was not used as part of quantifying the benefits in this report.
MatchType	Either “ATC_APPROVED,” “SELECTED,” “EXACT_MATCH,” or “AMEND_MATCH.” These corresponding to Table 4, Step 3 Classifications 1 to 4 respectively. There will be four rows corresponding to each flight since the calculations are performed separately for each match type.
LateralExecutedCount	Number of TAP-inspired lateral changes that the Python scripts identify.
VerticalExecutedCount	Number of TAP-inspired altitude changes that the Python scripts identify.
ComboExecutedCount	Number of TAP-inspired combination lateral-altitude changes that the Python scripts identify.
FuelSavingsLbs	Fuel savings component of $C^{flown} - C^{predicted}$ in units of lbs corresponding to TAP flights.
TimeSavingsSec	Time savings component of $C^{flown} - C^{predicted}$ in units of sec corresponding to TAP flights.
LookAheadLocSec	Time component of $C^{predicted}$ in units of sec corresponding to TAP flights.
LookAheadLocLbs	Fuel component of $C^{predicted}$ in units of lbs corresponding to TAP flights.
PredictionType	Equals “Flight_Plan” if flight plan was used for $C^{predicted}$ as specified by the use_flight_plan parameter defined in Table 23. Equals “TAP” if TAP was used for $C^{predicted}$.
OffRouteAtRequestNmi	Distance from TSP to predicted route in units of nautical miles using the method described in Table 5.
OffRouteRejoinNmi	Distance from TFP to predicted route in units of nautical miles using the method described in Table 5.

The Python script ..\tap_analysis_tools\non_tap_data\flight_plan\fp_import.py imports a single flight plan from a text file. The file contains only one flight plan in the format used by Alaska Airlines.

Appendix D: TAP Benefit Opportunity

TAP continuously computed and recorded advisories that were predicted to save fuel and time during the operational evaluation. Table 1 in Section 2.1 described a TAP data record (TapAdvisoryRefreshDataRecord) that included TAP-predicted fuel and time savings corresponding to advisories generated by TAP. This appendix presents aggregate fuel and time benefit characteristics derived from this data record. Two sets of results are presented: (1) advisories computed but not displayed to pilots during Stage 1 and (2) advisories displayed to pilots during Stages 2 and 3.

D.1. Opportunities during Stage 1

Recall from Section 3 that during the baseline flights (Stage 1) TAP computed advisories onboard Alaska revenue flights but did not display them to pilots. The fuel and time outcomes of these advisories were used to approximate the opportunity for TAP benefits. The Stage 1 opportunity results are based on 158 Stage 1 flights from January 2018 to October 2018 where TAP was able to successfully calculate advisories. The optimization objective was set to "trip cost" which uses the flight plan cost index for each flight to generate advisories that would save operating costs according to this time-fuel cost ratio.

The median and box-plot of these TAP-computed savings per advisory are shown in Figures 13 to 20. Figure 13 shows curves representing the median TAP-predicted fuel benefit of all TAP advisories generated by advisory type (lateral, altitude, and combination lateral-altitude). The x-axis is the distance to the destination airport when the advisory was computed. The y-axis is the fuel savings that would have been shown to the pilots if the TAP Display had been launched.

Also shown is the average benefit per flight from the achieved benefits in Table 9, Section 5. Fuel benefits were converted from 31.2 gallons/flight to 212.4 lbs/flight since fuel savings are shown in units of lbs on the TAP Display. Achieved benefits are higher than the median lines for reasons including (1) pilots may only request TAP advisories that have higher than median benefits, (2) the achieved benefits are an average of requests both closer to and farther from the destination airport, and (3) there may be multiple TAP-inspired requests per flight. Box plots of fuel benefit opportunities shown in Figures 14 to 16 are used to illustrate (1).

Figures 17 to 20 show the similar time savings opportunity plots that correspond to the fuel savings opportunity plots shown in Figures 13 to 16. Note that in all of these plots the sample size decreases at farther distances from the destination airport. This smaller sample size, which is shown in Table 26, causes the median curves to be influenced by a few flights beyond about 1000 nmi from the destination airport.

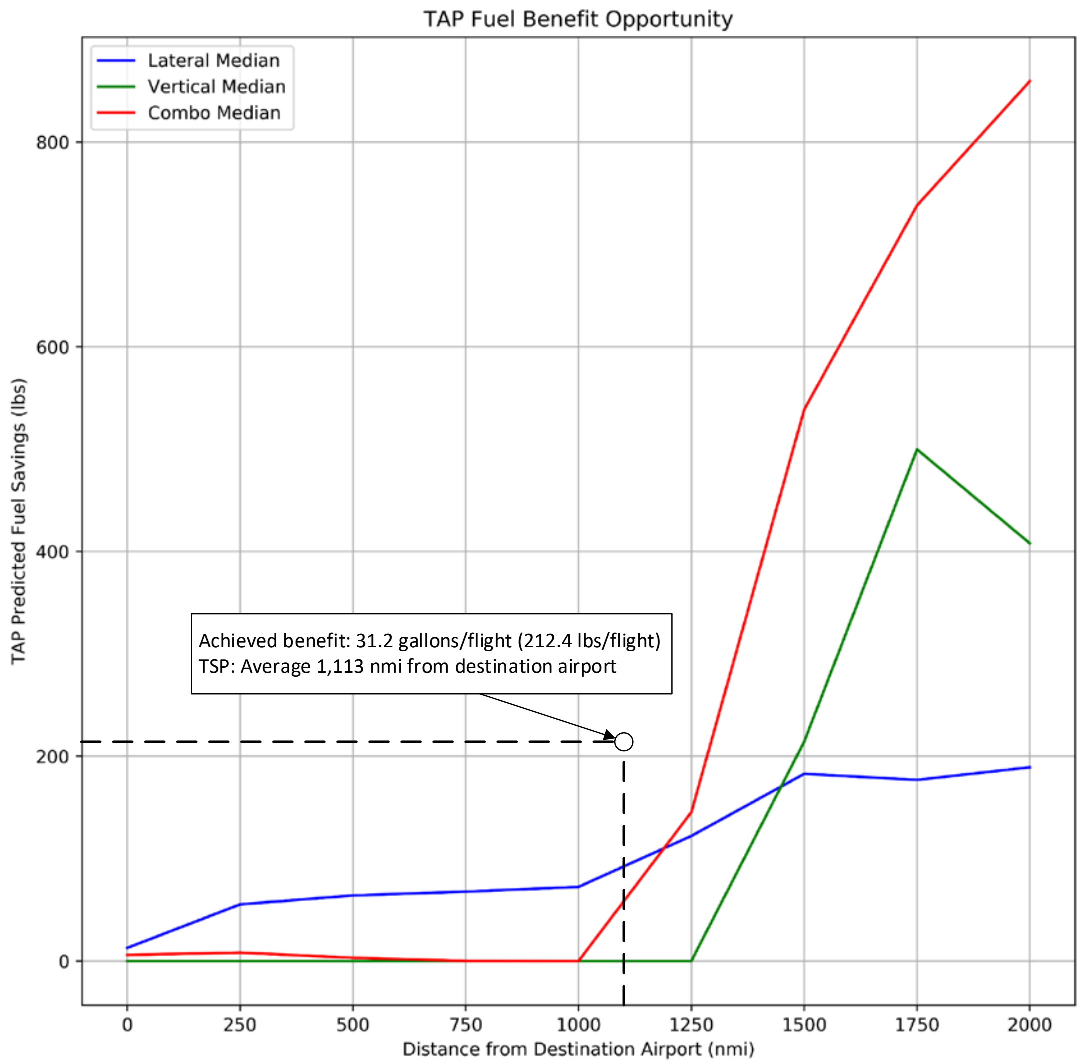

Figure 13. TAP-predicted opportunity to save fuel per advisory. Achieved benefit per flight from Table 9 also shown.

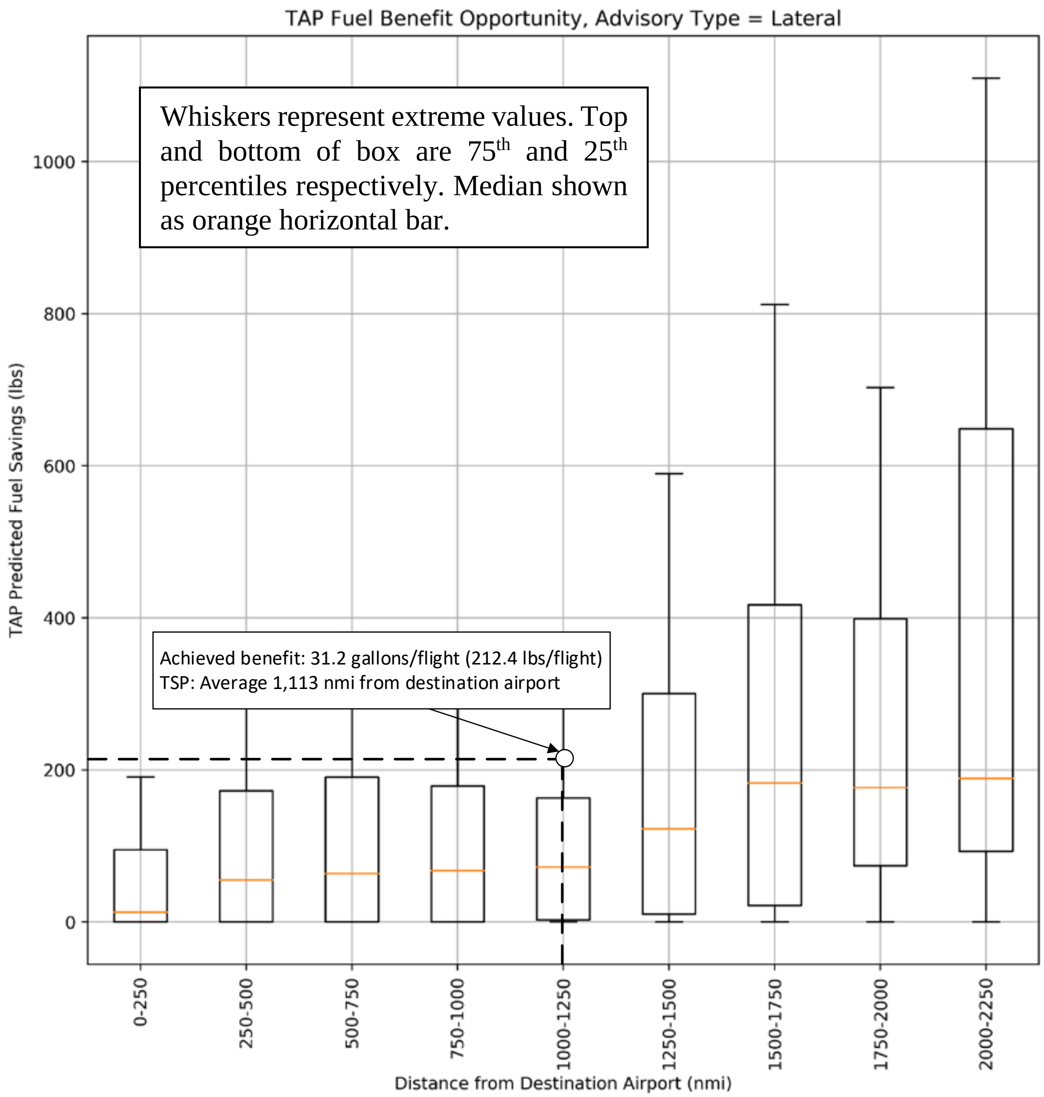

Figure 14. Estimated fuel savings opportunity per advisory based on TAP-computed lateral advisories.

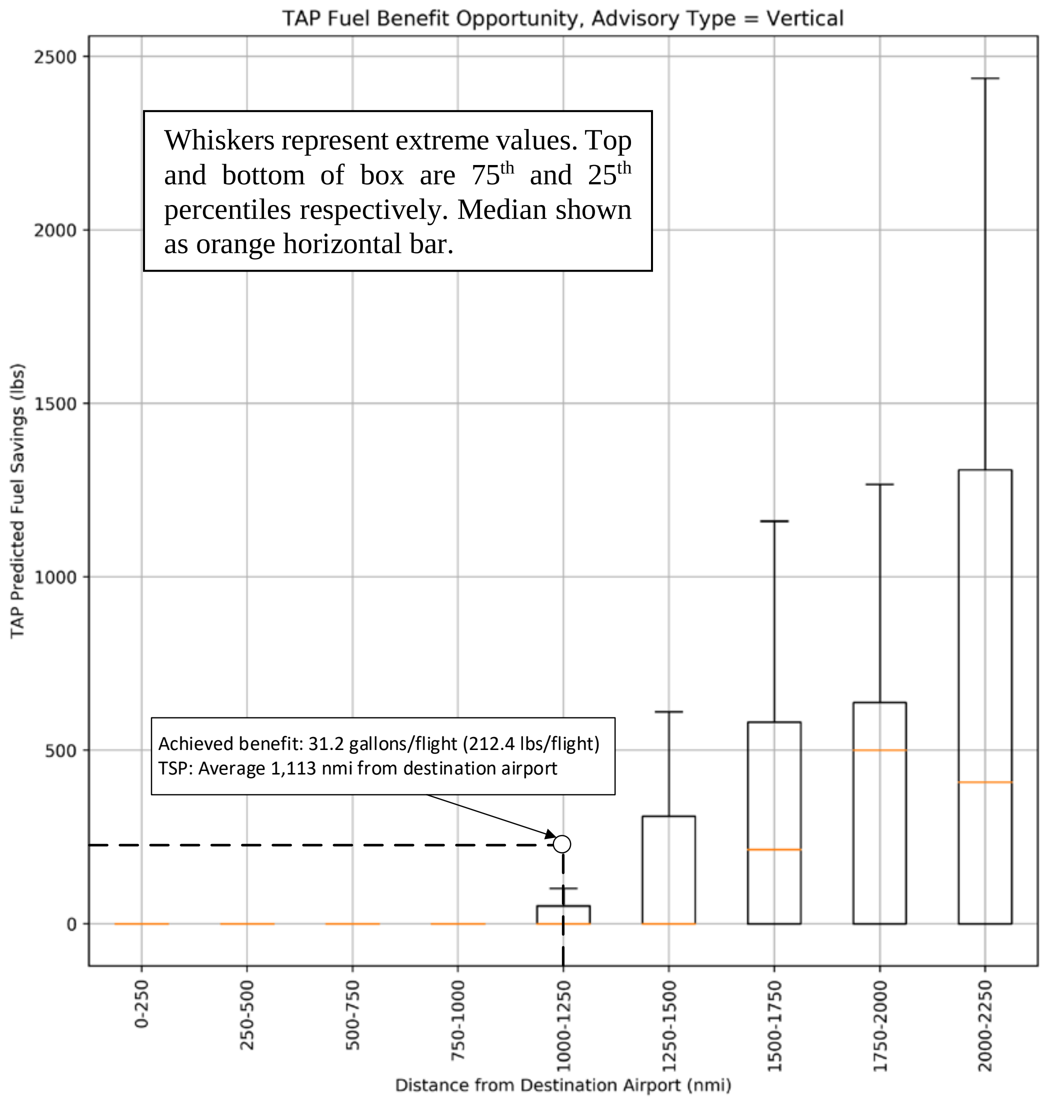

Figure 15. Estimated fuel savings opportunity per advisory based on TAP-computed altitude advisories.

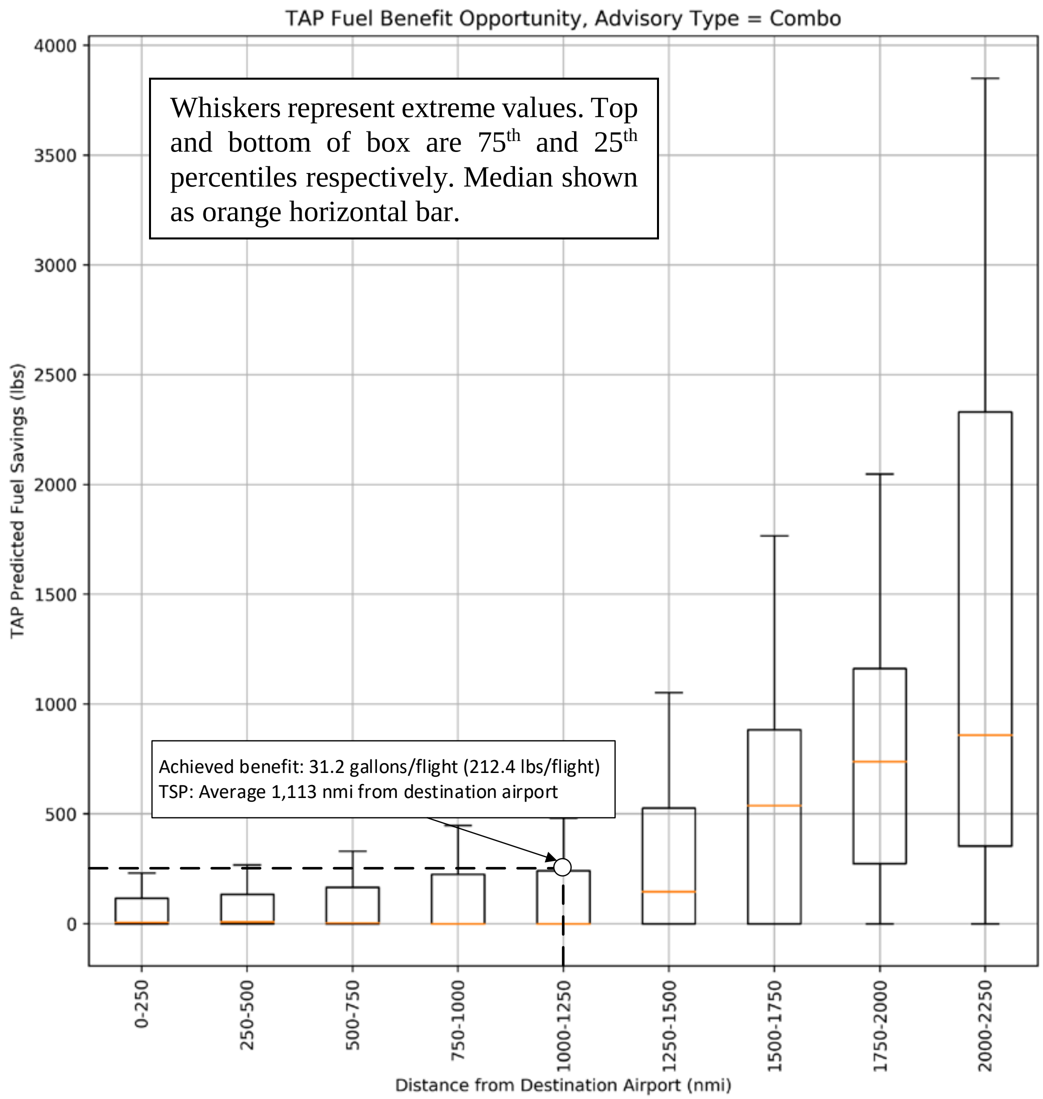

Figure 16. Estimated fuel savings opportunity per advisory based on TAP-computed combination lateral-altitude advisories.

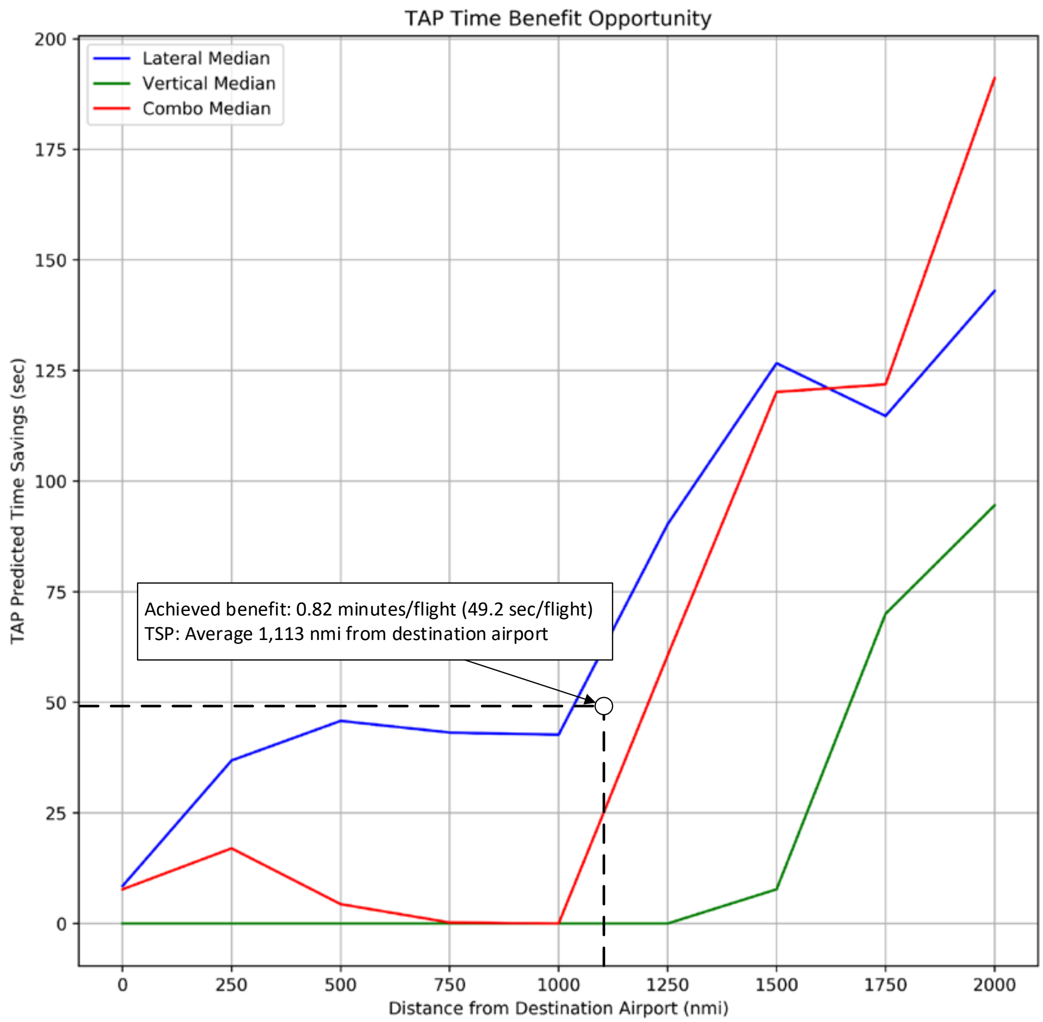

Figure 17. TAP-predicted opportunity to save time per advisory. Achieved benefit per flight from Table 9 also shown.

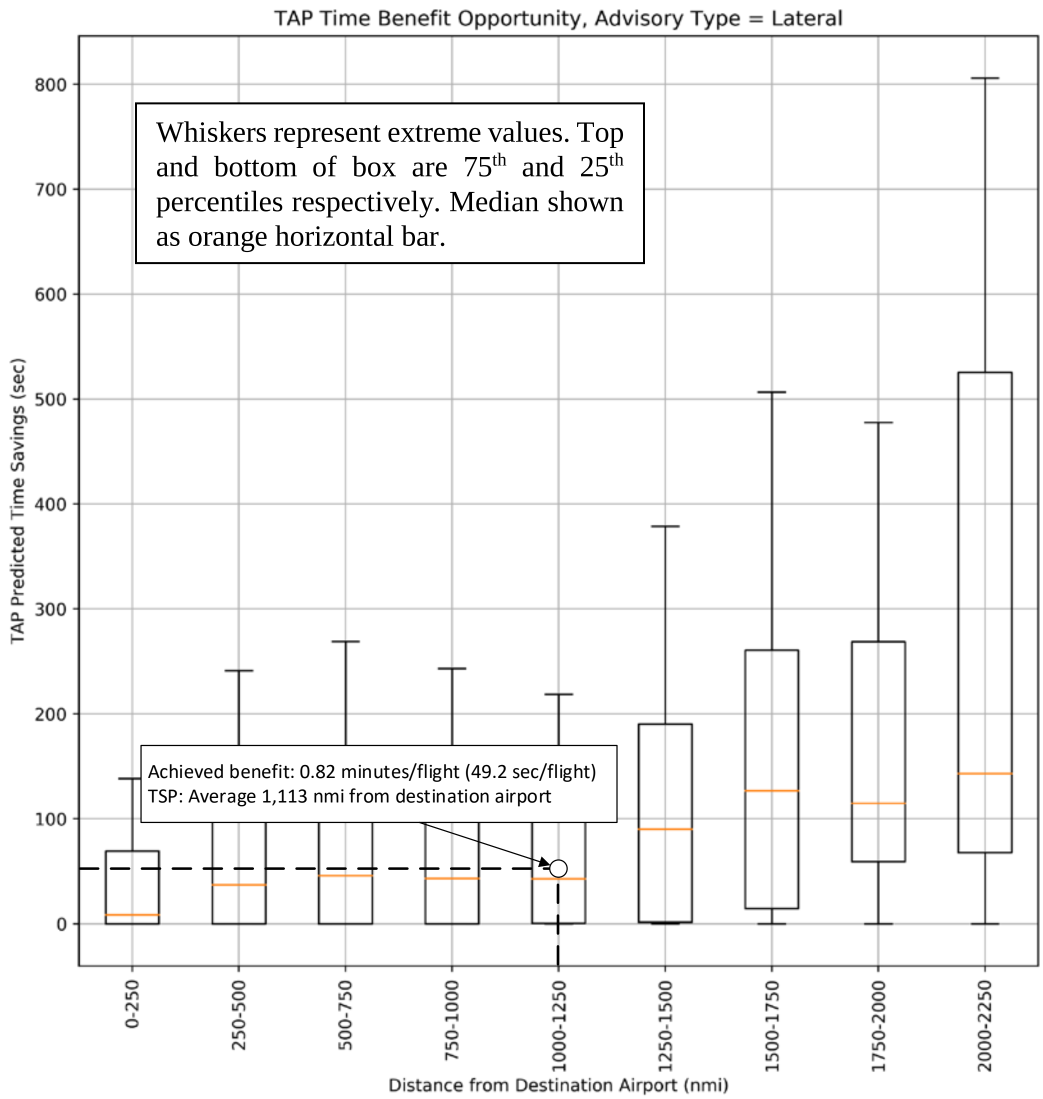

Figure 18. Estimated time savings opportunity per advisory based on TAP-computed lateral advisories.

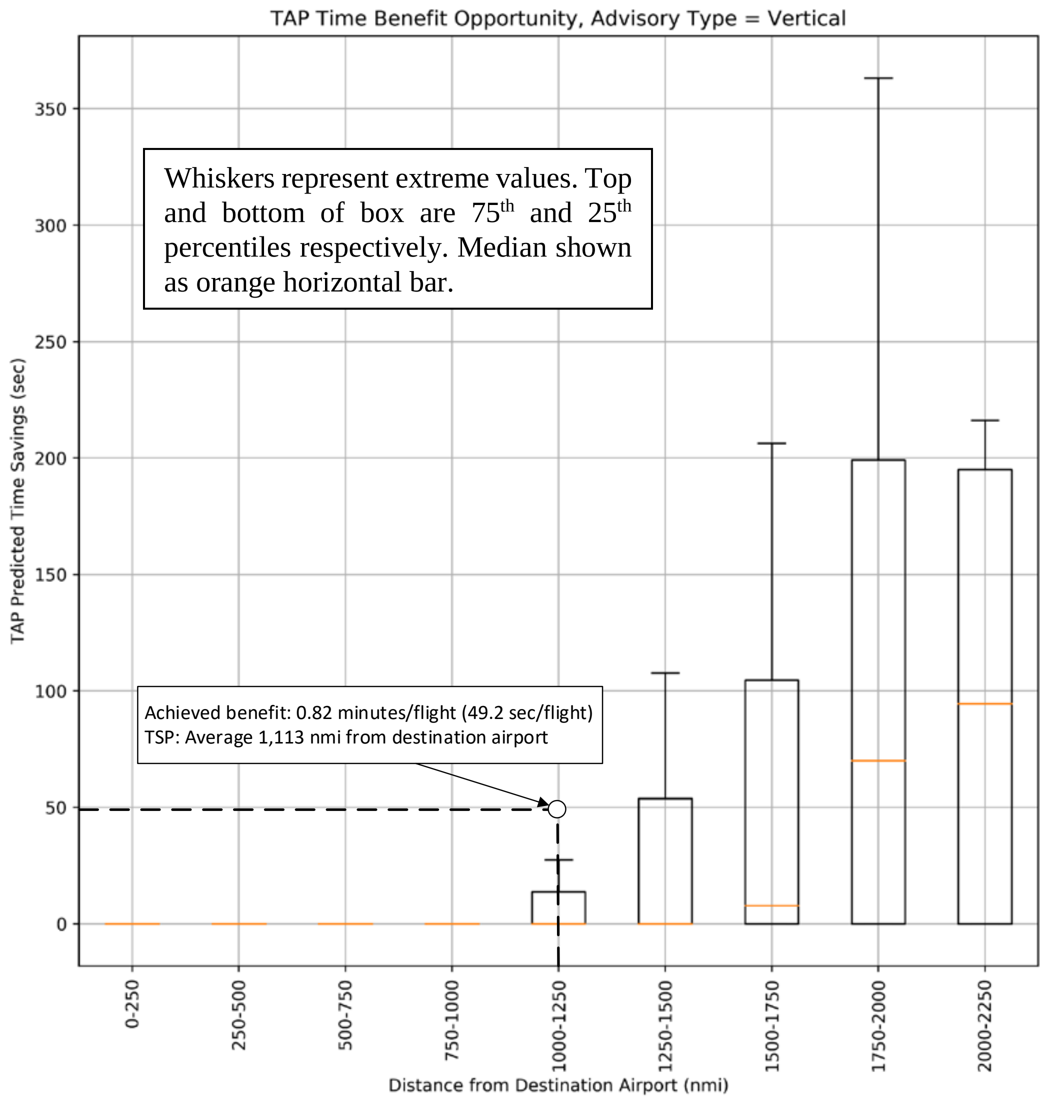

Figure 19. Estimated time savings opportunity per advisory based on TAP-computed altitude advisories.

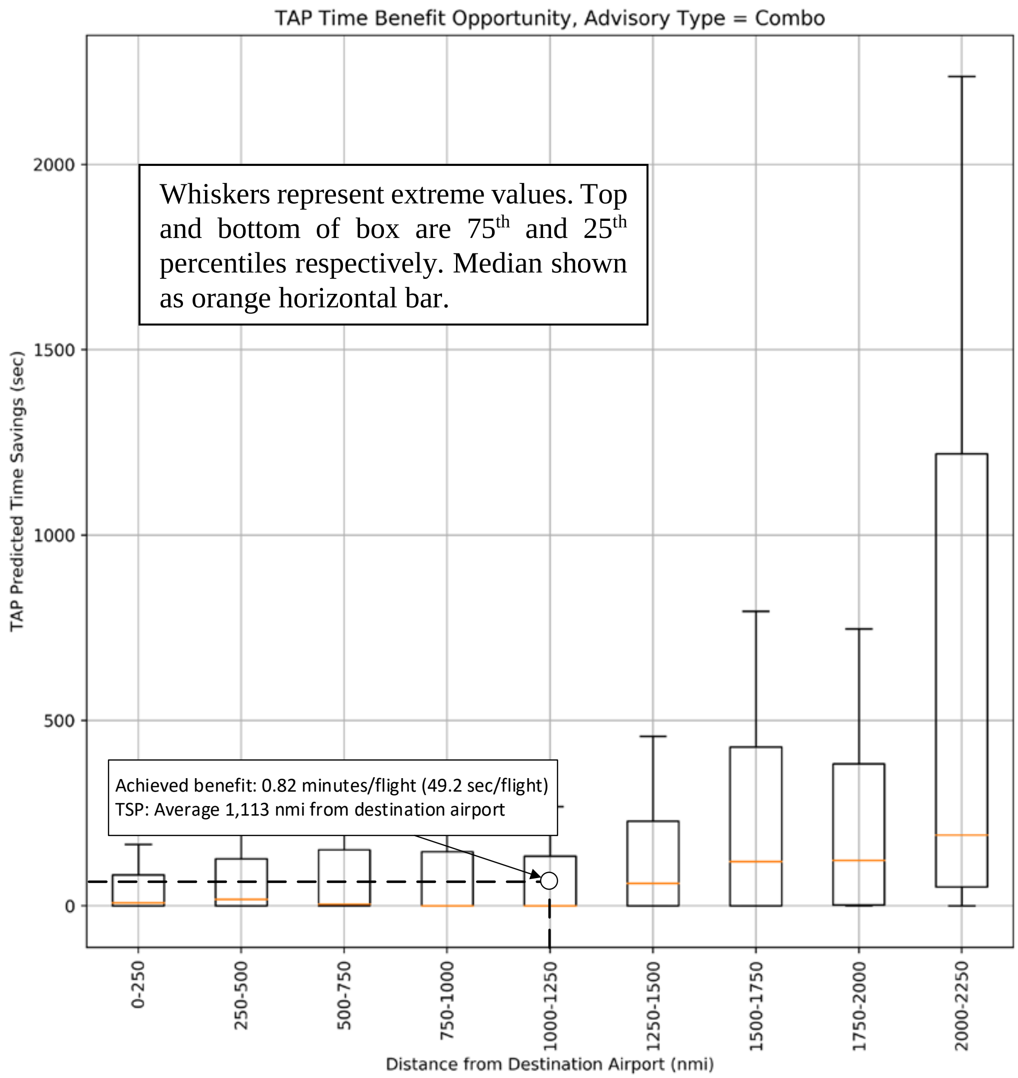

Figure 20. Estimated time savings opportunity per advisory based on TAP-computed combination lateral-altitude advisories.

Table 26. Sample size of TAP advisory outcomes used in Figures 13 to 20. The left two columns contain the lower and upper bound of the distance range from the destination airport when TAP generated the advisory.

Distance Lower Bound	Distance Upper Bound	Number of Advisories
0 nmi	250 nmi	31,017
250 nmi	500 nmi	31,692
500 nmi	750 nmi	24,918
750 nmi	1,000 nmi	15,981
1,000 nmi	1,250 nmi	9,934
1,250 nmi	1,500 nmi	6,590
1,500 nmi	1,750 nmi	4,790
1,750 nmi	2,000 nmi	3,989
2,000 nmi	> 2,000 nmi	593

D.2. Opportunities during Stages 2 and 3

During the TAP flights (Stages 2 and 3) beneficial TAP advisories were displayed to pilots. Certain TAP advisories were requested to ATC and approved. However, there were beneficial TAP advisories that pilots did not use to make a request. For this reason fuel and time predicted savings on flights without a TAP-inspired request were compared to predicted savings on flights with a TAP-inspired request. All savings correspond to TAP advisory displayed savings regardless of whether the TAP advisory was requested or not. For the purpose of this analysis TAP advisories were selected on the basis of their predicted fuel and time savings and not whether these savings were achieved.

The maximum TAP-predicted fuel savings for each of lateral advisories, vertical advisories, combo advisories, and all types of advisories was extracted from each Stage 2 and 3 flight and used to generate the box plot shown in Figure 21 (i.e., each input data point represented a single flight). For flights with approved requests, statistics are based on displayed TAP advisories and not those advisories that were requested. Data source for the box plot is the maximum TAP advisory predicted fuel savings for each flight for each of lateral advisories, vertical advisories, combo advisories, and all types of advisories. Median savings shown as orange horizontal bar. Mean savings shown as a dashed green horizontal bar. The figure shows that, while flights with an approved TAP-inspired request had higher TAP-predicted savings, the flights without an approved TAP-inspired request had similar predicted savings. Figures 22 and 23 show similar trends for time and cost savings respectively.

The median fuel, time, and cost outcomes during each flight was used to generate Figures 24, 25, and 26. Using the median was intended to remove large savings that may not occur consistently throughout the flight. The figures show that Stages 2 and 3 flights without an approved TAP-inspired request still had potential for benefits on the same order of magnitude as the flights with an approved TAP-inspired request. However, vertical and combo advisories with significant benefits seemed to occur less frequently than lateral advisories. This may be due to vertical requests near the beginning of the flight removing the potential for benefits later in the flight and therefore reducing the median savings potential.

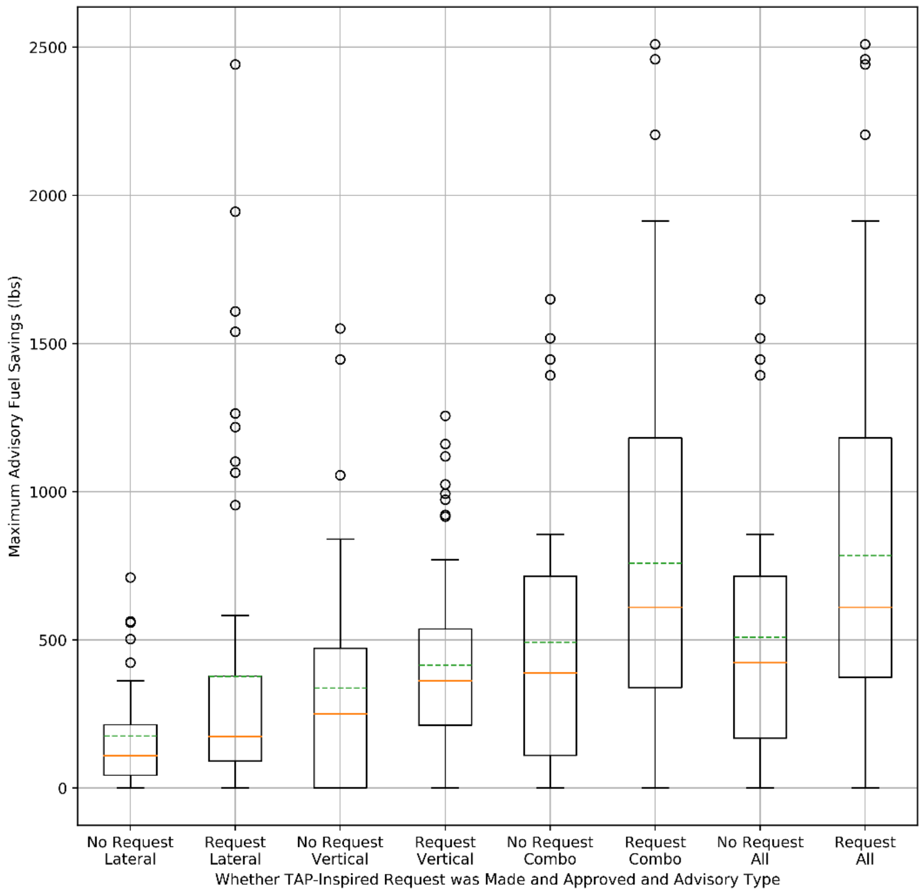

Figure 21. Fuel savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

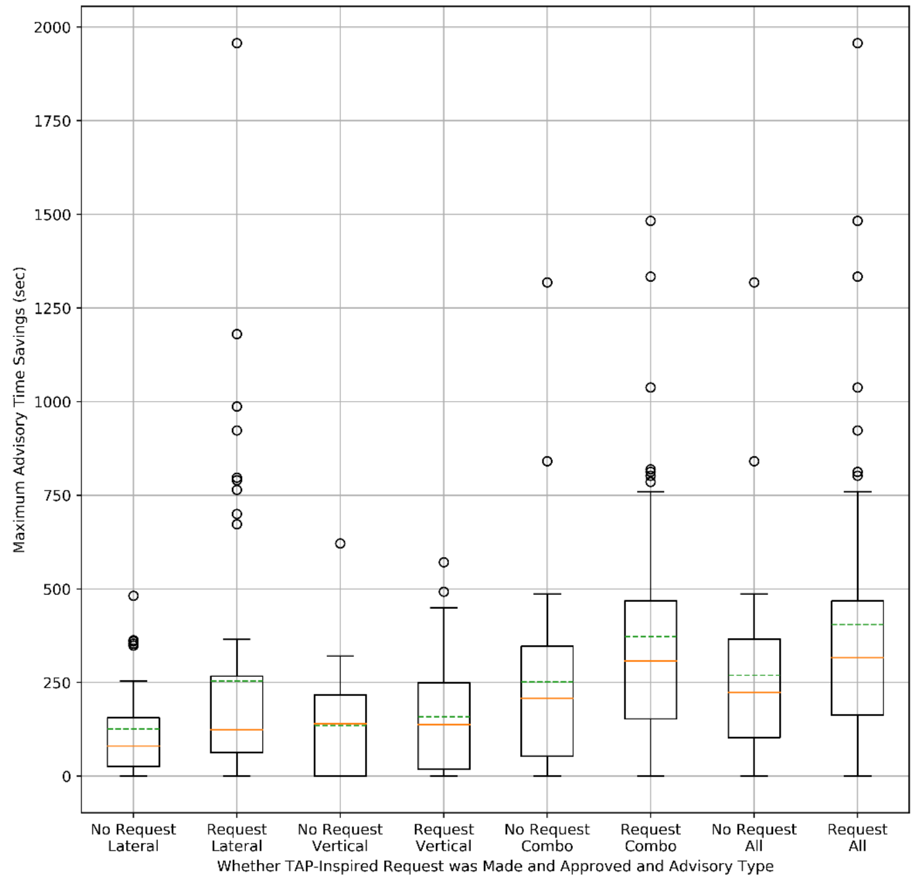

Figure 22. Time savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

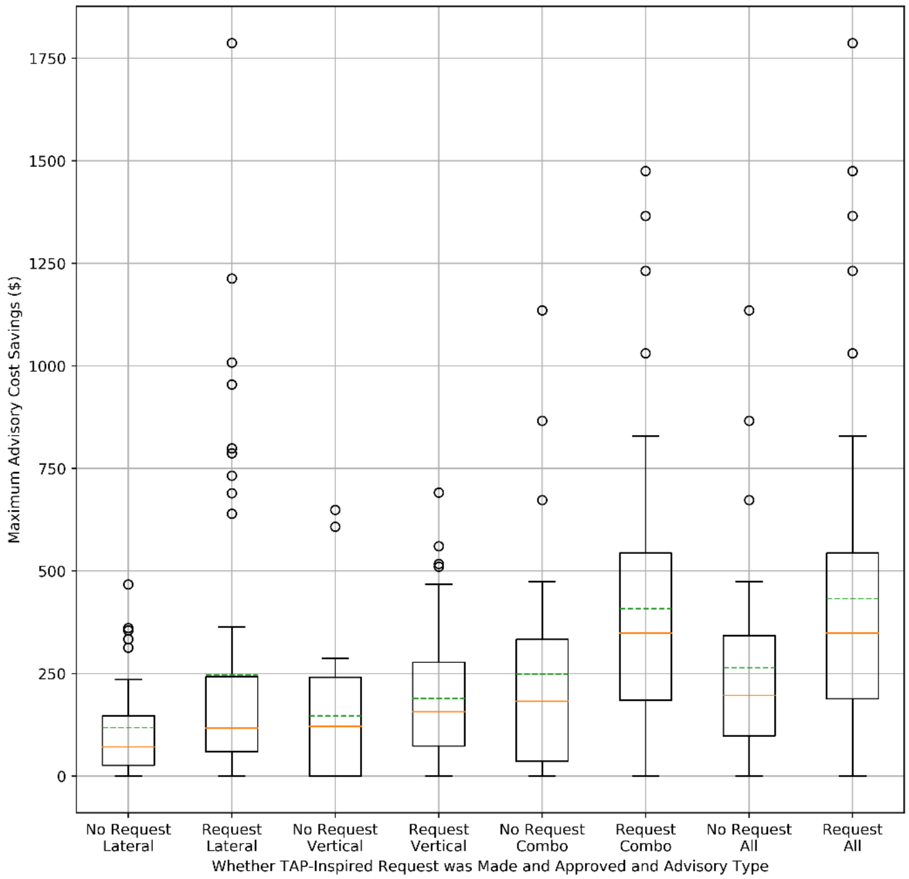

Figure 23. Cost savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

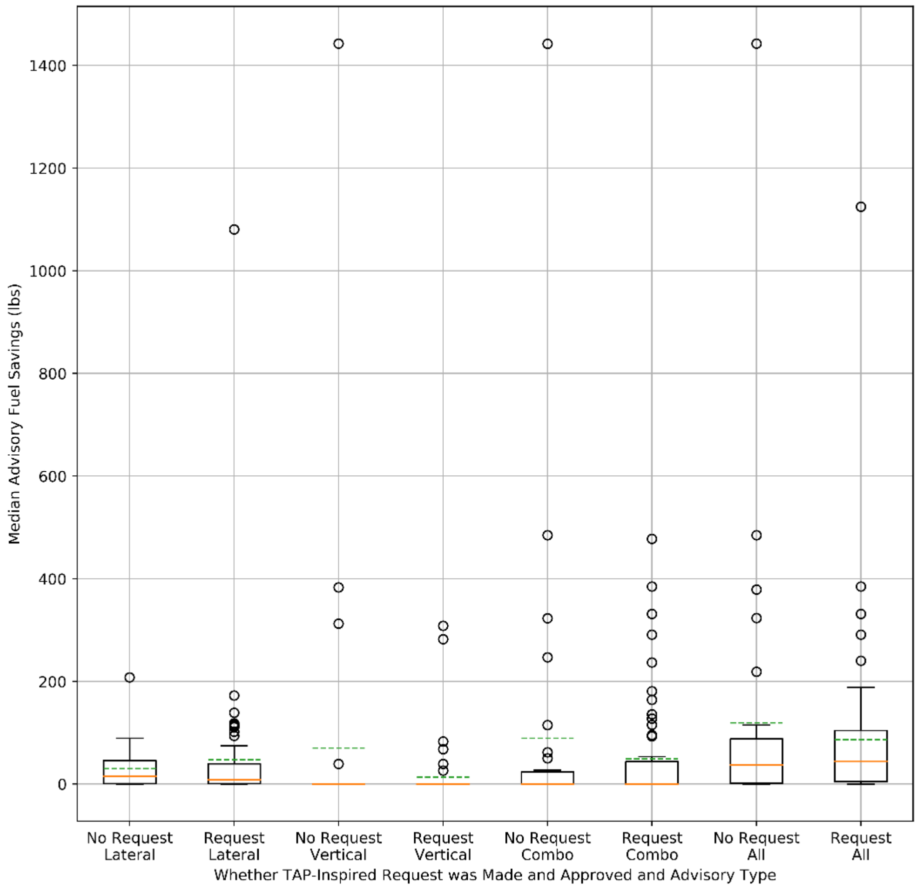

Figure 24. Fuel savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

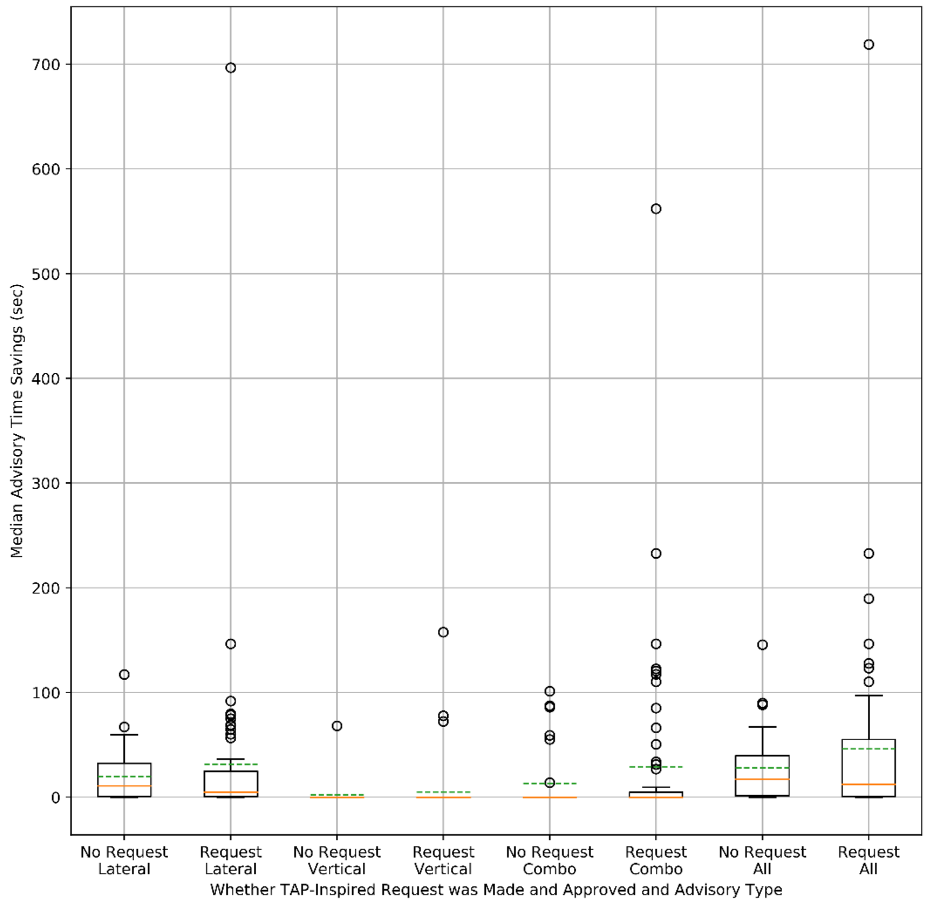

Figure 25. Time savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

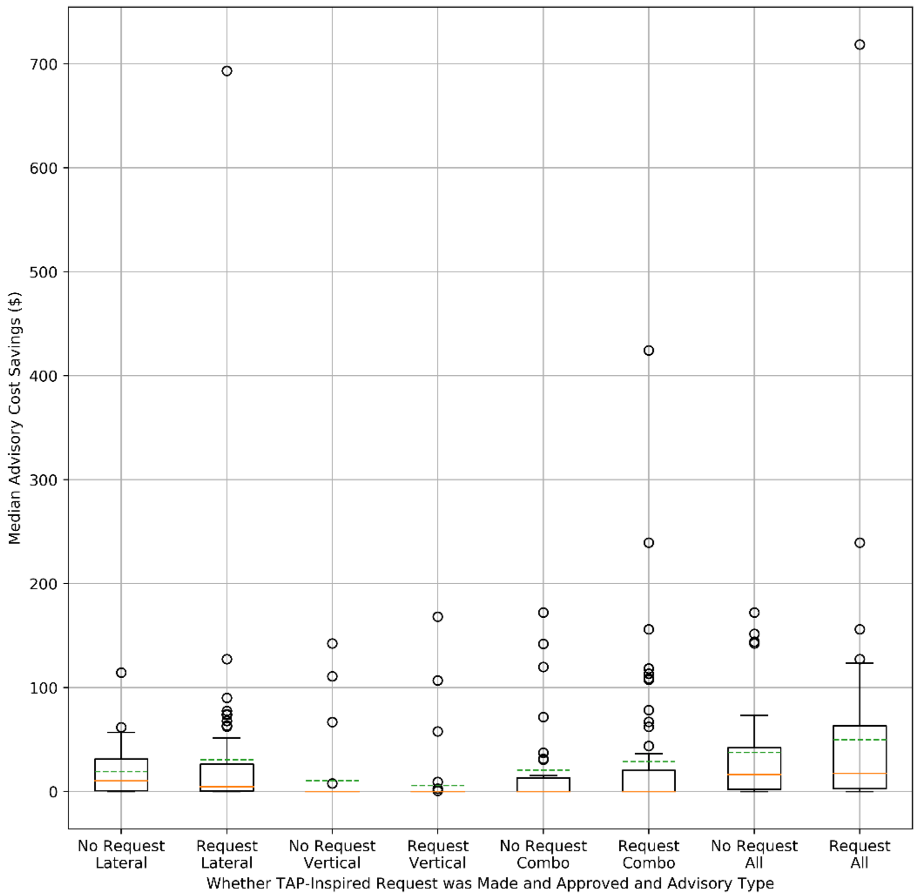

Figure 26. Cost savings opportunity during Stages 2 and 3 flights both with and without approved TAP-inspired requests.

Appendix E: TAP and Pre-departure Flight Plan Prediction Accuracy from TOC to TOD

Whether TAP can generate advisories that accurately predict fuel and time savings depends on the ability of TAP to accurately predict fuel burned and flight time along alternative trajectories. To quantify accuracy, the four comparisons in Table 27 were quantified. The interpolation methods described in Table 5, Section 3.4 were applied to this accuracy study to obtain flown and TAP predicted fuel and time at the flight plan predicted TOC and TOD. The last TAP prediction prior to TOC was used for this analysis.

Table 27. TAP and Flight Plan Prediction Comparisons.

Comparison	Metric		Prediction		Description
	Fuel burned	Flight time	Flight Plan	TAP	
1	✓		✓		Flown ownship state Δfuel minus flight plan predicted Δfuel from flight plan predicted TOC to flight plan predicted TOD.
2	✓			✓	Flown ownship state Δfuel minus TAP predicted Δfuel from flight plan predicted TOC to flight plan predicted TOD.
3		✓	✓		Flown ownship state Δtime minus flight plan predicted Δtime from flight plan predicted TOC to flight plan predicted TOD.
4		✓		✓	Flown ownship state Δtime minus TAP predicted Δtime from flight plan predicted TOC to flight plan predicted TOD.

A total of 60 Stage 1 flights from October 2017 to October 2018 were analyzed. The two conditions to be included in the analysis set were (1) a flight plan was received for the flight and (2) flown ownship state was within 5 nmi laterally of both the flight plan predicted TOC and TOD.

Figure 27 shows fuel accuracy corresponding to comparisons 1 and 2. Positive y-axis values indicate that more fuel was burned than was predicted (either flight plan or TAP prediction). Each dot represents one of the 60 flights analyzed (120 dots total). On average the fuel burn prediction accuracy relative to flown was similar for the flight plan predictions (mean = 233 lbs, std dev = 413 lbs) and TAP predictions (mean = 193 lbs, std dev = 436 lbs). There does not seem to be a trend indicating that either the flight plan or TAP generate better predictions corresponding to longer flights (i.e., larger values along x-axis).

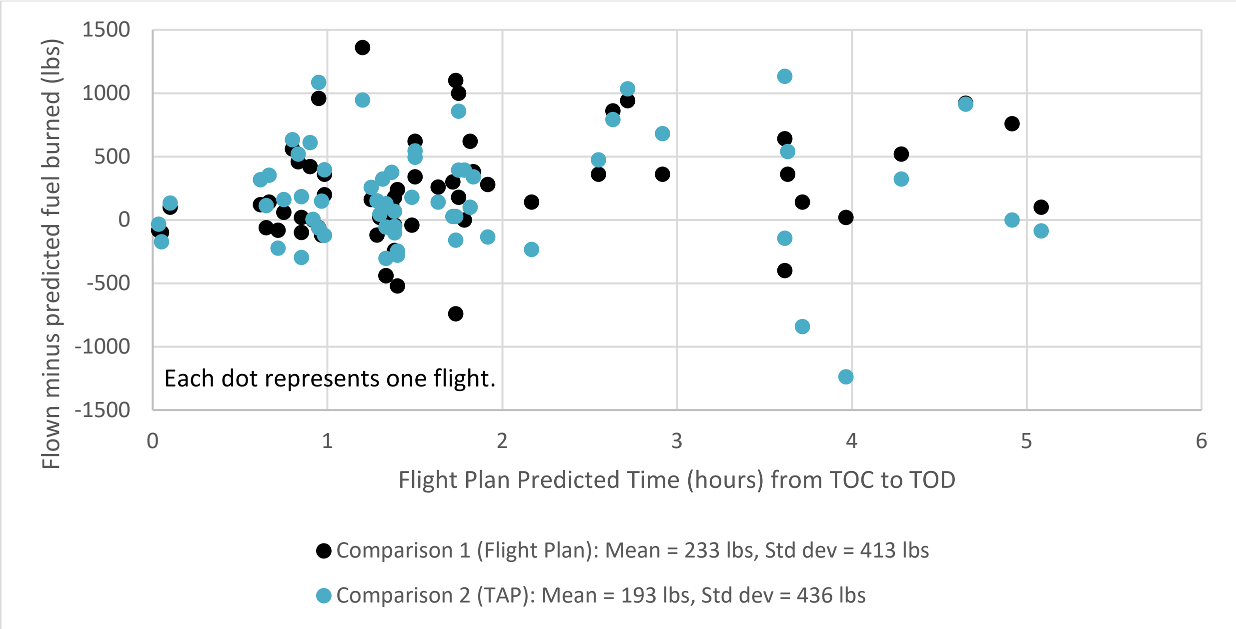

Figure 27. Flown minus predicted total fuel burned from TOC to TOD.

Figure 28 shows that predicted flight time relative to flown was longer for the flight plan predictions (mean = 1.0 min, std dev = 3.6 min) as compared to the TAP predictions (mean = -0.9 min, std dev = 6.3 min). This difference is likely caused by step climbs which are predicted by flight plans but not TAP. The lower comparison 3 (flight plan) standard deviation of 3.6 minutes as compared to the comparison 4 (TAP) standard deviation of 6.3 minutes indicated that the flight plan had better elapsed time predictions from TOC to TOD than TAP, also likely due to the step climbs.

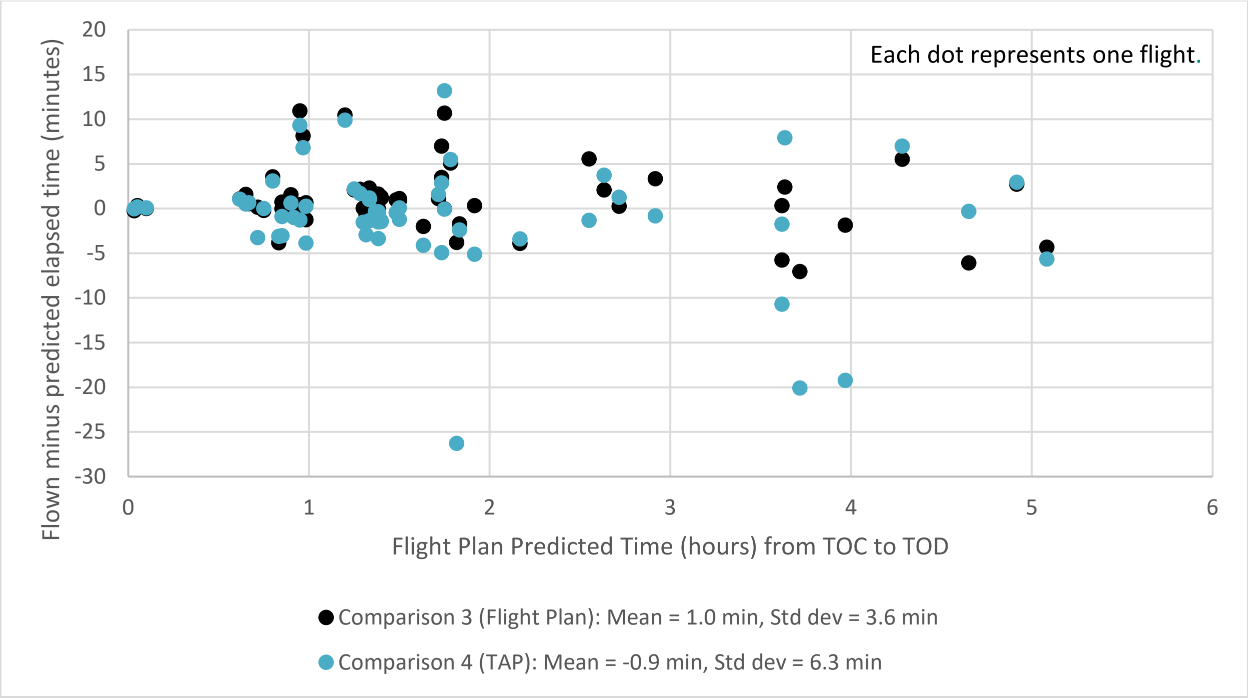

Figure 28. Flown minus predicted flight time from TOC to TOD.

Appendix F: Annualized Benefits of TAP Estimated for other US Airlines

This appendix describes calculating annualized benefits for the top 10 US carriers based on the number of annual Continental US operations and achieved fuel and time benefits from the Alaska Airlines TASAR operational evaluation. Benefits were calculated for: Alaska Airlines, Allegiant Air, American Airlines, Delta Airlines, Frontier Airlines, JetBlue Airways, Southwest Airlines, Spirit Airlines, Sun Country, and United Airlines.

Operational evaluation achieved time benefits reported in Table 10, Section 5.2 are unadjusted and assumed to apply to each of the top 10 US carriers. One exception is time and fuel savings corresponding to flights less than 2 hours which had negative achieved benefits. It was assumed that either (1) TAP would not be used in the future if negative benefits persisted or (2) the reasons for the negative benefits would be resolved. Time and fuel savings for flights less than 2 hours were assumed to be zero for the analysis in this appendix.

Operational evaluation achieved fuel benefits reported in Table 10, Section 5.2 are scaled based on the aircraft fuel burn rate relative to the Alaska Airlines 737-900ER aircraft fuel burn rate since fuel savings were all obtained from the 737-900ER. Table 28 provides background on the calculation method and data sources used throughout this appendix.

Table 28. Benefit calculations method and data.

Item	Description/Note
Results order	Results are ordered alphabetically by airline name. Calculations are shown for the top 10 US carriers based on 2018 annual Continental US operations.
Fuel cost	Fuel costs are calculated separately for each airline. All aircraft within the airline are assumed to have the same fuel cost for the purpose of the benefit calculations. The BTS Form 41, Schedule P5.2[6] was the data source used for this calculation (January 2018 to September 2018 reporting period). Average fuel cost is obtained by dividing the total cost spent on fuel by the total fuel issued.
Aircraft type	Aircraft are grouped according to BTS aircraft type classifications that were present in the BTS Form 41, Schedule P5.2 database as of September 2018. Regional jets and older aircraft that are no longer being produced were excluded from the analysis. Benefits by aircraft type are not presented in any specific order.
Hourly direct operating cost (DOC) excluding fuel	The DOC calculation method described in Section 2.5 is applied separately for each aircraft type and airline (i.e., different DOCs are used for the same aircraft type across different airlines). BTS Form 41, Schedule P5.2 from the January 2018 to September 2018 reporting period is the data source for the DOC calculation.
Average fuel burn rate	Calculated from BTS Form 41, Schedule P5.2 as the total air fuel issued divided by the total airborne hours from wheels-off to wheels-on. Fuel is also issued for taxi, which is not included in the airborne hours, which biases the average fuel burn rate to be high.
Ratio to Alaska 737-900ER average fuel burn rate	Fuel cost savings calculated in Section 5.2 were based on 737-900ER fuel burn rates. The average fuel burn rate described in the previous row was multiplied by the cost savings to adjust for other aircraft types that have higher or lower fuel burn rates than the 737-900ER.
Number of flights	The estimated annual number of flights by airline, aircraft type, and flight duration are calculated from the BTS Air Carrier Statistics T-100 Domestic Segment database[9] using data from the January 2018 to December 2018 reporting period. Each row contains the number of domestic departures and total air time between two US cities in a month for a specific airline and aircraft type. Flights that start or end outside the Continental US are excluded from the totals.
Number of aircraft	The number of unique tail numbers for each aircraft type by airline is obtained from the BTS Airline On-Time Performance Data[10].

Three sections are presented for each airline: (1) operating costs calculated from the Bureau of Transportation Statistics (BTS) data, (2) summary plots of cost saving benefits, and (3) tables representing benefit calculations corresponding to each aircraft type. A part of the Department of Transportation, BTS is considered the preeminent source of statistics on commercial aviation.

F.1. Alaska Airlines (AS)

This section estimates the annualized benefit of TAP to Alaska Airlines. Benefits are categorized by aircraft type. Tables and figures that summarize the calculations are described for Alaska Airlines. These same tables and figures will be included for the other nine airlines but not described since they are similar.

F.1.A. Alaska Airlines operating costs calculated from BTS data

Recall that fuel costs are assumed to be the same across aircraft types within an airline. That fuel cost is $2.18 per gallon for Alaska Airlines.

Table 29 lists the six aircraft types included in the annualized benefit calculations for Alaska Airlines. The hourly direct operating cost excluding fuel and average fuel burn rate is included in the table for each of the six aircraft types. The three aircraft used during the operational evaluation were the Alaska Airlines Boeing 737-900ER aircraft listed in the second row from the bottom with an average fuel burn rate of 912 gallons/hour. The average fuel burn rate for all aircraft types, including aircraft types from other airlines, is divided by 912 gallons/hour to obtain the ratio shown in the right column of Table 29. This ratio is multiplied by the achieved fuel savings to adjust for different fuel burn rates by aircraft type.

Table 29. Alaska Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_737-700/700LR/Max_7 (612)	$3,242/hour	839 gallons/hour	0.92
Boeing_737-800 (614)	$2,468/hour	886 gallons/hour	0.97
Airbus_Industrie_A321-200n (721)	$4,127/hour	1,086 gallons/hour	1.19
Boeing_737-900 (634)	$3,376/hour	954 gallons/hour	1.05
Boeing_737-900ER (888)	$1,768/hour	912 gallons/hour	1.00
Airbus_Industrie_A319 (698)	$3,629/hour	1,262 gallons/hour	1.38

F.1.B. Alaska Airlines summary plots

Figure 29 summarized the annual fuel savings categorized by aircraft type and flight duration. For each of the six aircraft types the annual fuel savings are shown separately for flights less than 2 hours, flights between 2 to 4 hours, and flights greater than 4 hours. Figure 30 similarly shows the annual time savings categorized by aircraft type and flight duration. Both Figure 29 and Figure 30 are aggregated across all aircraft of a specified type within the Alaska Airlines fleet.

Figure 31 is the annualized cost savings of TAP per aircraft type. The cost savings in Figure 31 is obtained by multiplying fuel savings in Figure 29 by $2.18 per gallon and the time savings in Figure 30 by the hourly direct operating cost excluding fuel from Table 29. Dividing Figure 31 by the number of aircraft of a specified type within Alaska Airlines' fleet produces the per aircraft annual cost savings shown in Figure 32.

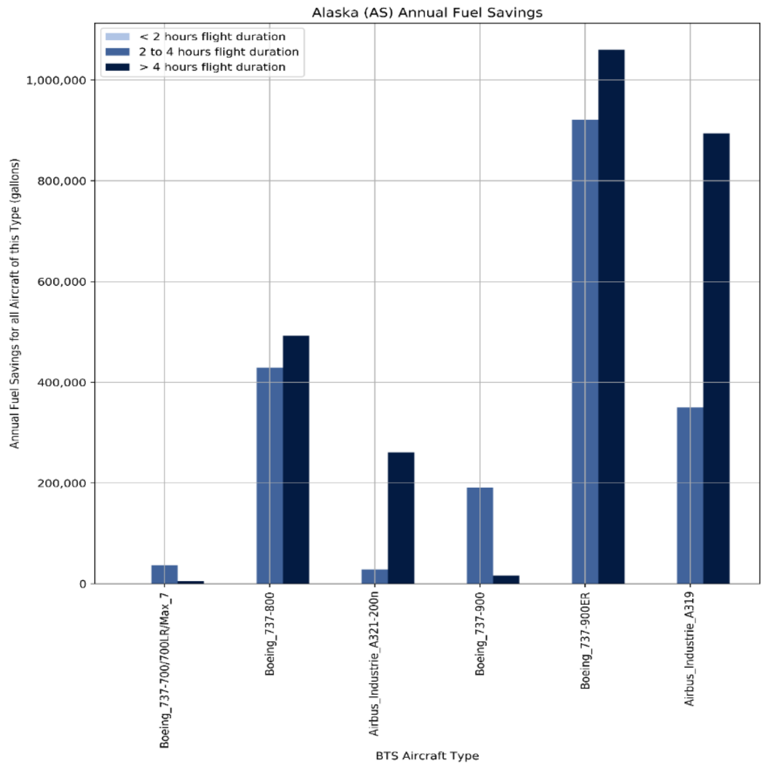

Figure 29. Alaska Airlines fleet-wide annual fuel savings by aircraft type.

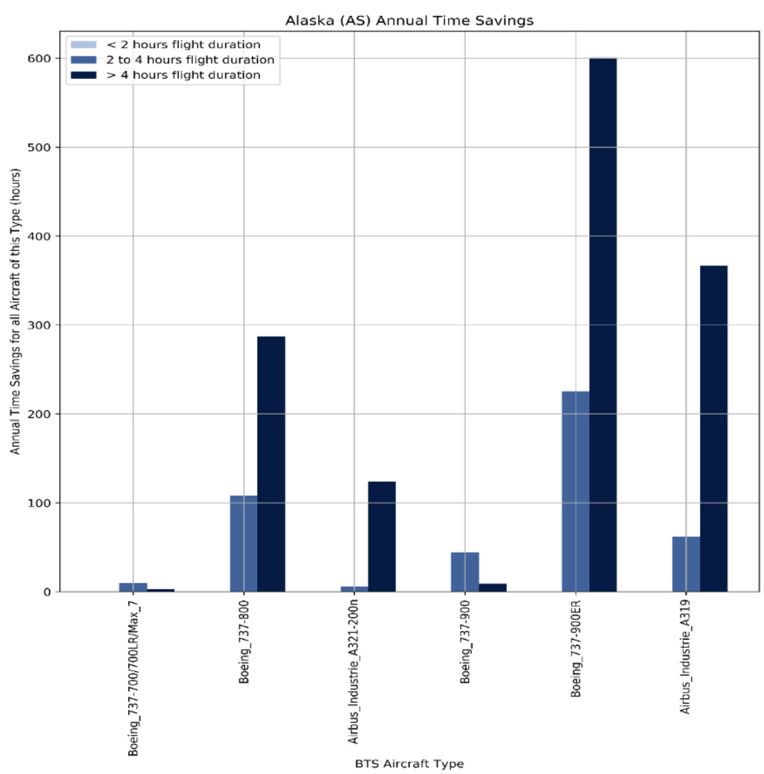

Figure 30. Alaska Airlines fleet-wide annual time savings by aircraft type.

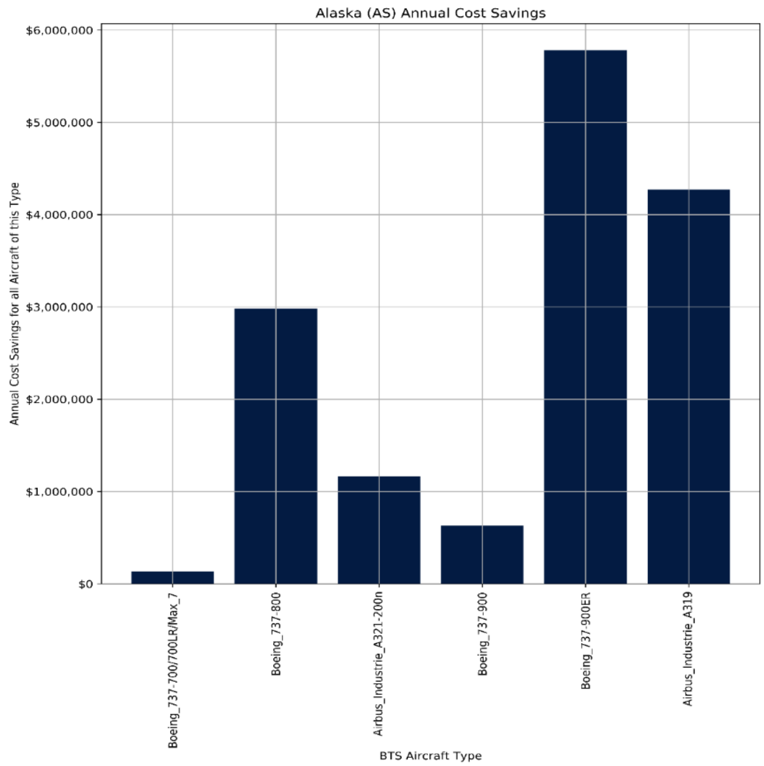

Figure 31. Alaska Airlines fleet-wide annual cost savings by aircraft type.

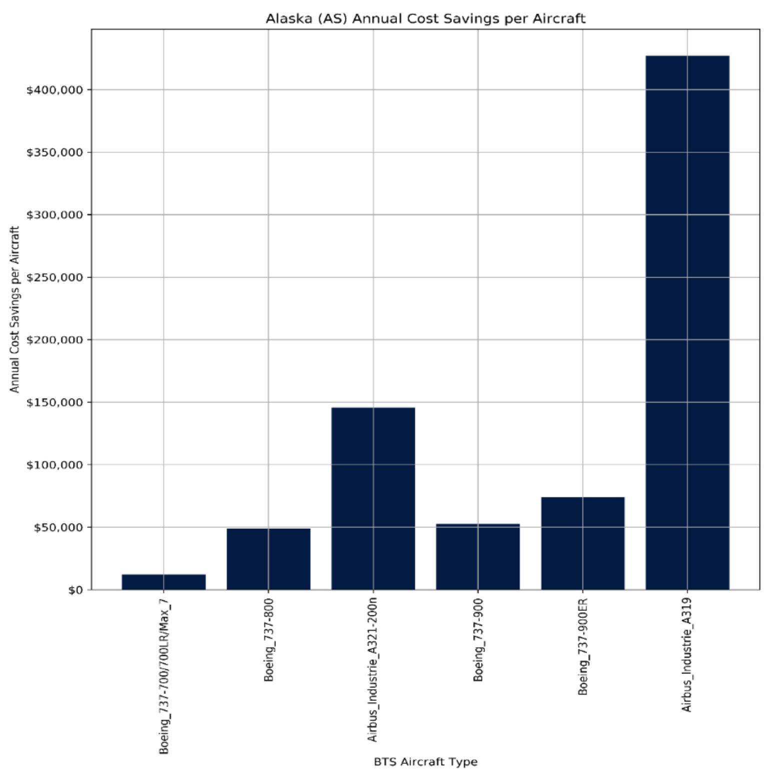

Figure 32. Alaska Airlines annual cost savings per aircraft by aircraft type.

F.1.C. Alaska Airlines benefit calculation tables

Tables 30 to 35 contain the calculations corresponding to the six Alaska Airlines aircraft types. Row A contains the estimated TAP time savings per flight obtained from the operational evaluation. Time savings is the same for all aircraft types for all airlines and is not adjusted. Row B contains the estimated TAP fuel savings per flight obtained from the operational evaluation. Row B is multiplied by the ratio in the right column of Table 29 to produce the adjusted fuel savings shown in Row C. Row D contains the estimated annual operations for each of the three flight length durations. Multiplying row A by row D produces the estimated annual time savings shown in row E which corresponds to Figure 30. Similarly, multiplying row C by row D produces the estimated annual fuel savings shown in row F which corresponds to Figure 29. Multiplying rows E and F by their respective operating costs generates the aggregate cost savings by flight length in row G. Row H, which is plotted in Figure 31, is the summation of the three right columns in row G. Dividing the row H aggregate cost savings by the number of aircraft in row I produces the cost savings per aircraft in row J which is plotted in Figure 32.

Table 30. Alaska Airlines Boeing_737-700/700LR/Max_7 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	26.9468 gal/flight	52.5044 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,838	1,367	99
E. Annual time savings (A*D)	0.00 min	587.81 min	192.06 min
F. Annual fuel savings (C*D)	0.00 gal	36,836.28 gal	5,197.94 gal
G. Annual cost savings ((E/60)*$3242/hour + F*$2.18 per gallon)	$0.00	$112,064.42	$21,709.15
H. Annual cost savings (all flight lengths)	$133,773.57		
I. Number of aircraft of this type	11		
J. Annual cost savings per aircraft	$12,161.23/aircraft		

Table 31. Alaska Airlines Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.4113 gal/flight	55.3579 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	13,418	15,098	8,888
E. Annual time savings (A*D)	0.00 min	6,492.14 min	17,242.72 min
F. Annual fuel savings (C*D)	0.00 gal	428,953.81 gal	492,021.02 gal
G. Annual cost savings ((E/60)*$2468/hour + F*$2.18 per gallon)	$0.00	$1,202,162.66	$1,781,856.37
H. Annual cost savings (all flight lengths)	$2,984,019.03		
I. Number of aircraft of this type	61		
J. Annual cost savings per aircraft	$48,918.34/aircraft		

Table 32. Alaska Airlines Airbus_Industrie_A321-200n annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	34.8551 gal/flight	67.9133 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	2,816	806	3,836
E. Annual time savings (A*D)	0.00 min	346.58 min	7,441.84 min
F. Annual fuel savings (C*D)	0.00 gal	28,093.21 gal	260,515.42 gal
G. Annual cost savings ((E/60)*$4127/hour + F*$2.18 per gallon)	$0.00	$85,082.13	$1,079,798.18
H. Annual cost savings (all flight lengths)	$1,164,880.31		
I. Number of aircraft of this type	8		
J. Annual cost savings per aircraft	$145,610.04/aircraft		

Table 33. Alaska Airlines Boeing_737-900 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	30.7545 gal/flight	59.9235 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	6,362	6,203	276
E. Annual time savings (A*D)	0.00 min	2,667.29 min	535.44 min
F. Annual fuel savings (C*D)	0.00 gal	190,770.16 gal	16,538.89 gal
G. Annual cost savings ((E/60)*$3376/hour + F*$2.18 per gallon)	$0.00	$565,958.47	$66,182.20
H. Annual cost savings (all flight lengths)	$632,140.67		
I. Number of aircraft of this type	12		
J. Annual cost savings per aircraft	$52,678.39/aircraft		

Table 34. Alaska Airlines Boeing_737-900ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	29.2900 gal/flight	57.0700 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	20,501	31,468	18,575
E. Annual time savings (A*D)	0.00 min	13,531.24 min	36,035.50 min
F. Annual fuel savings (C*D)	0.00 gal	921,697.72 gal	1,060,075.25 gal
G. Annual cost savings ((E/60)*$1768/hour + F*$2.18 per gallon)	$0.00	$2,408,021.57	$3,372,810.11
H. Annual cost savings (all flight lengths)	$5,780,831.68		
I. Number of aircraft of this type	78		
J. Annual cost savings per aircraft	$74,113.23/aircraft		

Table 35. Alaska Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	40.4202 gal/flight	78.7566 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	14,886	8,661	11,355
E. Annual time savings (A*D)	0.00 min	3,724.23 min	22,028.70 min
F. Annual fuel savings (C*D)	0.00 gal	350,079.35 gal	894,281.19 gal
G. Annual cost savings ((E/60)*$3629/hour + F*$2.18 per gallon)	$0.00	$988,426.83	$3,281,902.20
H. Annual cost savings (all flight lengths)	$4,270,329.03		
I. Number of aircraft of this type	10		
J. Annual cost savings per aircraft	$427,032.90/aircraft		

F.2. Allegiant Air (G4)

F.2.A. Allegiant Air operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.33 per gallon

Table 36. Allegiant Air aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Airbus_Industrie_A319 (698)	$2,136/hour	884 gallons/hour	0.97

F.2.B. Allegiant Air summary plots

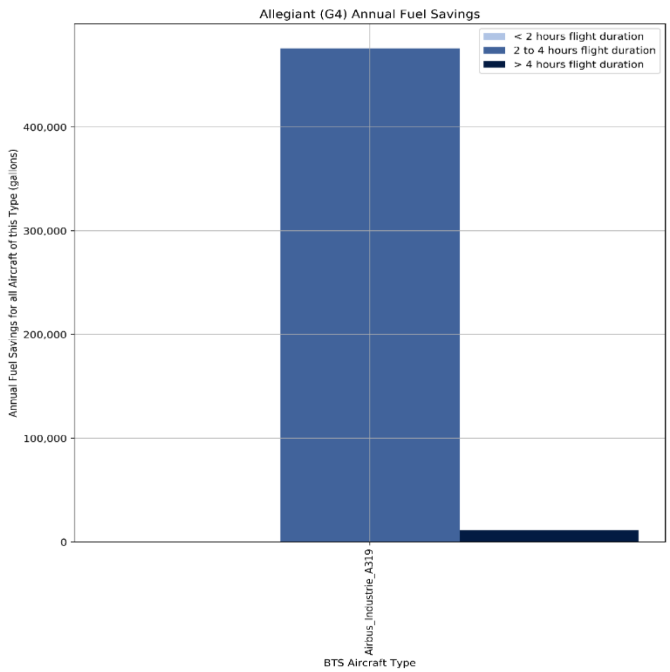

Figure 33. Allegiant Air fleet-wide annual fuel savings by aircraft type.

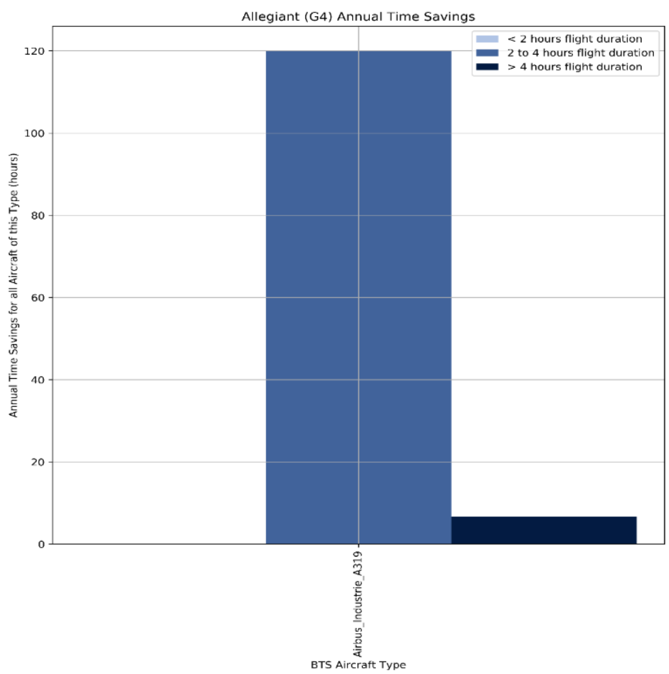

Figure 34. Allegiant Air fleet-wide annual time savings by aircraft type.

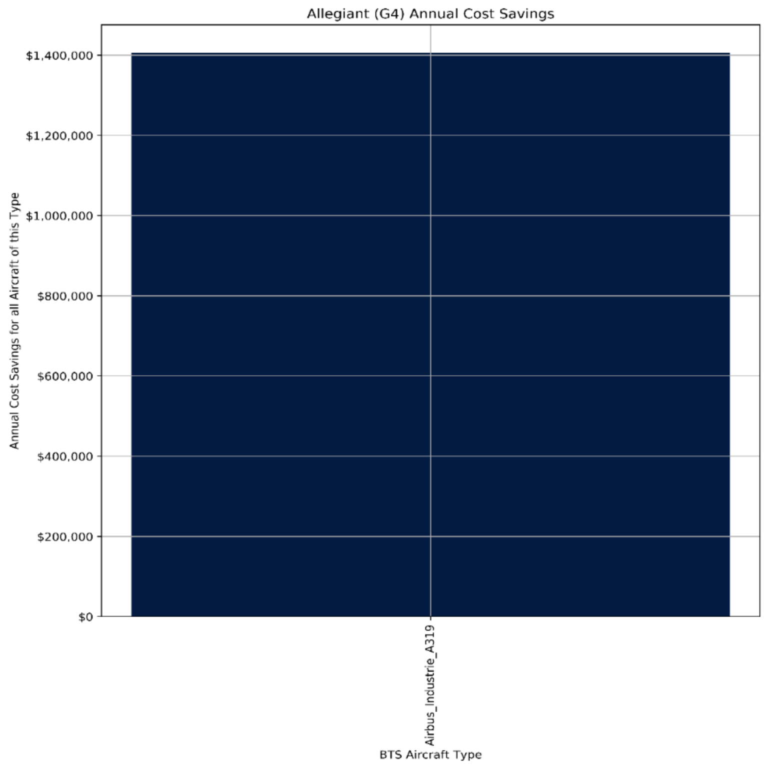

Figure 35. Allegiant Air fleet-wide annual cost savings by aircraft type.

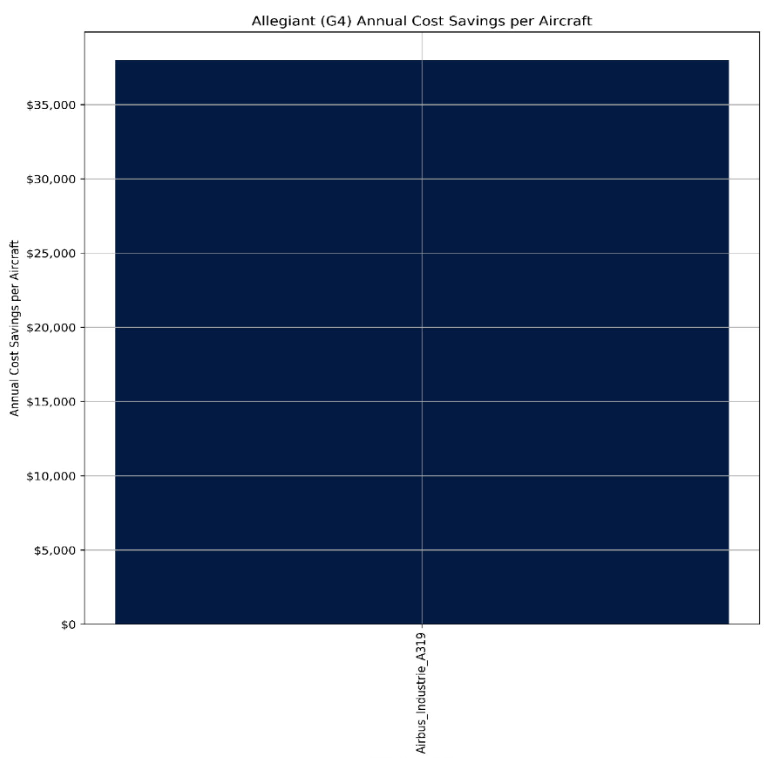

Figure 36. Allegiant Air annual cost savings per aircraft by aircraft type.

F.2.C. Allegiant Air benefit calculation tables

Table 37. Allegiant Air Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.4113 gal/flight	55.3579 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	14,005	16,741	207
E. Annual time savings (A*D)	0.00 min	7,198.63 min	401.58 min
F. Annual fuel savings (C*D)	0.00 gal	475,633.57 gal	11,459.09 gal
G. Annual cost savings ((E/60)*$2136/hour + F*$2.33 per gallon)	$0.00	$1,364,497.45	$40,995.93
H. Annual cost savings (all flight lengths)	$1,405,493.38		
I. Number of aircraft of this type	37		
J. Annual cost savings per aircraft	$37,986.31/aircraft		

F.3. American Airlines (AA)

F.3.A. American Airlines operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.15 per gallon

Table 38. American Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_B737_Max_800 (838)	$3,335/hour	822 gallons/hour	0.90
Boeing_737-800 (614)	$3,147/hour	952 gallons/hour	1.04
Airbus_Industrie_A330-300 (687)	$6,359/hour	2,067 gallons/hour	2.27
Boeing_767-300/300ER (626)	$4,445/hour	1,664 gallons/hour	1.82
Boeing_777-200ER/200LR/233LR (627)	$6,227/hour	2,364 gallons/hour	2.59
B787-800_Dreamliner (887)	$5,302/hour	1,715 gallons/hour	1.88
Airbus_Industrie_A330-200 (696)	$5,392/hour	1,892 gallons/hour	2.07
B787-900_Dreamliner (889)	$6,703/hour	1,897 gallons/hour	2.08
Airbus_Industrie_A319 (698)	$2,424/hour	925 gallons/hour	1.01
Airbus_Industrie_A321 (699)	$3,598/hour	1,079 gallons/hour	1.18
Boeing_777-300/300ER/333ER (637)	$7,168/hour	2,733 gallons/hour	3.00

F.3.B. American Airlines summary plots

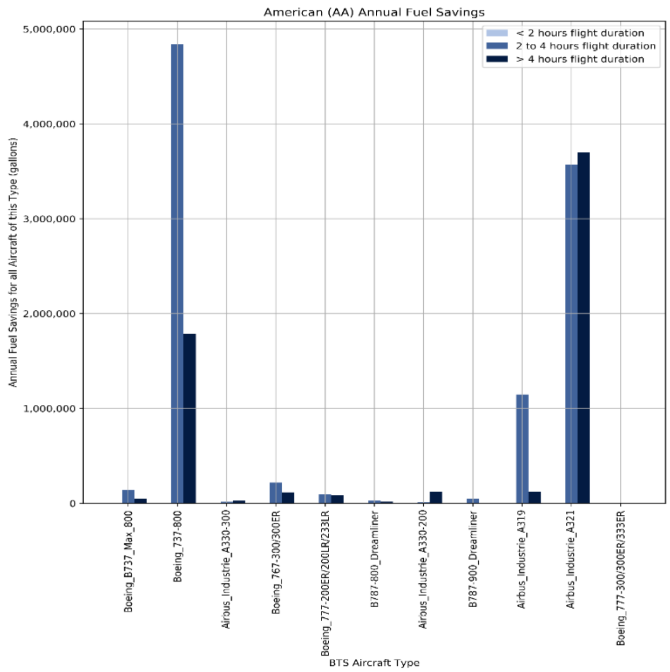

Figure 37. American Airlines fleet-wide annual fuel savings by aircraft type.

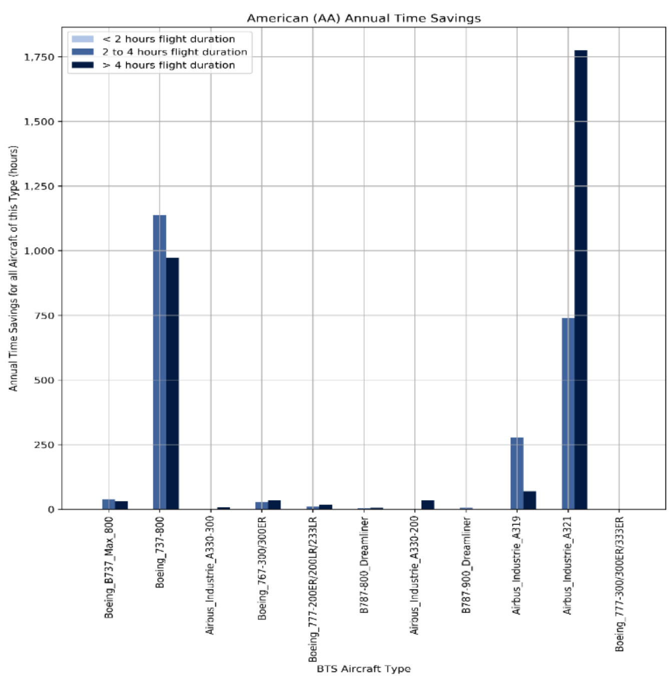

Figure 38. American Airlines fleet-wide annual time savings by aircraft type.

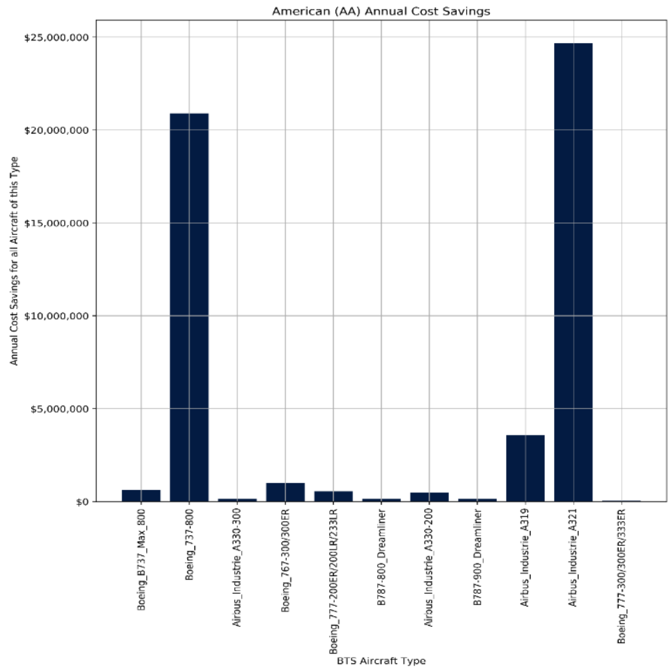

Figure 39. American Airlines fleet-wide annual cost savings by aircraft type.

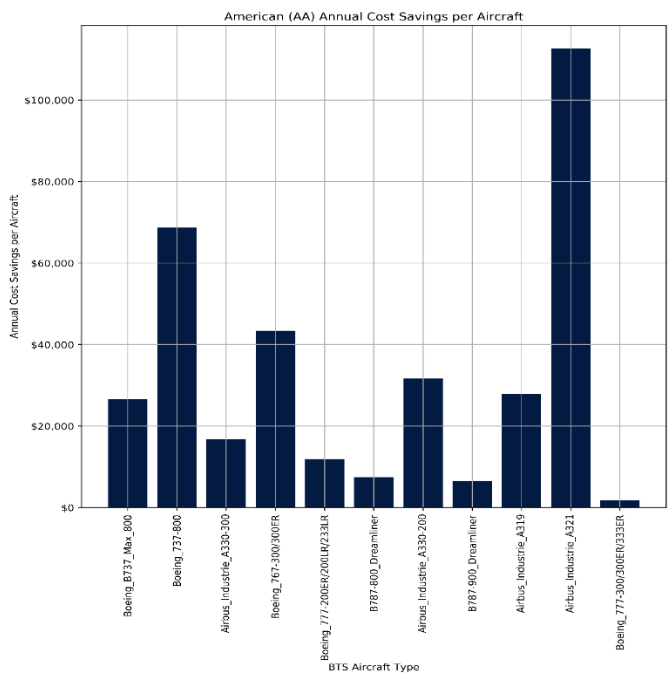

Figure 40. American Airlines annual cost savings per aircraft by aircraft type.

F.3.C. American Airlines benefit calculation tables

Table 39. American Airlines Boeing_B737_Max_800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	26.3610 gal/flight	51.3630 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,858	5,378	929
E. Annual time savings (A*D)	0.00 min	2,312.54 min	1,802.26 min
F. Annual fuel savings (C*D)	0.00 gal	141,769.46 gal	47,716.23 gal
G. Annual cost savings ((E/60)*$3335/hour + F*$2.15 per gallon)	$0.00	$433,343.02	$202,765.51
H. Annual cost savings (all flight lengths)	$636,108.53		
I. Number of aircraft of this type	24		
J. Annual cost savings per aircraft	$26,504.52/aircraft		

Table 40. American Airlines Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	30.4616 gal/flight	59.3528 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	127,697	158,855	30,127
E. Annual time savings (A*D)	0.00 min	68,307.65 min	58,446.38 min
F. Annual fuel savings (C*D)	0.00 gal	4,838,977.47 gal	1,788,121.81 gal
G. Annual cost savings ((E/60)*$3147/hour + F*$2.15 per gallon)	$0.00	$13,986,537.80	$6,909,974.52
H. Annual cost savings (all flight lengths)	$20,896,512.32		
I. Number of aircraft of this type	304		
J. Annual cost savings per aircraft	$68,738.53/aircraft		

Table 41. American Airlines Airbus_Industrie_A330-300 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	66.4883 gal/flight	129.5489 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	69	218	226
E. Annual time savings (A*D)	0.00 min	93.74 min	438.44 min
F. Annual fuel savings (C*D)	0.00 gal	14,494.45 gal	29,278.05 gal
G. Annual cost savings ((E/60)*$6359/hour + F*$2.15 per gallon)	$0.00	$41,097.95	$109,415.14
H. Annual cost savings (all flight lengths)	$150,513.09		
I. Number of aircraft of this type	9		
J. Annual cost savings per aircraft	$16,723.68/aircraft		

Table 42. American Airlines Boeing_767-300/300ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	53.3078 gal/flight	103.8674 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	76	4,049	1,102
E. Annual time savings (A*D)	0.00 min	1,741.07 min	2,137.88 min
F. Annual fuel savings (C*D)	0.00 gal	215,843.28 gal	114,461.87 gal
G. Annual cost savings ((E/60)*$4445/hour + F*$2.15 per gallon)	$0.00	$593,047.32	$404,474.30
H. Annual cost savings (all flight lengths)	$997,521.62		
I. Number of aircraft of this type	23		
J. Annual cost savings per aircraft	$43,370.51/aircraft		

Table 43. American Airlines Boeing_777-200ER/200LR/233LR annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	75.8611 gal/flight	147.8113 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	46	1,268	565
E. Annual time savings (A*D)	0.00 min	545.24 min	1,096.10 min
F. Annual fuel savings (C*D)	0.00 gal	96,191.87 gal	83,513.38 gal
G. Annual cost savings ((E/60)*$6227/hour + F*$2.15 per gallon)	$0.00	$263,399.35	$293,310.68
H. Annual cost savings (all flight lengths)	$556,710.03		
I. Number of aircraft of this type	47		
J. Annual cost savings per aircraft	$11,844.89/aircraft		

Table 44. American Airlines B787-800_Dreamliner annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	55.0652 gal/flight	107.2916 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,040	518	168
E. Annual time savings (A*D)	0.00 min	222.74 min	325.92 min
F. Annual fuel savings (C*D)	0.00 gal	28,523.77 gal	18,024.99 gal
G. Annual cost savings ((E/60)*$5302/hour + F*$2.15 per gallon)	$0.00	$81,008.90	$67,554.19
H. Annual cost savings (all flight lengths)	$148,563.09		
I. Number of aircraft of this type	20		
J. Annual cost savings per aircraft	$7,428.15/aircraft		

Table 45. American Airlines Airbus_Industrie_A330-200 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	60.6303 gal/flight	118.1349 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	566	148	1,052
E. Annual time savings (A*D)	0.00 min	63.64 min	2,040.88 min
F. Annual fuel savings (C*D)	0.00 gal	8,973.28 gal	124,277.91 gal
G. Annual cost savings ((E/60)*$5392/hour + F*$2.15 per gallon)	$0.00	$25,011.67	$450,604.59
H. Annual cost savings (all flight lengths)	$475,616.26		
I. Number of aircraft of this type	15		
J. Annual cost savings per aircraft	$31,707.75/aircraft		

Table 46. American Airlines B787-900_Dreamliner annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	60.9232 gal/flight	118.7056 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	133	797	0
E. Annual time savings (A*D)	0.00 min	342.71 min	0.00 min
F. Annual fuel savings (C*D)	0.00 gal	48,555.79 gal	0.00 gal
G. Annual cost savings ((E/60)*$6703/hour + F*$2.15 per gallon)	$0.00	$142,681.37	$0.00
H. Annual cost savings (all flight lengths)	$142,681.37		
I. Number of aircraft of this type	22		
J. Annual cost savings per aircraft	$6,485.52/aircraft		

Table 47. American Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	29.5829 gal/flight	57.6407 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	104,618	38,749	2,135
E. Annual time savings (A*D)	0.00 min	16,662.07 min	4,141.90 min
F. Annual fuel savings (C*D)	0.00 gal	1,146,307.79 gal	123,062.89 gal
G. Annual cost savings ((E/60)*$2424/hour + F*$2.15 per gallon)	$0.00	$3,137,709.38	$431,917.97
H. Annual cost savings (all flight lengths)	$3,569,627.35		
I. Number of aircraft of this type	128		
J. Annual cost savings per aircraft	$27,887.71/aircraft		

Table 48. American Airlines Airbus_Industrie_A321 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	34.5622 gal/flight	67.3426 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	83,812	103,244	54,919
E. Annual time savings (A*D)	0.00 min	44,394.92 min	106,542.86 min
F. Annual fuel savings (C*D)	0.00 gal	3,568,339.78 gal	3,698,388.25 gal
G. Annual cost savings ((E/60)*$3598/hour + F*$2.15 per gallon)	$0.00	$10,334,145.90	$14,340,554.91
H. Annual cost savings (all flight lengths)	$24,674,700.81		
I. Number of aircraft of this type	219		
J. Annual cost savings per aircraft	$112,669.87/aircraft		

Table 49. American Airlines Boeing_777-300/300ER/333ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	87.8700 gal/flight	171.2100 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	17	64	36
E. Annual time savings (A*D)	0.00 min	27.52 min	69.84 min
F. Annual fuel savings (C*D)	0.00 gal	5,623.68 gal	6,163.56 gal
G. Annual cost savings ((E/60)*$7168/hour + F*$2.15 per gallon)	$0.00	$15,378.63	$21,595.21
H. Annual cost savings (all flight lengths)	$36,973.84		
I. Number of aircraft of this type	20		
J. Annual cost savings per aircraft	$1,848.69/aircraft		

F.4. Delta Airlines (DL)

F.4.A. Delta Airlines operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.11 per gallon

Table 50. Delta Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_737-700/700LR/Max_7 (612)	$3,001/hour	889 gallons/hour	0.97
Boeing_737-800 (614)	$2,969/hour	972 gallons/hour	1.07
Airbus_Industrie_A350-900 (359)	$3,588/hour	2,127 gallons/hour	2.33
Airbus_Industrie_A330-300 (687)	$3,316/hour	2,083 gallons/hour	2.28
Boeing_767-300/300ER (626)	$3,266/hour	1,711 gallons/hour	1.88
Boeing_777-200ER/200LR/233LR (627)	$3,606/hour	2,525 gallons/hour	2.77
Boeing_737-900ER (888)	$2,938/hour	1,006 gallons/hour	1.10
Airbus_Industrie_A330-200 (696)	$3,399/hour	2,014 gallons/hour	2.21
Airbus_Industrie_A319 (698)	$2,991/hour	946 gallons/hour	1.04
Airbus_Industrie_A321 (699)	$2,927/hour	1,093 gallons/hour	1.20

F.4.B. Delta Airlines summary plots

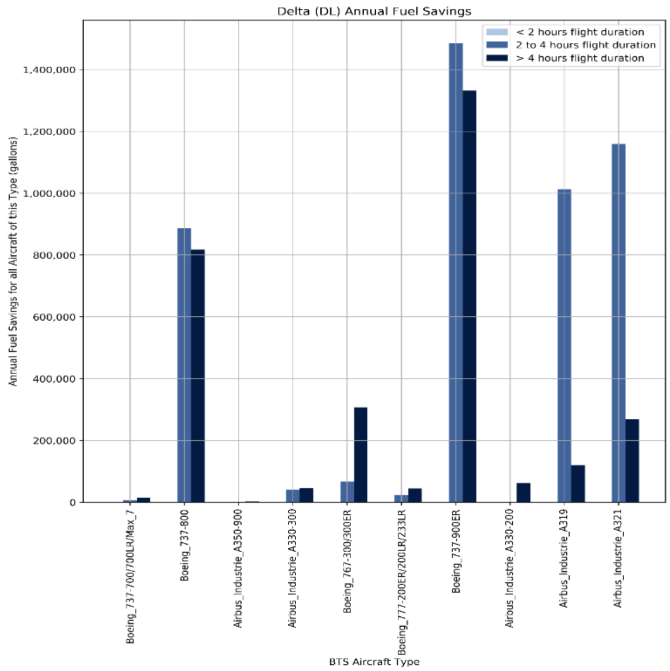

Figure 41. Delta Airlines fleet-wide annual fuel savings by aircraft type.

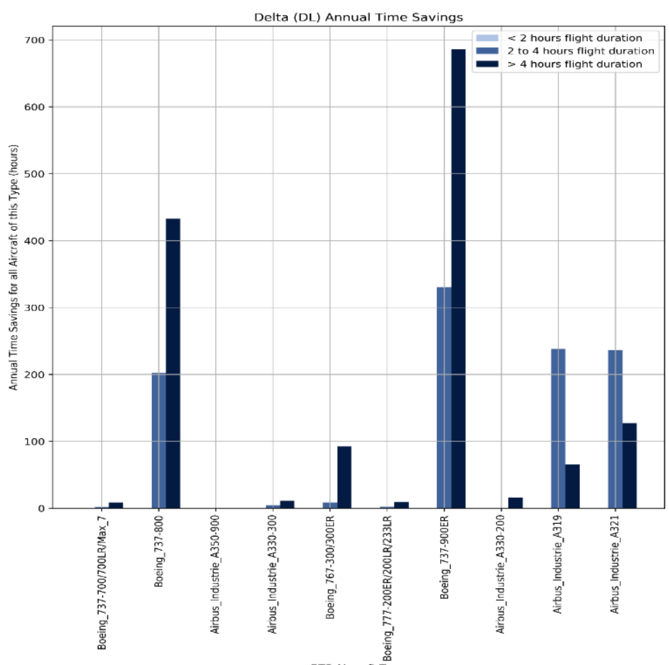

Figure 42. Delta Airlines fleet-wide annual time savings by aircraft type.

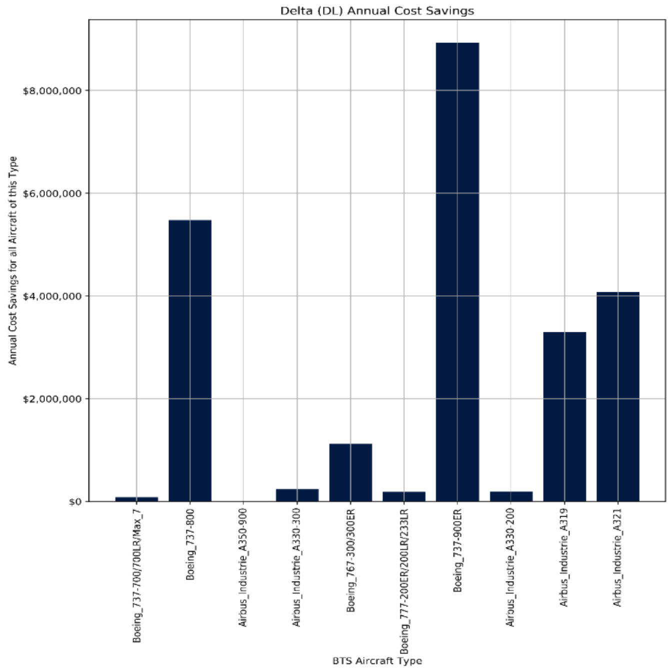

Figure 43. Delta Airlines fleet-wide annual cost savings by aircraft type.

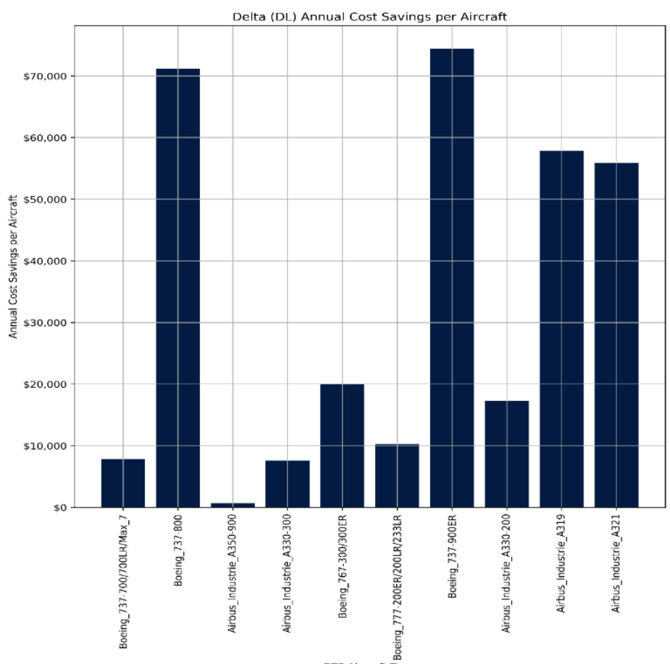

Figure 44. Delta Airlines annual cost savings per aircraft by aircraft type.

F.4.C. Delta Airlines benefit calculation tables

Table 51. Delta Airlines Boeing_737-700/700LR/Max_7 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.4113 gal/flight	55.3579 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	9,812	260	269
E. Annual time savings (A*D)	0.00 min	111.80 min	521.86 min
F. Annual fuel savings (C*D)	0.00 gal	7,386.94 gal	14,891.28 gal
G. Annual cost savings ((E/60)*$3001/hour + F*$2.11 per gallon)	$0.00	$21,178.31	$57,522.30
H. Annual cost savings (all flight lengths)	$78,700.61		
I. Number of aircraft of this type	10		
J. Annual cost savings per aircraft	$7,870.06/aircraft		

Table 52. Delta Airlines Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	31.3403 gal/flight	61.0649 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	37,732	28,287	13,379
E. Annual time savings (A*D)	0.00 min	12,163.41 min	25,955.26 min
F. Annual fuel savings (C*D)	0.00 gal	886,523.07 gal	816,987.30 gal
G. Annual cost savings ((E/60)*$2969/hour + F*$2.11 per gallon)	$0.00	$2,472,449.75	$3,008,195.99
H. Annual cost savings (all flight lengths)	$5,480,645.74		
I. Number of aircraft of this type	77		
J. Annual cost savings per aircraft	$71,177.22/aircraft		

Table 53. Delta Airlines Airbus_Industrie_A350-900 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	68.2457 gal/flight	132.9731 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	24	12	18
E. Annual time savings (A*D)	0.00 min	5.16 min	34.92 min
F. Annual fuel savings (C*D)	0.00 gal	818.95 gal	2,393.52 gal
G. Annual cost savings ((E/60)*$3588/hour + F*$2.11 per gallon)	$0.00	$2,036.55	$7,138.54
H. Annual cost savings (all flight lengths)	$9,175.09		
I. Number of aircraft of this type	13		
J. Annual cost savings per aircraft	$705.78/aircraft		

Table 54. Delta Airlines Airbus_Industrie_A330-300 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	66.7812 gal/flight	130.1196 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	89	606	355
E. Annual time savings (A*D)	0.00 min	260.58 min	688.70 min
F. Annual fuel savings (C*D)	0.00 gal	40,469.41 gal	46,192.46 gal
G. Annual cost savings ((E/60)*$3316/hour + F*$2.11 per gallon)	$0.00	$99,791.84	$135,528.24
H. Annual cost savings (all flight lengths)	$235,320.08		
I. Number of aircraft of this type	31		
J. Annual cost savings per aircraft	$7,590.97/aircraft		

Table 55. Delta Airlines Boeing_767-300/300ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	55.0652 gal/flight	107.2916 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	509	1,214	2,865
E. Annual time savings (A*D)	0.00 min	522.02 min	5,558.10 min
F. Annual fuel savings (C*D)	0.00 gal	66,849.15 gal	307,390.43 gal
G. Annual cost savings ((E/60)*$3266/hour + F*$2.11 per gallon)	$0.00	$169,467.00	$951,139.72
H. Annual cost savings (all flight lengths)	$1,120,606.72		
I. Number of aircraft of this type	56		
J. Annual cost savings per aircraft	$20,010.83/aircraft		

Table 56. Delta Airlines Boeing_777-200ER/200LR/233LR annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	81.1333 gal/flight	158.0839 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	39	293	281
E. Annual time savings (A*D)	0.00 min	125.99 min	545.14 min
F. Annual fuel savings (C*D)	0.00 gal	23,772.06 gal	44,421.58 gal
G. Annual cost savings ((E/60)*$3606/hour + F*$2.11 per gallon)	$0.00	$57,731.05	$126,492.45
H. Annual cost savings (all flight lengths)	$184,223.50		
I. Number of aircraft of this type	18		
J. Annual cost savings per aircraft	$10,234.64/aircraft		

Table 57. Delta Airlines Boeing_737-900ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	32.2190 gal/flight	62.7770 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	38,464	46,099	21,220
E. Annual time savings (A*D)	0.00 min	19,822.57 min	41,166.80 min
F. Annual fuel savings (C*D)	0.00 gal	1,485,263.68 gal	1,332,127.94 gal
G. Annual cost savings ((E/60)*$2938/hour + F*$2.11 per gallon)	$0.00	$4,104,551.54	$4,826,590.93
H. Annual cost savings (all flight lengths)	$8,931,142.47		
I. Number of aircraft of this type	120		
J. Annual cost savings per aircraft	$74,426.19/aircraft		

Table 58. Delta Airlines Airbus_Industrie_A330-200 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	64.7309 gal/flight	126.1247 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	24	29	494
E. Annual time savings (A*D)	0.00 min	12.47 min	958.36 min
F. Annual fuel savings (C*D)	0.00 gal	1,877.20 gal	62,305.60 gal
G. Annual cost savings ((E/60)*$3399/hour + F*$2.11 per gallon)	$0.00	$4,667.32	$185,755.91
H. Annual cost savings (all flight lengths)	$190,423.23		
I. Number of aircraft of this type	11		
J. Annual cost savings per aircraft	$17,311.20/aircraft		

Table 59. Delta Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	30.4616 gal/flight	59.3528 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	28,430	33,226	2,021
E. Annual time savings (A*D)	0.00 min	14,287.18 min	3,920.74 min
F. Annual fuel savings (C*D)	0.00 gal	1,012,117.12 gal	119,952.01 gal
G. Annual cost savings ((E/60)*$2991/hour + F*$2.11 per gallon)	$0.00	$2,847,783.05	$448,547.63
H. Annual cost savings (all flight lengths)	$3,296,330.68		
I. Number of aircraft of this type	57		
J. Annual cost savings per aircraft	$57,830.36/aircraft		

Table 60. Delta Airlines Airbus_Industrie_A321 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	35.1480 gal/flight	68.4840 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	35,445	32,995	3,933
E. Annual time savings (A*D)	0.00 min	14,187.85 min	7,630.02 min
F. Annual fuel savings (C*D)	0.00 gal	1,159,708.26 gal	269,347.57 gal
G. Annual cost savings ((E/60)*$2927/hour + F*$2.11 per gallon)	$0.00	$3,139,115.04	$940,541.18
H. Annual cost savings (all flight lengths)	$4,079,656.22		
I. Number of aircraft of this type	73		
J. Annual cost savings per aircraft	$55,885.70/aircraft		

F.5. Frontier Airlines (F9)

F.5.A. Frontier Airlines operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.22 per gallon

Table 61. Frontier Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Airbus_Industrie_A320-200n (722)	$2,388/hour	777 gallons/hour	0.85
Airbus_Industrie_A319 (698)	$1,876/hour	899 gallons/hour	0.99
Airbus_Industrie_A321 (699)	$3,169/hour	1,041 gallons/hour	1.14

F.5.B. Frontier Airlines summary plots

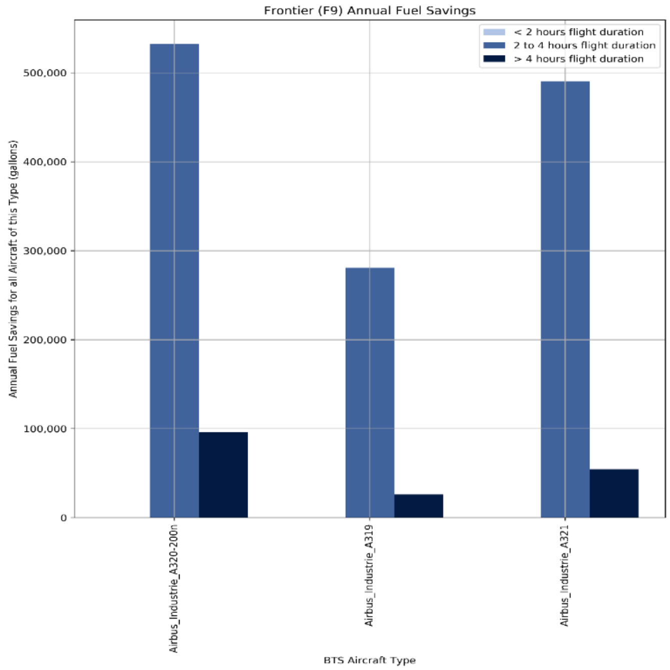

Figure 45. Frontier Airlines fleet-wide annual fuel savings by aircraft type.

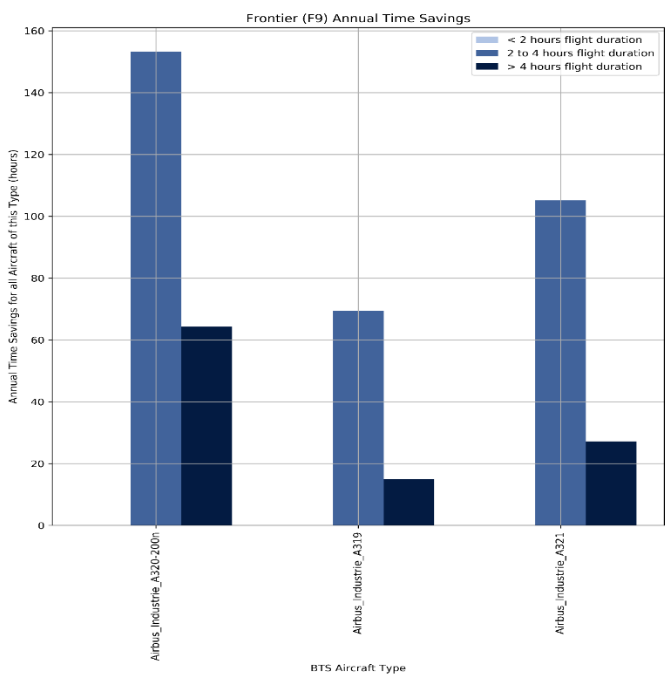

Figure 46. Frontier Airlines fleet-wide annual time savings by aircraft type.

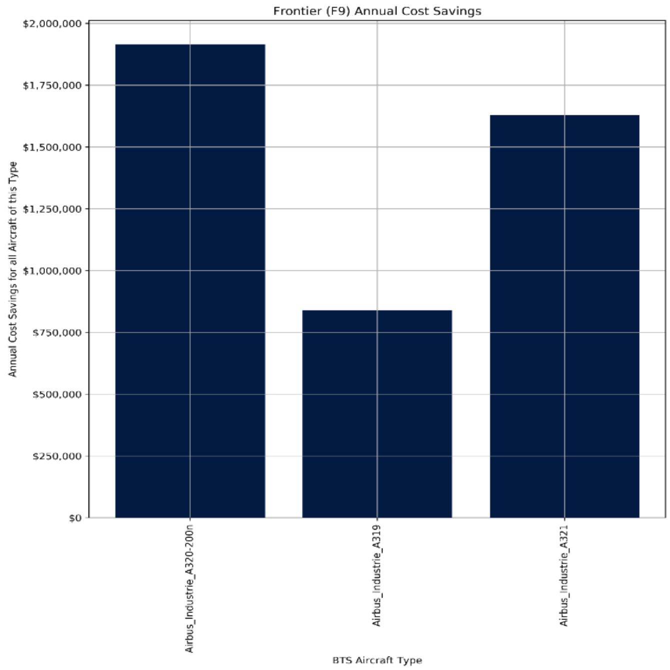

Figure 47. Frontier Airlines fleet-wide annual cost savings by aircraft type.

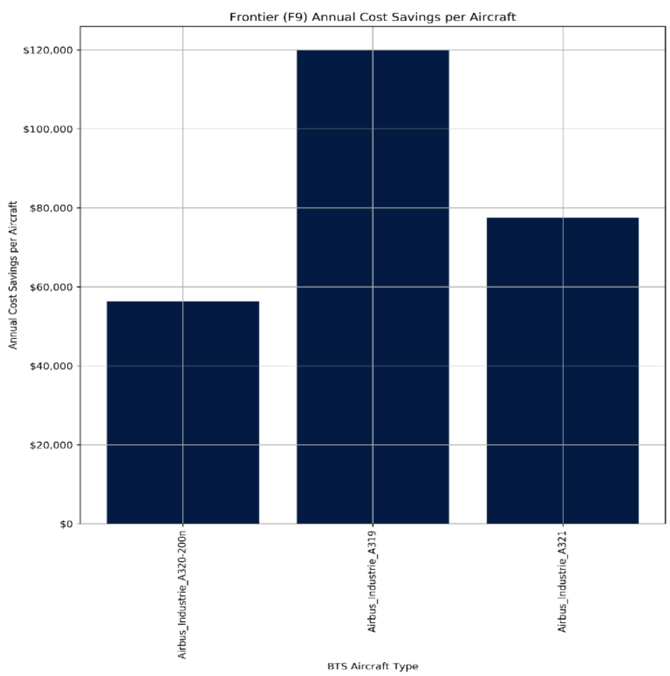

Figure 48. Frontier Airlines annual cost savings per aircraft by aircraft type.

F.5.C. Frontier Airlines benefit calculation tables

Table 62. Frontier Airlines Airbus_Industrie_A320-200n annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	24.8965 gal/flight	48.5095 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	16,675	21,394	1,987
E. Annual time savings (A*D)	0.00 min	9,199.42 min	3,854.78 min
F. Annual fuel savings (C*D)	0.00 gal	532,635.72 gal	96,388.38 gal
G. Annual cost savings ((E/60)*$2388/hour + F*$2.22 per gallon)	$0.00	$1,548,588.21	$367,402.45
H. Annual cost savings (all flight lengths)	$1,915,990.66		
I. Number of aircraft of this type	34		
J. Annual cost savings per aircraft	$56,352.67/aircraft		

Table 63. Frontier Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.9971 gal/flight	56.4993 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	10,188	9,687	461
E. Annual time savings (A*D)	0.00 min	4,165.41 min	894.34 min
F. Annual fuel savings (C*D)	0.00 gal	280,894.91 gal	26,046.18 gal
G. Annual cost savings ((E/60)*$1876/hour + F*$2.22 per gallon)	$0.00	$753,825.19	$85,785.55
H. Annual cost savings (all flight lengths)	$839,610.74		
I. Number of aircraft of this type	7		
J. Annual cost savings per aircraft	$119,944.39/aircraft		

Table 64. Frontier Airlines Airbus_Industrie_A321 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	33.3906 gal/flight	65.0598 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	10,596	14,686	839
E. Annual time savings (A*D)	0.00 min	6,314.98 min	1,627.66 min
F. Annual fuel savings (C*D)	0.00 gal	490,374.35 gal	54,585.17 gal
G. Annual cost savings ((E/60)*$3169/hour + F*$2.22 per gallon)	$0.00	$1,422,167.25	$207,146.65
H. Annual cost savings (all flight lengths)	$1,629,313.90		
I. Number of aircraft of this type	21		
J. Annual cost savings per aircraft	$77,586.38/aircraft		

F.6. JetBlue Airways (B6)

F.6.A. JetBlue Airways operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.16 per gallon

Table 65. JetBlue Airways aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Airbus_Industrie_A321 (699)	$1,549/hour	1,008 gallons/hour	1.11

F.6.B. JetBlue Airways summary plots

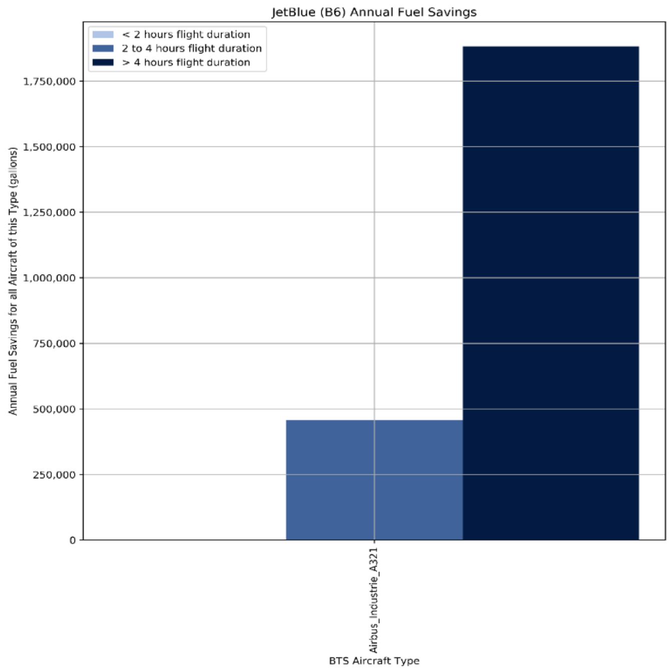

Figure 49. JetBlue Airways fleet-wide annual fuel savings by aircraft type.

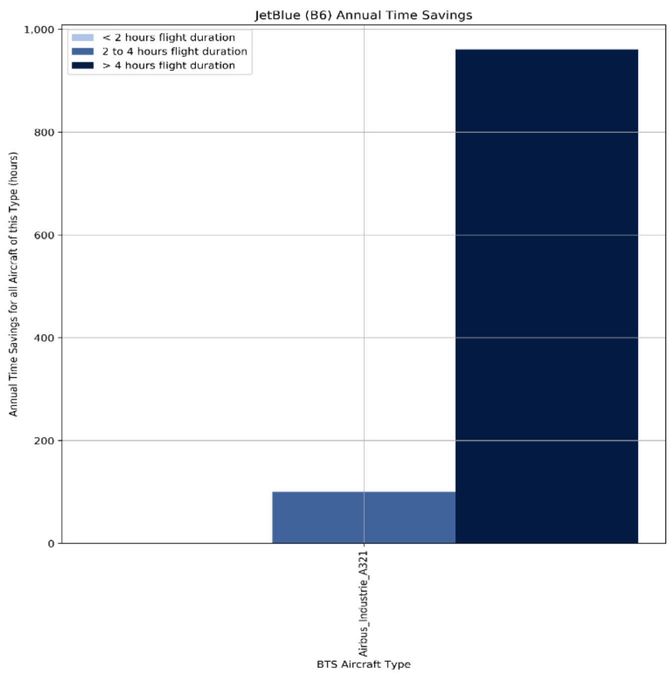

Figure 50. JetBlue Airways fleet-wide annual time savings by aircraft type.

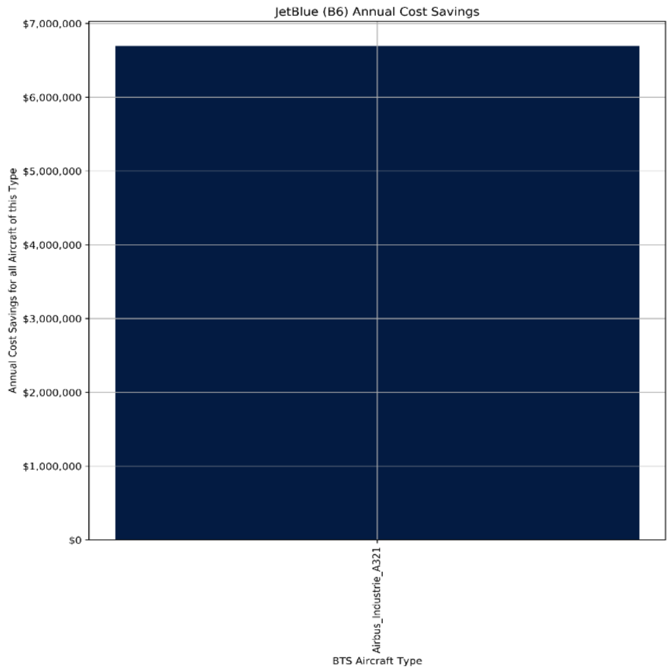

Figure 51. JetBlue Airways fleet-wide annual cost savings by aircraft type.

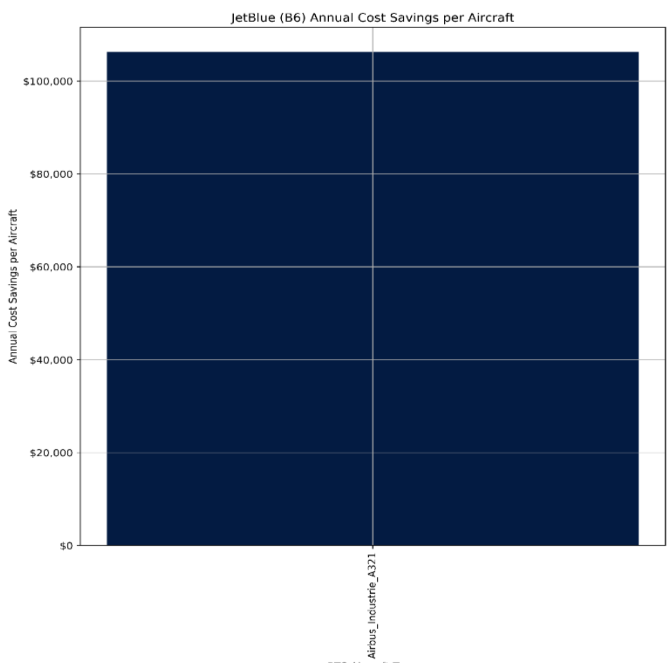

Figure 52. JetBlue Airways annual cost savings per aircraft by aircraft type.

F.6.C. JetBlue Airways benefit calculation tables

Table 66. JetBlue Airways Airbus_Industrie_A321 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	32.5119 gal/flight	63.3477 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	292	14,029	29,710
E. Annual time savings (A*D)	0.00 min	6,032.47 min	57,637.40 min
F. Annual fuel savings (C*D)	0.00 gal	456,109.45 gal	1,882,060.17 gal
G. Annual cost savings ((E/60)*$1549/hour + F*$2.16 per gallon)	$0.00	$1,140,934.68	$5,553,255.51
H. Annual cost savings (all flight lengths)	$6,694,190.19		
I. Number of aircraft of this type	63		
J. Annual cost savings per aircraft	$106,256.99/aircraft		

F.7. Southwest Airways (WN)

F.7.A. Southwest Airways operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.08 per gallon

Table 67. Southwest Airways aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_737-800 (614)	$1,988/hour	889 gallons/hour	0.97
Boeing_737-700/700LR/Max_7 (612)	$2,732/hour	871 gallons/hour	0.96
Boeing_B737_Max_800 (838)	$1,891/hour	771 gallons/hour	0.85

F.7.B. Southwest Airways summary plots

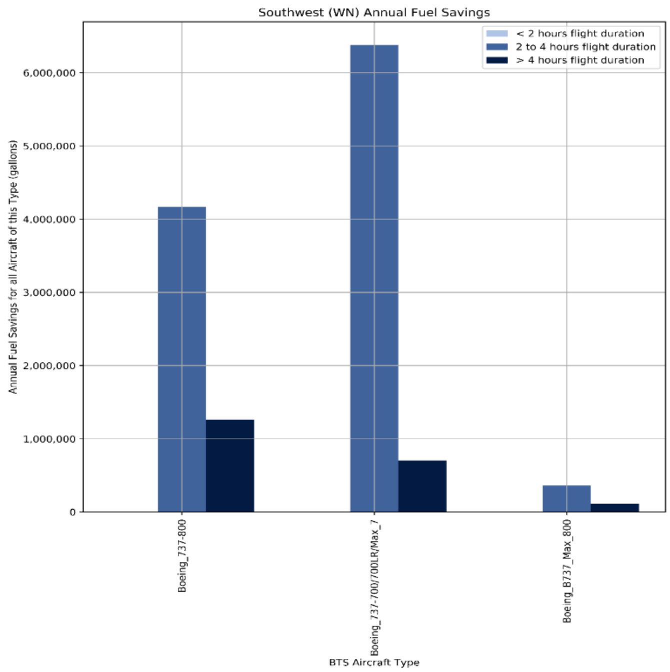

Figure 53. Southwest Airways fleet-wide annual fuel savings by aircraft type.

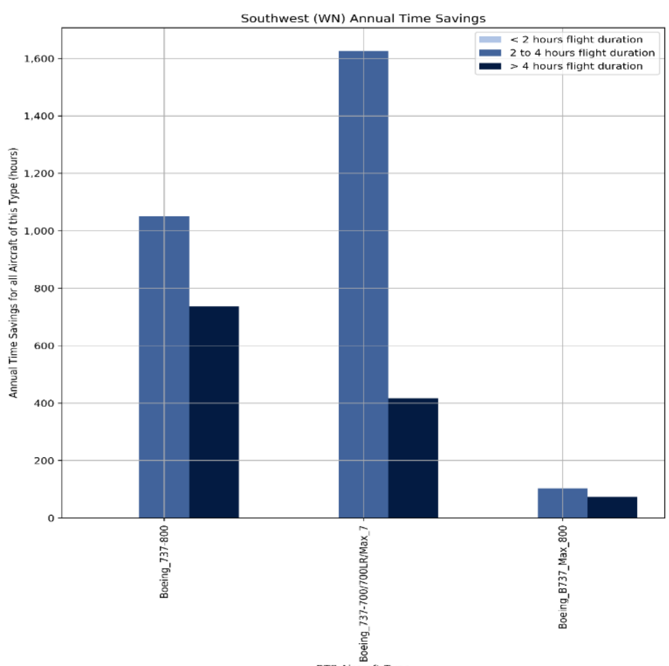

Figure 54. Southwest Airways fleet-wide annual time savings by aircraft type.

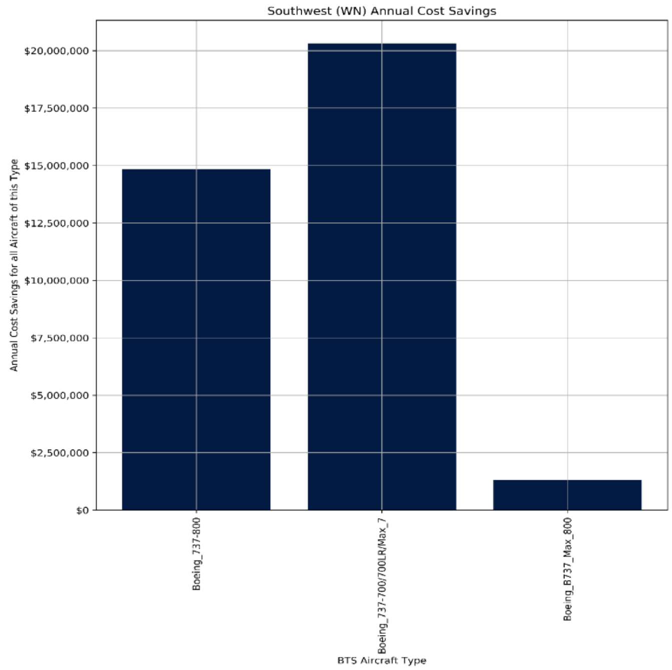

Figure 55. Southwest Airways fleet-wide annual cost savings by aircraft type.

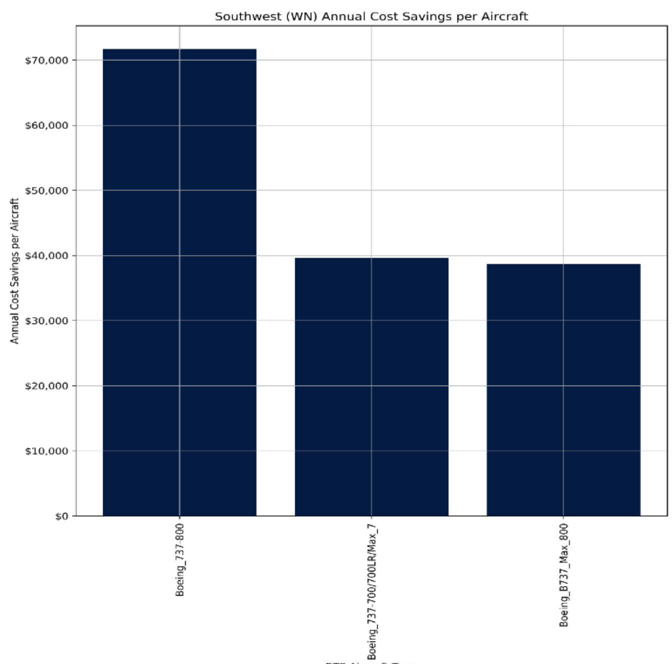

Figure 56. Southwest Airways annual cost savings per aircraft by aircraft type.

F.7.C. Southwest Airways benefit calculation tables

Table 68. Southwest Airways Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.4113 gal/flight	55.3579 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	134,606	146,653	22,769
E. Annual time savings (A*D)	0.00 min	63,060.79 min	44,171.86 min
F. Annual fuel savings (C*D)	0.00 gal	4,166,602.38 gal	1,260,444.03 gal
G. Annual cost savings ((E/60)*$1988/hour + F*$2.08 per gallon)	$0.00	$10,755,947.13	$4,085,284.54
H. Annual cost savings (all flight lengths)	$14,841,231.67		
I. Number of aircraft of this type	207		
J. Annual cost savings per aircraft	$71,696.77/aircraft		

Table 69. Southwest Airways Boeing_737-700/700LR/Max_7 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	28.1184 gal/flight	54.7872 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	768,436	226,849	12,876
E. Annual time savings (A*D)	0.00 min	97,545.07 min	24,979.44 min
F. Annual fuel savings (C*D)	0.00 gal	6,378,630.92 gal	705,439.99 gal
G. Annual cost savings ((E/60)*$2732/hour + F*$2.08 per gallon)	$0.00	$17,709,104.50	$2,604,712.35
H. Annual cost savings (all flight lengths)	$20,313,816.85		
I. Number of aircraft of this type	513		
J. Annual cost savings per aircraft	$39,598.08/aircraft		

Table 70. Southwest Airways Boeing_B737_Max_800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	24.8965 gal/flight	48.5095 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	11,948	14,510	2,278
E. Annual time savings (A*D)	0.00 min	6,239.30 min	4,419.32 min
F. Annual fuel savings (C*D)	0.00 gal	361,248.22 gal	110,504.64 gal
G. Annual cost savings ((E/60)*$1891/hour + F*$2.08 per gallon)	$0.00	$948,038.24	$369,131.89
H. Annual cost savings (all flight lengths)	$1,317,170.13		
I. Number of aircraft of this type	34		
J. Annual cost savings per aircraft	$38,740.30/aircraft		

F.8. Spirit Airlines (NK)

F.8.A. Spirit Airlines operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.15 per gallon

Table 71. Spirit Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Airbus_Industrie_A319 (698)	$2,151/hour	928 gallons/hour	1.02
Airbus_Industrie_A321 (699)	$2,152/hour	929 gallons/hour	1.02

F.8.B. Spirit Airlines summary plots

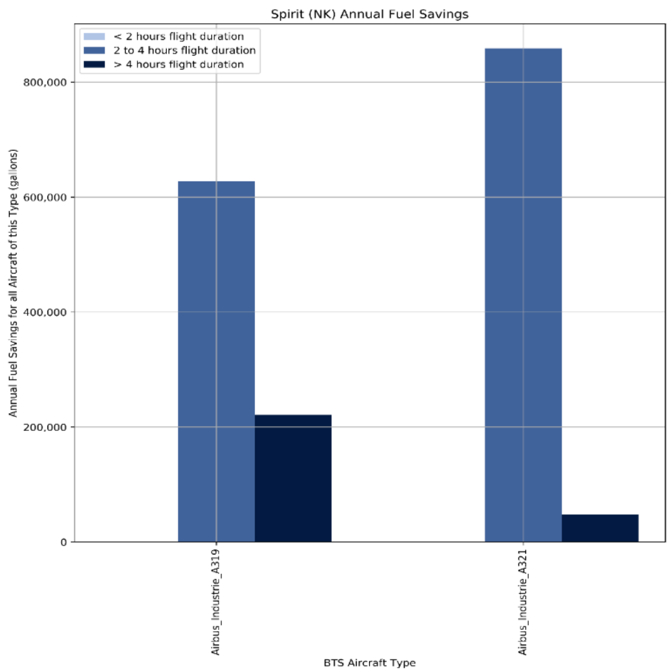

Figure 57. Spirit Airlines fleet-wide annual fuel savings by aircraft type.

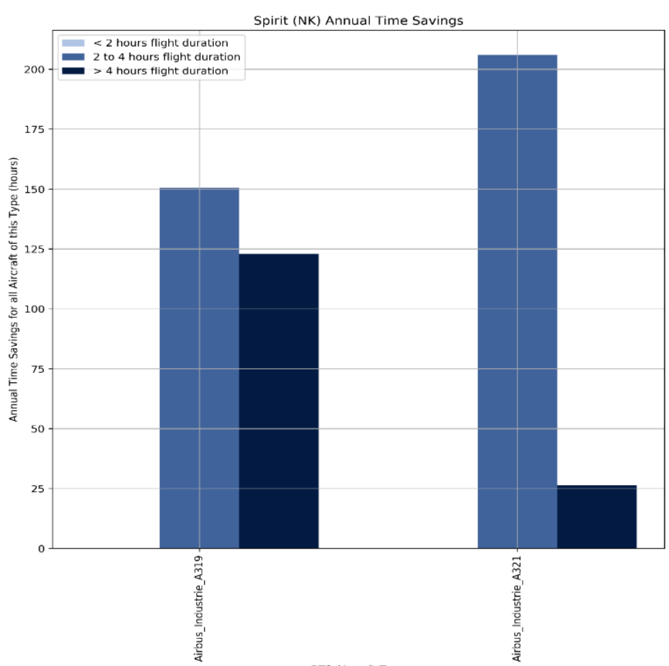

Figure 58. Spirit Airlines fleet-wide annual time savings by aircraft type.

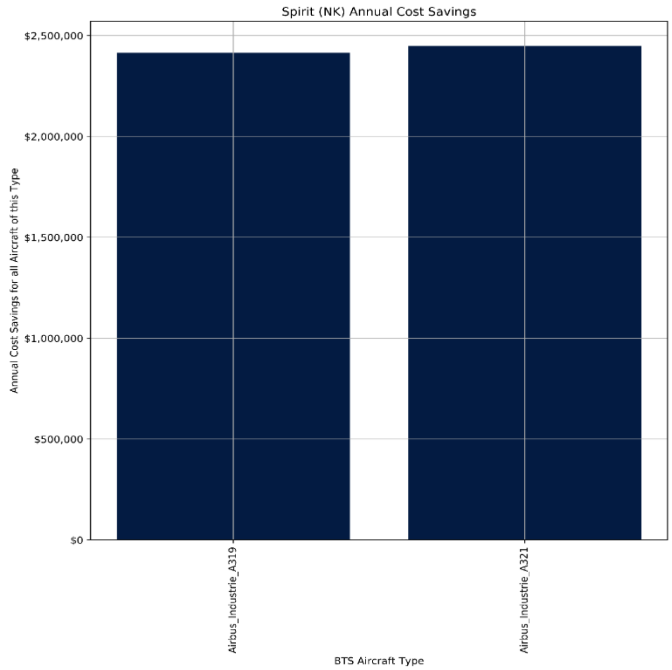

Figure 59. Spirit Airlines fleet-wide annual cost savings by aircraft type.

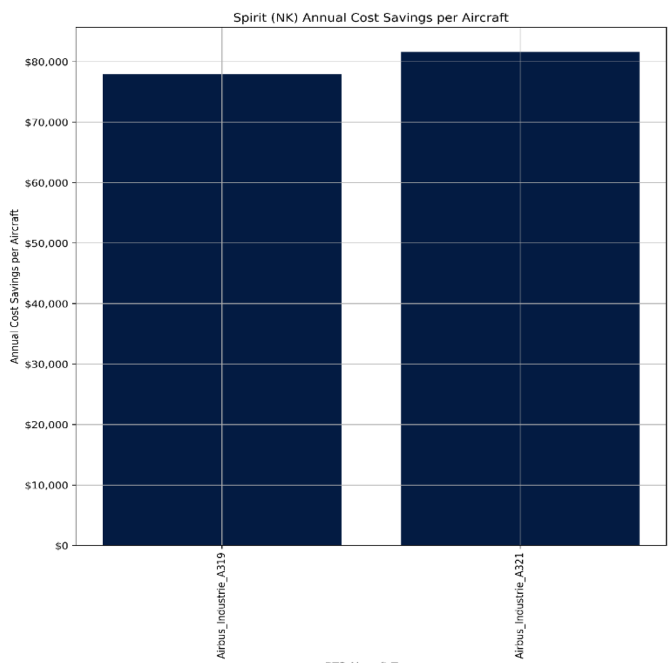

Figure 60. Spirit Airlines annual cost savings per aircraft by aircraft type.

F.8.C. Spirit Airlines benefit calculation tables

Table 72. Spirit Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	29.8758 gal/flight	58.2114 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	17,662	21,025	3,805
E. Annual time savings (A*D)	0.00 min	9,040.75 min	7,381.70 min
F. Annual fuel savings (C*D)	0.00 gal	628,138.70 gal	221,494.38 gal
G. Annual cost savings ((E/60)*$2151/hour + F*$2.15 per gallon)	$0.00	$1,674,609.09	$740,846.86
H. Annual cost savings (all flight lengths)	$2,415,455.95		
I. Number of aircraft of this type	31		
J. Annual cost savings per aircraft	$77,917.93/aircraft		

Table 73. Spirit Airlines Airbus_Industrie_A321 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	29.8758 gal/flight	58.2114 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	9,204	28,737	817
E. Annual time savings (A*D)	0.00 min	12,356.91 min	1,584.98 min
F. Annual fuel savings (C*D)	0.00 gal	858,540.86 gal	47,558.71 gal
G. Annual cost savings ((E/60)*$2152/hour + F*$2.15 per gallon)	$0.00	$2,289,064.02	$159,099.18
H. Annual cost savings (all flight lengths)	$2,448,163.20		
I. Number of aircraft of this type	30		
J. Annual cost savings per aircraft	$81,605.44/aircraft		

F.9. Sun Country (SY)

F.9.A. Sun Country operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.43 per gallon

Table 74. Sun Country aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_737-700/700LR/Max_7 (612)	$2,509/hour	745 gallons/hour	0.82
Boeing_737-800 (614)	$2,304/hour	852 gallons/hour	0.93

F.9.B. Sun Country summary plots

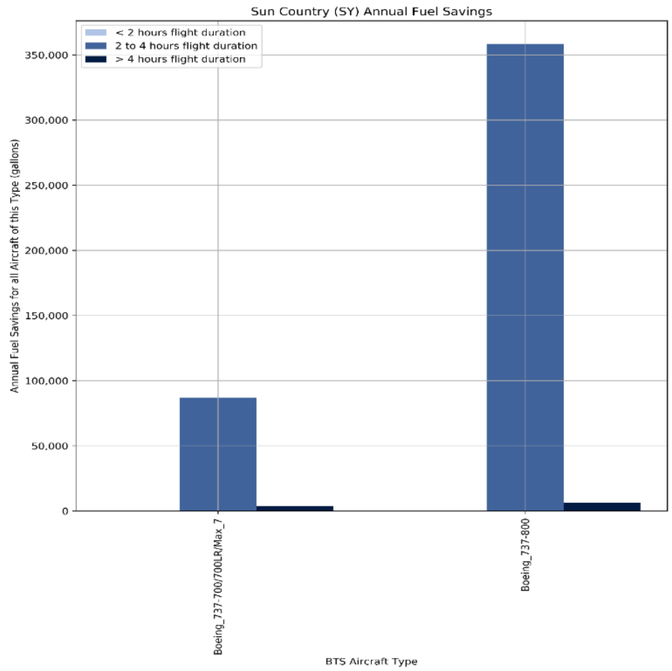

Figure 61. Sun Country fleet-wide annual fuel savings by aircraft type.

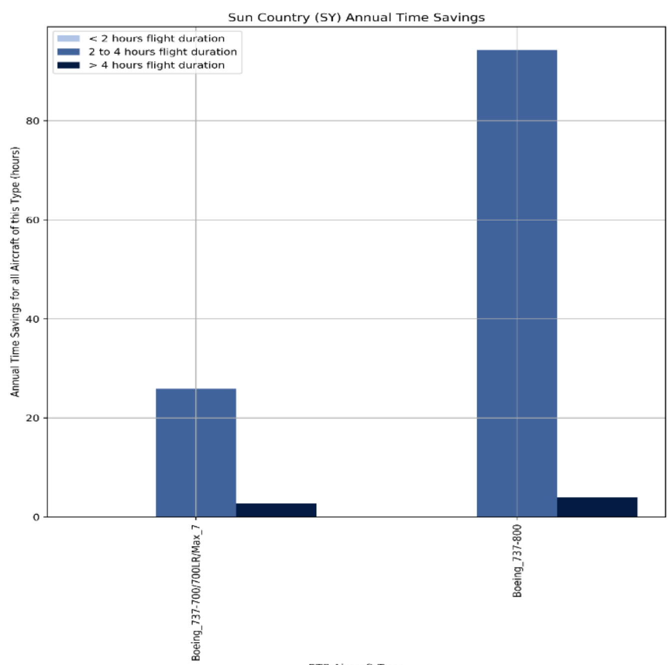

Figure 62. Sun Country fleet-wide annual time savings by aircraft type.

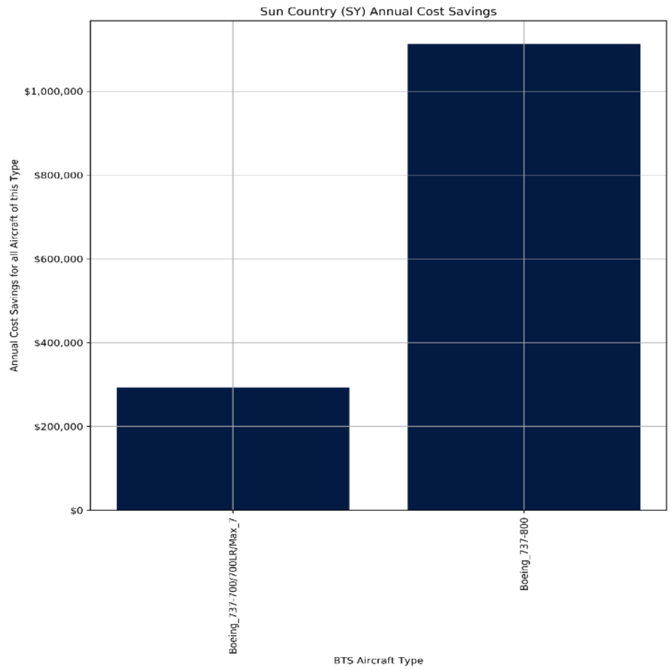

Figure 63. Sun Country fleet-wide annual cost savings by aircraft type.

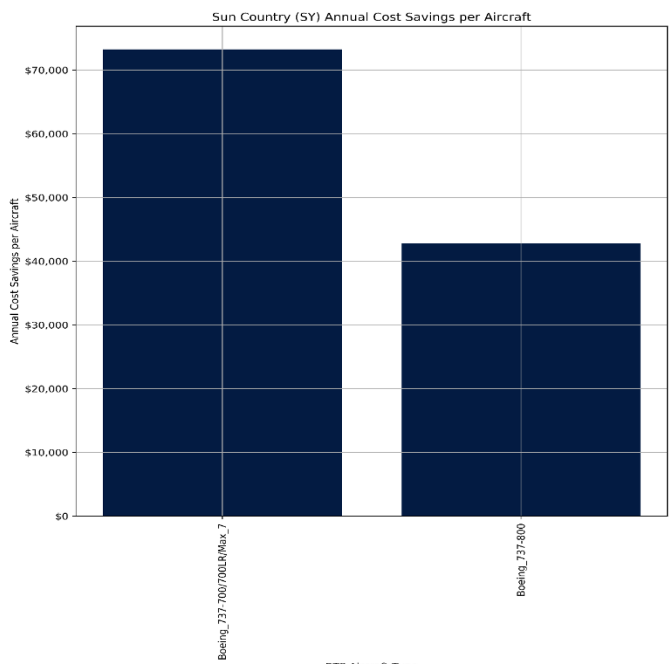

Figure 64. Sun Country annual cost savings per aircraft by aircraft type.

F.9.C. Sun Country benefit calculation tables

Table 75. Sun Country Boeing_737-700/700LR/Max_7 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	24.0178 gal/flight	46.7974 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,116	3,622	84
E. Annual time savings (A*D)	0.00 min	1,557.46 min	162.96 min
F. Annual fuel savings (C*D)	0.00 gal	86,992.47 gal	3,930.98 gal
G. Annual cost savings ((E/60)*$2509/hour + F*$2.43 per gallon)	$0.00	$276,519.49	$16,366.73
H. Annual cost savings (all flight lengths)	$292,886.22		
I. Number of aircraft of this type	4		
J. Annual cost savings per aircraft	$73,221.55/aircraft		

Table 76. Sun Country Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	27.2397 gal/flight	53.0751 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,726	13,155	122
E. Annual time savings (A*D)	0.00 min	5,656.65 min	236.68 min
F. Annual fuel savings (C*D)	0.00 gal	358,338.25 gal	6,475.16 gal
G. Annual cost savings ((E/60)*$2304/hour + F*$2.43 per gallon)	$0.00	$1,087,977.31	$24,823.15
H. Annual cost savings (all flight lengths)	$1,112,800.46		
I. Number of aircraft of this type	26		
J. Annual cost savings per aircraft	$42,800.02/aircraft		

F.10. United Airlines (UA)

F.10.A. United Airlines operating costs calculated from BTS data

Average fuel cost used in benefit calculations: $2.16 per gallon

Table 77. United Airlines aircraft direct operating costs (excluding fuel) and fuel savings multiplier that adjusts for different fuel burn rates.

Aircraft Type (BTS Code)	Hourly Direct Operating Cost Excluding Fuel ($/hour)	Average Fuel Burn Rate (gallons/hour)	Ratio to Alaska 737-900ER Average Fuel Burn Rate
Boeing_737-700/700LR/Max_7 (612)	$2,635/hour	732 gallons/hour	0.80
Boeing_737-800 (614)	$2,539/hour	815 gallons/hour	0.89
Boeing_B737_Max_900 (839)	$1,956/hour	725 gallons/hour	0.79
Boeing_767-300/300ER (626)	$4,009/hour	1,600 gallons/hour	1.75
Boeing_777-200ER/200LR/233LR (627)	$4,753/hour	2,221 gallons/hour	2.44
B787-800_Dreamliner (887)	$3,854/hour	1,568 gallons/hour	1.72
Boeing_737-900ER (888)	$1,889/hour	850 gallons/hour	0.93
B787-900_Dreamliner (889)	$3,757/hour	1,748 gallons/hour	1.92
Airbus_Industrie_A319 (698)	$2,626/hour	743 gallons/hour	0.81
Boeing_777-300/300ER/333ER (637)	$3,693/hour	2,548 gallons/hour	2.79

F.10.B. United Airlines summary plots

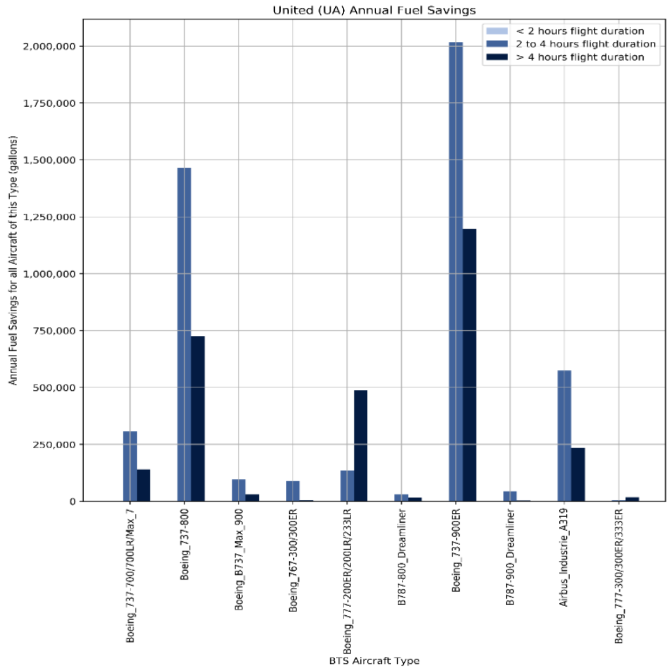

Figure 65. United Airlines fleet-wide annual fuel savings by aircraft type.

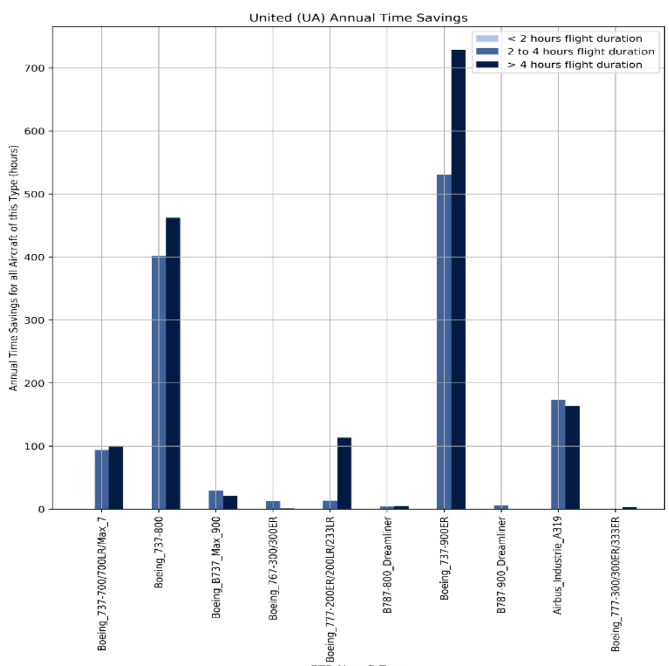

Figure 66. United Airlines fleet-wide annual time savings by aircraft type.

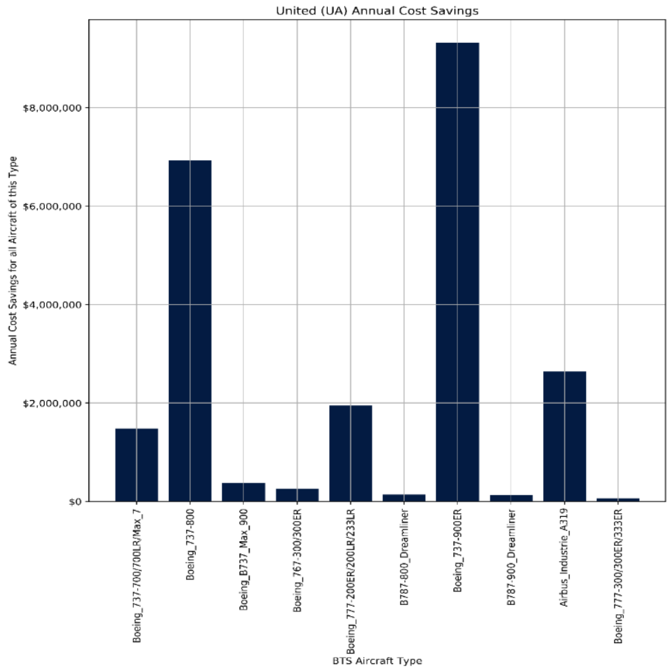

Figure 67. United Airlines fleet-wide annual cost savings by aircraft type.

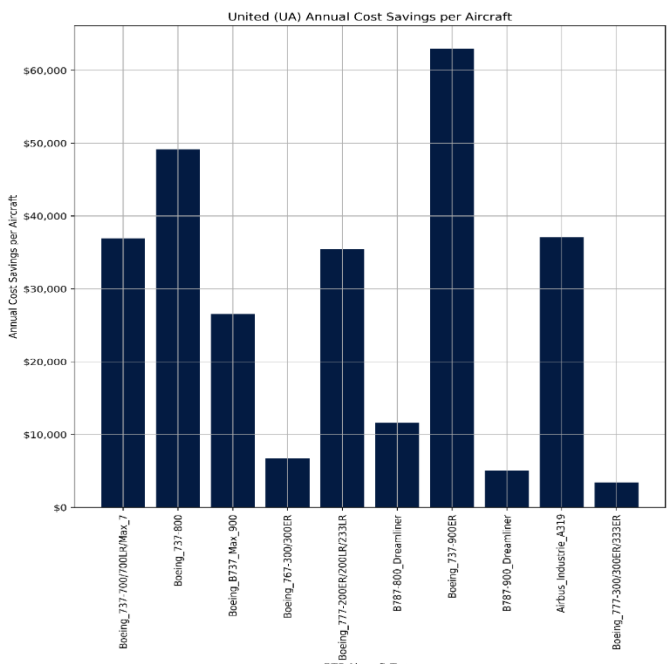

Figure 68. United Airlines annual cost savings per aircraft by aircraft type.

F.10.C. United Airlines benefit calculation tables

Table 78. United Airlines Boeing_737-700/700LR/Max_7 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	23.4320 gal/flight	45.6560 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	20,105	13,094	3,087
E. Annual time savings (A*D)	0.00 min	5,630.42 min	5,988.78 min
F. Annual fuel savings (C*D)	0.00 gal	306,818.61 gal	140,940.07 gal
G. Annual cost savings ((E/60)*$2635/hour + F*$2.16 per gallon)	$0.00	$909,997.48	$567,437.81
H. Annual cost savings (all flight lengths)	$1,477,435.29		
I. Number of aircraft of this type	40		
J. Annual cost savings per aircraft	$36,935.88/aircraft		

Table 79. United Airlines Boeing_737-800 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	26.0681 gal/flight	50.7923 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	58,363	56,135	14,306
E. Annual time savings (A*D)	0.00 min	24,138.05 min	27,753.64 min
F. Annual fuel savings (C*D)	0.00 gal	1,463,332.79 gal	726,634.64 gal
G. Annual cost savings ((E/60)*$2539/hour + F*$2.16 per gallon)	$0.00	$4,182,240.64	$2,743,972.36
H. Annual cost savings (all flight lengths)	$6,926,213.00		
I. Number of aircraft of this type	141		
J. Annual cost savings per aircraft	$49,122.08/aircraft		

Table 80. United Airlines Boeing_B737_Max_900 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	23.1391 gal/flight	45.0853 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	2,094	4,158	657
E. Annual time savings (A*D)	0.00 min	1,787.94 min	1,274.58 min
F. Annual fuel savings (C*D)	0.00 gal	96,212.38 gal	29,621.04 gal
G. Annual cost savings ((E/60)*$1956/hour + F*$2.16 per gallon)	$0.00	$266,105.58	$105,532.75
H. Annual cost savings (all flight lengths)	$371,638.33		
I. Number of aircraft of this type	14		
J. Annual cost savings per aircraft	$26,545.60/aircraft		

Table 81. United Airlines Boeing_767-300/300ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	51.2575 gal/flight	99.8725 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	97	1,743	36
E. Annual time savings (A*D)	0.00 min	749.49 min	69.84 min
F. Annual fuel savings (C*D)	0.00 gal	89,341.82 gal	3,595.41 gal
G. Annual cost savings ((E/60)*$4009/hour + F*$2.16 per gallon)	$0.00	$243,056.75	$12,432.56
H. Annual cost savings (all flight lengths)	$255,489.31		
I. Number of aircraft of this type	38		
J. Annual cost savings per aircraft	$6,723.40/aircraft		

Table 82. United Airlines Boeing_777-200ER/200LR/233LR annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	71.4676 gal/flight	139.2508 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	1,655	1,898	3,502
E. Annual time savings (A*D)	0.00 min	816.14 min	6,793.88 min
F. Annual fuel savings (C*D)	0.00 gal	135,645.50 gal	487,656.30 gal
G. Annual cost savings ((E/60)*$4753/hour + F*$2.16 per gallon)	$0.00	$357,646.17	$1,591,526.14
H. Annual cost savings (all flight lengths)	$1,949,172.31		
I. Number of aircraft of this type	55		
J. Annual cost savings per aircraft	$35,439.50/aircraft		

Table 83. United Airlines B787-800_Dreamliner annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	50.3788 gal/flight	98.1604 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	52	612	165
E. Annual time savings (A*D)	0.00 min	263.16 min	320.10 min
F. Annual fuel savings (C*D)	0.00 gal	30,831.83 gal	16,196.47 gal
G. Annual cost savings ((E/60)*$3854/hour + F*$2.16 per gallon)	$0.00	$83,500.40	$55,545.47
H. Annual cost savings (all flight lengths)	$139,045.87		
I. Number of aircraft of this type	12		
J. Annual cost savings per aircraft	$11,587.16/aircraft		

Table 84. United Airlines Boeing_737-900ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	27.2397 gal/flight	53.0751 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	61,304	74,043	22,540
E. Annual time savings (A*D)	0.00 min	31,838.49 min	43,727.60 min
F. Annual fuel savings (C*D)	0.00 gal	2,016,909.11 gal	1,196,312.75 gal
G. Annual cost savings ((E/60)*$1889/hour + F*$2.16 per gallon)	$0.00	$5,358,905.47	$3,960,726.15
H. Annual cost savings (all flight lengths)	$9,319,631.62		
I. Number of aircraft of this type	148		
J. Annual cost savings per aircraft	$62,970.48/aircraft		

Table 85. United Airlines B787-900_Dreamliner annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	**2 to 4 hours**	**4+ hours**
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	56.2368 gal/flight	109.5744 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	38	780	28
E. Annual time savings (A*D)	0.00 min	335.40 min	54.32 min
F. Annual fuel savings (C*D)	0.00 gal	43,864.70 gal	3,068.08 gal
G. Annual cost savings ((E/60)*$3757/hour + F*$2.16 per gallon)	$0.00	$115,749.38	$10,028.39
H. Annual cost savings (all flight lengths)	$125,777.77		
I. Number of aircraft of this type	25		
J. Annual cost savings per aircraft	$5,031.11/aircraft		

Table 86. United Airlines Airbus_Industrie_A319 annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	23.7249 gal/flight	46.2267 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	60,386	24,245	5,066
E. Annual time savings (A*D)	0.00 min	10,425.35 min	9,828.04 min
F. Annual fuel savings (C*D)	0.00 gal	575,210.20 gal	234,184.46 gal
G. Annual cost savings ((E/60)*$2626/hour + F*$2.16 per gallon)	$0.00	$1,698,736.85	$935,978.98
H. Annual cost savings (all flight lengths)	$2,634,715.83		
I. Number of aircraft of this type	71		
J. Annual cost savings per aircraft	$37,108.67/aircraft		

Table 87. United Airlines Boeing_777-300/300ER/333ER annual benefit calculations.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
A. TAP time savings per flight	0.0 min/flight	0.43 min/flight	1.94 min/flight
B. TAP fuel savings per flight (unadjusted)	0.0 gal/flight	29.29 gal/flight	57.07 gal/flight
C. TAP fuel savings per flight (adjusted by ratio to Alaska 737-900ER fuel burn rate)	0.0000 gal/flight	81.7191 gal/flight	159.2253 gal/flight
D. Annual flights across air carrier fleet of this aircraft type	50	62	107
E. Annual time savings (A*D)	0.00 min	26.66 min	207.58 min
F. Annual fuel savings (C*D)	0.00 gal	5,066.58 gal	17,037.11 gal
G. Annual cost savings ((E/60)*$3693/hour + F*$2.16 per gallon)	$0.00	$12,584.74	$49,576.71
H. Annual cost savings (all flight lengths)	$62,161.45		
I. Number of aircraft of this type	18		
J. Annual cost savings per aircraft	$3,453.41/aircraft		

Appendix G: TAP Stand-alone Preliminary Benefit Estimation Methodology

Alaska Airlines markets and flight plan routes differ from regions and routes flown by other airlines. The achieved benefits data that was used to generate the Appendix F annualized benefits results is restricted to the routes actually flown during the operational evaluation and may not accurately represent the fuel and time benefits achievable between other city pairs and regions of the US. To partially mitigate this limitation, the TAP optimization algorithm can be exercised in a stand-alone condition to obtain TAP benefit opportunity estimates between different city pairs, effectively acting as an alternative data source for TAP benefit estimations. The method produces idealized opportunity benefits data similar to Appendix D and then scales the benefits to account for factors addressed by the baseline flights (e.g. ATC and pilot actions independent of TAP).

Preliminary fast-time simulation benefits assessments were conducted in 2012 and 2014 to estimate the benefit of equipping: (1) a generic airline with TAP[11], (2) Alaska Airlines aircraft[8], and (3) Virgin America aircraft[12]. The simulation platform, adapted to estimate TASAR benefits, contained the nine types of models shown in the left column of Table 88. The right column of this table describes how to achieve similar functionality using the TAP stand-alone optimization algorithm executable. Instructions to use the executable, which is named cr_test.exe and runs with an XML input file, are included after Table 88. It is assumed that an existing XML input file is used as a starting point and modified. The XML input file is named AOP_TapOptimizationTask_yyyymmdd_hhmmss.xml.

Table 88. Preliminary benefits assessment models.

Model	Stand-alone TAP optimization algorithm discussion

1. Simulation: Traffic Generation	Historical ownship state, ownship route, and ADS-B traffic states are specified in the XML input file.
	
	Ownship state is defined at the following element hierarchy:
	- IntentResolutionProcessingRequestMessage
	    - cd_result
	        - ownship
	            - state
	                - time
	
	The following state attributes are required to be set within the "state" element:
	- latitude: ownship latitude. e.g., 34.087104
	- longitude: ownship longitude. e.g., -114.737836
	- altitude: ownship altitude (ft). e.g., 35000.0
	- TAS: ownship true airspeed (knots), e.g., 443.875
	- V_rate: ownship vertical rate (feet/minute), e.g., -0.125
	- groundspeed: ownship groundspeed (knots), e.g., 471.625
	- mach: ownship Mach, e.g., 0.781
	- track_mag: ownship track angle magnetic (degrees), e.g., 0.0
	- track_true: ownship track angle true (degrees), e.g., 72.206742
	- heading_mag: ownship magnetic heading (degrees), e.g., 0.0
	- CAS: ownship computed airspeed (knots). e.g., 254.716406
	- weight: ownship gross weight (pounds). e.g., 173640.0
	- max_altitude: ownship maximum achievable altitude at weight (feet), e.g., 37000.0
	- zero_fuel_weight: ownship weight excluding fuel (pounds). e.g., 138000.0
	
	The "time" element is a child of the "state" element and has the following required UTC attributes:
	- year: e.g., 2019

Model	Stand-alone TAP optimization algorithm discussion

	- month: e.g., 4
	- day: e.g., 3
	- hour: e.g., 16
	- minute: e.g., 3
	- second: e.g., 14.0
	
	Ownship route is defined at the following element hierarchy:
	- IntentResolutionProcessingRequestMessage
	    - cd_result
	        - ownship
	            - intent
	                - route
	                    - waypoint
	
	The following “route” element attributes are required to be set:
	- cost_index: Ownship cost index. e.g., 67
	- cruise_altitude: Current target cruise altitude (feet). e.g., 35000.0
	
	The “waypoint” elements are children of the route element and have the following required attributes that need to be set:
	- acms: 3 or 5 letter waypoint identifier. e.g., KA24O
	- latitude: waypoint latitude. e.g., 34.0
	- longitude: waypoint longitude. e.g., -112.0
	- inbound_true_course: inbound course at the waypoint (degrees). e.g., 93.377214
	- outbound_true_course: outbound course at the waypoint (degrees). e.g., 89.44077
	
	ADS-B traffic aircraft (optional) are defined at the following element hierarchy:
	- IntentResolutionProcessingRequestMessage
	    - cd_result
	        - traffic
	            - state
	
	The aircraft identification (ACID) attribute of the “traffic” element defines the ADS-B traffic aircraft identifier (e.g., AAL10). The traffic element has a “state” element child. This state element has the same required attributes as the ownship state element.

2. Simulation: Trajectory Synthesizer	A TAP aircraft performance model for the ownship is required to run cr_test.exe. The model is set using the aircraft_type attribute of the ownship element (e.g., B737_900ERW_bada).
	
	ADS-B traffic are predicted using state projection and do not require aircraft performance models for these aircraft.
	
	Wind is defined at the following hierarchy in the XML file to support TAP aircraft trajectory predictions:
	- IntentResolutionProcessingRequestMessage
	    - cd_result
	        - atmosphere
	            - latitude

<table>
<tr><th>Model</th><th>Stand-alone TAP optimization algorithm discussion</th></tr>
<tr><td></td><td>
element
longitude
element
altitude
element
speeds
slice
row
element
directions
slice
row
element
temperature
slice
row
element
There is one latitude element per atmosphere element. The latitude element attribute “units” is always set to “Degree.” The “value” attribute of the element children of latitude define the latitude coordinates of the wind grid. There is similarly one longitude element per atmosphere element with children that define the longitude coordinates of the wind grid. The longitude element attribute “units” is always set to “Degree.”
The altitude element defines the altitude slices of the wind grid. The altitude element attribute “units” is always set to “Feet.”
The data within the speeds, directions, and temperatures elements are indexed as follows. The i^{th} “slice” sub element to each of speeds, direction, and temperature corresponds to the i^{th} latitude. The j^{th} “row” sub element to the “slice” element corresponds to the j^{th} longitude. The k^{th} “element” sub element to the “row” element corresponds to the k^{th} altitude.
Speeds are in units of feet per second. However, this was not implemented in the XML format so the “units” attribute is set to “unity.” Similarly, direction are in units of degrees from North (-180^{o} to 180^{o}) and temperature are in units of Rankine but both their “units” attributes are set to “unity.”
</td></tr>
<tr><td>3. Aircrew Model: Airborne Surveillance</td><td>
This model, along with the controller model described in #7, was used to account for different knowledge of traffic between the ground and the air during the 2012 and 2015 studies.
For benefit purposes it can be assumed that the ground and air have the same traffic aircraft knowledge due to the approaching ADS-B mandate deadline.
There are no required changes to the XML input file to implement this model.
</td></tr>
<tr><td>4. Aircrew Model: Probe for Aircraft-</td><td>
Ownship probes for Aircraft-Aircraft conflicts and Aircraft-Weather conflicts are performed automatically by cr_test.exe and do not require changes to the XML input file.
Weather and SUAs are defined at the following hierarchy in the XML file:
</td></tr>
</table>

Model	Stand-alone TAP optimization algorithm discussion

Aircraft and Aircraft-Weather Conflicts	- IntentResolutionProcessingRequestMessage
	    - cd_result
	        - area
	            - model
	                - polygon
	                    - Nodes
	                        - Node
	            - activation_start
	            - activation_end
	
	There is one “area” element per weather or SUA polygon. The following are required attributes.
	- class: either “STATIC” or “TIME_VARIANT”
	- id: sequential integer with one id per area. e.g., 1002009
	
	There is one “model” element per “area” element. The following are required attributes.
	- class: always “POLYGON”
	- hazard_id: alphanumeric hazard identifier that is required to be set but does not influence optimization or conflict detection. e.g., 2102C
	- type: either “AIRSPACE” or “WEATHER”
	- severity: always “ZERO”
	
	There is one “polygon” element per “model” element that is used to set the minimum and maximum altitude extents of the hazard using the following two attributes:
	- MinAltitude: Hazard floor (feet). e.g., 12000.0
	- MaxAltitude: Hazard ceiling (feet), e.g., 30000.0
	
	There is one “Nodes” element per “polygon” element. The “Nodes” element has multiple “Node” element children that correspond to the polygon vertices. The following “Node” element attributes are required:
	- latitude: latitude of the node (degrees). e.g., 34.644444
	- longitude: longitude of the node (degrees). e.g., -86.716667
	
	If the area element class is “TIME_VARIANT” then there will be activation_start and activation_end elements with the following required UTC attributes:
	- year: e.g., 2019
	- month: e.g., 4
	- day: e.g., 3
	- hour: e.g., 16
	- minute: e.g., 3
	- second: e.g., 14.0

5. Aircrew Model: Alternative Trajectory Generation / Optimization	The 2012 and 2015 studies used a simplified model to generate optimization advisories. This was due to (1) TAP not yet being developed in 2012 and (2) the reduced input data requirements corresponding to the fast-time simulation model as compared to TAP. The cr_test.exe stand-alone optimizer uses the actual TAP optimization algorithm and therefore represents an improvement in this area relative to the earlier benefit studies.

Model	Stand-alone TAP optimization algorithm discussion
	Optimization is performed when launching cr_test.exe, which is described following this table.
6. Aircrew Model: TASAR Request	The 2012 and 2015 studies leveraged a fast-time simulation platform that periodically generated TAP advisories for the aircrew to request to ATC. This is in contrast to cr_test.exe which generates TAP advisories at a specific instance in time. It is suggested that TAP advisories be generated periodically throughout the flight, for example, at a rate of one set of advisories per sector or at a predefined time interval (i.e., every 30 minutes). A new XML input file that contains updated ownship state, ownship route, and ADS-B traffic at each advisory generation time instance is required to represent different conditions during flight progress. The fast-time simulation platform had functionality to prevent requests during situations that reduce ATC approvability including: multiple requests per sector, aircraft in handoff status, and aircraft within destination airport arrival route. It is suggested that these conditions be evaluated for each advisory generation time instance prior to running cr_test.exe and a decision be made whether to create a new XML input file to evaluate potential for flight optimization.
7. Controller Model: Ground Surveillance	For benefit purposes it can be assumed that the ground and air have the same traffic aircraft knowledge due to the approaching ADS-B mandate deadline. No changes to the XML input file are required to implement a controller surveillance model.
8. Probe for Aircraft-Aircraft Conflicts	No changes to the XML input file are required to implement a probe for aircraft-aircraft conflicts.
9. TASAR Request Evaluation Model	The 2012 and 2015 studies modelled the aircrew as not making requests that were less likely to be approvable. One aspect that was known to the controller but not the aircrew was airspace congestion when predicted demand for airspace resources exceeds capacity. The stand-alone cr_test.exe does not model airspace congestion. Instead, it is suggested to not generate TAP advisories (i.e., not create the input XML file) in congestion airspace such as New York and Cleveland Air Route Traffic Control Centers (ARTCCs).

G.1. Building and running stand-alone TAP optimization executable (cr_test.exe)

Building and running cr_test.exe on a Windows platform is described next.

G.1.A. Step 1: Build TAP

Build TAP using standard TAP build scripts. The cr_test.exe executable will also be created.

G.1.B. Step 2: Set AOP_CONFIG Environment Variable

The TAP build will contain a filed named “SetConfigOptions.bat” at “\aop\tools\SetConfigOptions.bat.” Running this file will set an Environment variable named AOP_CONFIG.

AOP_CONFIG sets the –c (configuration path), -cp (common path), and –dp (data path) cr_test.exe command line options used by the tap_optimize.bat launch script.

e.g., “AOP_CONFIG= -c ..\aop\tools\config -cp Common -dp ..\aop\tools\AATTData”

G.1.C. Step 3: Create Input File

Obtain an existing AOP_TapOptimizationTask_yyyymmdd_hhmmss.bin file that was created using the same version of TAP as cr_test to use as a starting point with an up-to-date file format. Convert this file to XML format using the dump argument to cr_test.exe:

i.e., cr_test.exe AOP_TapOptimizationTask_yyyymmdd_hhmmss.bin –dump AOP_TapOptimizationTask_yyyymmdd_hhmmss.xml

Remove all IntentResolutionProcessingRequestMessage XML elements and their children except the first IntentResolutionProcessingRequestMessage. This is done because there may be multiple optimization calls within a single file and we want to only run and edit the first optimization. Then create inputs according to the description in Table 88.

G.1.D. Step 4: Run Launch Script

Set the –actype parameter on line 25 in tap_optimize.bat in .".\aop\tools\test_pbga\tap_optimize.bat" to match the aircraft_type attribute of the ownship element described in Simulation: Trajectory Synthesizer row (model item 2) in Table 88.

Run tap_optimize.bat using the input XML file as the only command line argument.
i.e., tap_optimize.bat AOP_TapOptimizationTask_yyyymmdd_hhmmss.xml

G.1.E. Step 5: Process Output Data

Output files will be created in the .".\aop\output" and .".\aop\output\Data" folders. The pattern_test_yyyy-mm-dd_hh-mm-ss.dat file in the .".\aop\output\Data" folder contains the results in a binary format. Use the TAP data_translator.exe file from the command line to extract the data into CSV format.
i.e., data_translator.exe pattern_test_yyyy-mm-dd_hh-mm-ss.dat

A file named "AopStrategicReplanningCandidateDataRecord.csv" will be created containing the results of the optimization. Table 89 describes the fields in this file. The header rows contain the predicted fuel and time benefits used during the estimation. The header row containing the optimal result is identified using a unique chromosome identifier that is in "AopStrategicReplanningGenerationDataRecord.csv" and described in Table 90.

Table 89. AopStrategicReplanningCandidateDataRecord column field descriptions. Fuel and time results are included in a header line followed by the advisory route below the header.

Column Number (1 = leftmost column)	Field Label	Description
1 (Header)	Source	Always "AOP"
8 (Header)	Population	Specifies the optimization type. Options are HybridExhaustive (combo), Hybrid (combo), LateralExhaustive (lateral), Lateral (lateral), VerticalExhaustive (vertical), and Vertical (vertical).
9 (Header)	ChromosomeID	Unique solution identifier. AopStrategicReplanningGenerationDataRecord specifies the ChromosomeID corresponding to the selected solution. This data record is described next.
12 (Header)	FuelIncrease	Fuel difference in units of pounds. Negative values indicate a benefit.

Column Number (1 = leftmost column)	Field Label	Description
13 (Header)	TimeIncrease	Time difference in units of seconds. Negative values indicate a benefit.
1	WaypointType	Either “WAYPOINT” or “RECONNECT.” All waypoints are labelled “WAYPOINT” except the rejoin waypoint (lateral, combo advisories) and waypoint after climb (vertical advisories) are labelled “RECONNECT.”
2	WaypointName	3 or 5 letter waypoint identifier.
3	Latitude	Waypoint latitude
4	Longitude	Waypoint longitude
5	ConstraintType	Equals “STEP” at the waypoint where the climb will occur for combo and vertical advisories.
6	ConstraintValue	Combo and vertical advisory altitude in feet (e.g., 33000)

Table 90. AopStrategicReplanningGenerationDataRecord column field descriptions.

Column Number (1 = leftmost column)	Field Label	Description
1	Source	Always “AOP”
8	Population	Specifies the optimization type. Options are HybridExhaustive (combo), Hybrid (combo), LateralExhaustive (lateral), Lateral (lateral), VerticalExhaustive (vertical), and Vertical (vertical).
9	GenerationNumber	The row with the maximum generation number for each of the combo, lateral, and vertical advisory types contain the final chromosome identifier.
11	Chromosome	Unique solution identifier. Corresponds to ChromosomeID in AopStrategicReplanningCandidateDataRecord.

G.1.F. Step 6: Create and Run Additional Input Files

To simulate TAP request generation at multiple locations during the flight, as was described in the Aircrew Model: TASAR Request row (model item 6) in Table 88, multiple input XML files are created and run using the procedures described in Steps 4, 5, and 6.

One approach could be to generate input XML files at a set time interval (e.g., 30 minutes). Another approach could be distance-based (e.g., every 250 nmi). In either case, the ownship state to be used in the input XML file is obtained from the advisory trajectory prediction described next.

While the initial ownship state in the input XML file is obtained from historical data, subsequent locations will be obtained from the trajectory prediction corresponding to the selected advisory. The selected advisory is identified by the ChromosomeID field in Table 89 and the Chromosome field in Table 90. The trajectory prediction is in “AopStrategicReplanningTrajectoryDataRecord.csv” and described in Table 91. The ChromosomeID field in the header is used to identify the trajectory prediction corresponding to the selected advisory.

Table 91. AopStrategicReplanningTrajectoryDataRecord column field descriptions. Chromosome identifier is included in a header line followed by the predicted trajectory below the header.

Column Number (1 = leftmost column)	Field Label	Description
1 (Header)	Source	Always “AOP.”

Column Number (1 = leftmost column)	Field Label	Description
8 (Header)	Population	Specifies the optimization type. Options are HybridExhaustive (combo), Hybrid (combo), LateralExhaustive (lateral), Lateral (lateral), VerticalExhaustive (vertical), and Vertical (vertical).
9 (Header)	ChromosomeID	Unique solution identifier.
1	Timestamp	Predicted time to reach location when following advisory route.
2	Latitude	Latitude of location being predicted. Generally does not correspond with a route waypoint location.
3	Longitude	Longitude of location being predicted. Generally does not correspond with a route waypoint location.
4	Altitude	Predicted altitude, in units of feet, at the latitude longitude location.
7	Mach	Predicted Mach at the latitude longitude location. Mach is sensitive to the cost_index parameter set in the input XML file and described in Table 88.
8	CAS	Predicted CAS, in units of knots, at the latitude longitude location.
9	TAS	Predicted true airspace, in units of knots, at the latitude longitude location.
10	GroundSpeed	Predicted groundspeed, in units of knots, at the latitude longitude location.
11	VerticalSpeed	Predicted vertical rate, in units of feet per minute, at the latitude longitude location.
12	Weight	Predicted gross aircraft weight, in units of pounds, at the latitude longitude location.

G.2. Data Sources

Table 92 summarizes the data sources used to populate the input XML file corresponding to Step 3 above. Only flights scheduled to be operated using Boeing 737 aircraft (and preferably operated by 737-900ER aircraft) were sampled to be consistent with the aircraft performance model used by TAP. The scheduled flights consisted of Alaska Airlines and non-Alaska Airlines operators.

Table 92. Summary of data sources used for preliminary benefit estimation.

Data Type	Source	Comments
Ownship states	Flightaware.com	Latitude, longitude, altitude, groundspeed, and time is available from Flightaware.com and used to populate the input XML file. Vertical rate was set to zero since ownship state was selected to correspond with level flight soon after top-of-climb. Track angle and heading were computed. TAS, Mach, CAS, and ownship weight were obtained from in-flight TAP-recorded data under similar conditions.
Ownship route	Flightaware.com	Latitude, longitude, and waypoint identifier (acms) is available from Flightaware.com and used to populate the input XML file. Inbound and outbound true course were calculated based on the location of the previous and next waypoints.

Data Type	Source	Comments
Wind and temperature	NOAA Rapid Refresh (RAP)	RAP data was downloaded from https://nomads.ncdc.noaa.gov/data/rap252/. U and V components of wind were converted to wind speed and direction using wgrib2. Wind and temperature from ten altitude levels from 364 ft to 51,806 ft were populated in the input XML file. Grid latitude was from 22ºN to 52ºN at 1.2 degree increments. Grid longitude was from 128ºW to 68ºW at 1.2º increments.
SUA geometry	TAP navigation database	The TAP navigation database (e.g., nav_db_USA.bin) can be extracted to an XML file using TAP's dump_input.exe utility. The boundary of each SUA, including floor and ceiling, was obtained from the database.
SUA schedule	EDS output data	The name and scheduled activation start and end times corresponding to SUAs that are not always active were obtained from the EDS_SUA_TAP__*.csv file generated by EDS. The selected SUA schedule file was chosen to be closest (by time) to the ownship state used to populate the XML input file.
Weather hazard avoidance polygons	EDS output data	The start and end times, floor, ceiling, and boundary nodes of weather hazard polygons were obtained from the EDS_WEATHER_TAP__*.csv file generated by EDS. The selected weather hazard polygon file was chosen to be closest (by time) to the ownship state used to populate the XML input file.

G.3. Scaling Factor

Not all of the benefits predicted by TAP are achievable. For this reason the ratio of the achieved benefits by flight length from Table 10 (top data row in Table 93) to the average in-flight TAP-predicted benefit by flight length was calculated as a scaling factor using operational evaluation data. The benefit predicted by TAP (middle data row in Table 93) was calculated as the maximum of lateral, vertical, and combo solutions using Stage 2 and 3 TAP-predicted benefits segregated by flight length. These TAP-predicted benefits were also the data source for the plots shown in Appendix D.2. The scaling factor, shown in the bottom row of Table 93, was applied to conservatively scale TAP-predicted benefits corresponding to other city pairs. Flights less than 2 hours did not benefit during the operational evaluation and are therefore not sampled and not scaled.

Table 93. Scaling factor by flight length derived from operational evaluation data.

Item	Flown Flight Length		
	0 to 2 hours	2 to 4 hours	4+ hours
Benefit per valid flight ($/flight)	-$25.59/flight	$78.99/flight	$185.49/flight
Benefit predicted by TAP ($/flight)	$282.72/flight	$374.97/flight	$543.30/flight
Scaling factor	-	0.21	0.34

G.4. Results by City Pair Group

Predicted benefits corresponding to twenty-seven city pairs are shown in no particular order in Table 94. Unscaled cost savings were obtained by multiplying fuel and time savings by $2.28/gallon and

$1,710/hour to be consistent with Section 2.5. Scaled cost savings were obtained by multiplying the unscaled cost savings by the scaling factor in Table 93, which was selected by flight length. Three rows of benefits are shown for each city pair. The first row corresponds to benefits in one flight direction. The second row corresponds to benefits in the opposite flight direction. The third row is a "Combined Average" where benefits are weighted by the number of flights sampled.

The location of the sampled twenty-seven city pairs are shown in Figure 69. The 2,202 sampled flights were analyzed during one of two time periods. The first time period occurred between June 11, 2019 and June 24, 2019. The second time period occurred between July 17, 2019 and July 29, 2019. In each case the input file was created to correspond to a location soon after top-of-climb where benefits are expected to be the highest.

The aggregate TAP-predicted benefits are the same order of magnitude as those estimated from the operational evaluation. However, there is variation between city pairs with certain city pairs experiencing higher or lower predicted benefits than the average. Flights from Baltimore (BWI) to San Francisco (SFO) resulted in higher predicted benefits (about $190/flight) than was experienced during the operational evaluation. Flights between Houston (IAH) and Los Angeles (LAX) are examples of lower predicted benefits (less than $5/flight) than was experienced during the operational evaluation. This is consistent with the achieved benefit results that showed longer flights (i.e., the SFO-BWI transcontinental flights) experienced higher benefits than the shorter flights (i.e., the LAX-IAH mid-continental flights).

Table 94. TAP-predicted fuel and time savings by city pair groupings, shown in no particular order. All flights sampled during June and July 2019.

City Pair	Origin Airport	Destination Airport	Number of Flights Sampled	Average Fuel Savings (gal)	Average Time Savings (min)	Unscaled Cost Savings ($/flight)	Scaling Factor	Scaled Cost Savings ($/flight)	Std Dev Scaled Cost Savings ($/flight)
1	BWI	SEA	57	77.86	5.62	$337.61	0.34	$114.79	$116.27
	SEA	BWI	49	63.11	4.71	$278.05	0.34	$94.54	$71.08
	Combined Average		106	71.04	5.2	$310.08	0.34	$105.43	$98.52
2	DCA	SEA	41	80.71	6.11	$358.22	0.34	$121.79	$134.71
	SEA	DCA	29	60.29	4.7	$271.40	0.34	$92.28	$89.52
	Combined Average		70	72.25	5.53	$322.25	0.34	$109.57	$119.00
3	EWR	SEA	39	86.17	6.42	$379.45	0.34	$129.01	$131.43
	SEA	EWR	40	108.69	8.3	$484.43	0.34	$164.71	$80.23
	Combined Average		79	97.58	7.37	$432.61	0.34	$147.09	$110.02
4	BOS	SEA	44	68.47	5.14	$302.63	0.34	$102.89	$77.99
	SEA	BOS	11	155.8	11.72	$689.14	0.34	$234.31	$126.95
	Combined Average		55	85.94	6.46	$379.93	0.34	$129.18	$104.17
5	LAX	BWI	46	65.1	4.94	$289.27	0.34	$98.35	$87.11
	BWI	LAX	38	53.99	4.02	$237.66	0.34	$80.80	$120.17
	Combined Average		84	60.07	4.52	$265.92	0.34	$90.41	$103.75
6	LAX	ATL	44	37.6	2.78	$164.99	0.34	$56.10	$50.35
	ATL	LAX	35	11.55	0.86	$50.87	0.34	$17.30	$34.33
	Combined Average		79	26.06	1.93	$114.43	0.34	$38.91	$48.02
7	LAX	BOS	6	25.93	1.95	$114.70	0.34	$39.00	$42.74
	BOS	LAX	7	99.6	7.16	$431.25	0.34	$146.63	$186.12
	Combined Average		13	65.6	4.76	$285.15	0.34	$96.95	$149.58
8	LAX	DTW	12	47.86	3.53	$209.63	0.34	$71.27	$83.73
	DTW	LAX	8	22.55	1.66	$98.78	0.34	$33.58	$58.23

City Pair	Origin Airport	Destination Airport	Number of Flights Sampled	Average Fuel Savings (gal)	Average Time Savings (min)	Unscaled Cost Savings ($/flight)	Scaling Factor	Scaled Cost Savings ($/flight)	Std Dev Scaled Cost Savings ($/flight)
	Combined Average		20	37.74	2.78	$165.29	0.34	$56.20	$76.83
9	LAX	IAH	51	3.73	0.27	$16.16	0.21	$3.39	$13.88
	IAH	LAX	49	3.02	0.22	$13.06	0.21	$2.74	$6.41
	Combined Average		100	3.38	0.24	$14.64	0.21	$3.07	$10.88
10	LAX	MCI	20	43.26	3.1	$186.97	0.21	$39.26	$20.92
	MCI	LAX	23	11.53	0.85	$50.47	0.21	$10.60	$3.91
	Combined Average		43	26.29	1.9	$113.96	0.21	$23.93	$20.40
11	LAX	DEN	76	14.82	1	$62.22	0.21	$13.07	$11.24
	DEN	LAX	50	9.81	0.68	$41.78	0.21	$8.77	$6.32
	Combined Average		126	12.83	0.87	$54.11	0.21	$11.36	$9.82
12	SFO	DEN	65	13.94	0.98	$59.77	0.21	$12.55	$14.95
	DEN	SFO	48	3.74	0.26	$16.05	0.21	$3.37	$4.55
	Combined Average		113	9.61	0.68	$41.20	0.21	$8.65	$12.57
13	SFO	MCI	10	38.21	2.81	$167.22	0.21	$35.12	$26.60
	MCI	SFO	8	4.87	0.36	$21.48	0.21	$4.51	$5.17
	Combined Average		18	23.39	1.72	$102.44	0.21	$21.51	$25.22
14	SFO	IAH	52	44.14	3.22	$192.44	0.21	$40.41	$45.80
	IAH	SFO	53	5.93	0.43	$25.76	0.21	$5.41	$9.92
	Combined Average		105	24.85	1.81	$108.31	0.21	$22.74	$37.35
15	SFO	DTW	39	35.58	2.64	$156.47	0.34	$53.20	$77.42
	DTW	SFO	31	41.12	2.94	$177.54	0.34	$60.36	$91.15
	Combined Average		70	38.03	2.77	$165.80	0.34	$56.37	$83.86
16	SFO	EWR	25	64.12	4.84	$284.26	0.34	$96.65	$142.82
	EWR	SFO	21	22.3	1.65	$97.89	0.34	$33.28	$53.83
	Combined Average		46	45.03	3.39	$199.18	0.34	$67.72	$115.78
17	SFO	BWI	18	23.61	1.69	$102.11	0.34	$34.72	$70.64
	BWI	SFO	14	126.69	9.53	$560.35	0.34	$190.52	$182.48
	Combined Average		32	68.7	5.12	$302.59	0.34	$102.88	$152.80
18	SFO	ATL	91	40.15	2.96	$175.92	0.34	$59.81	$79.13
	ATL	SFO	49	33.85	2.54	$149.67	0.34	$50.89	$60.95
	Combined Average		140	37.95	2.81	$166.73	0.34	$56.69	$73.40
19	DEN	DTW	67	44.12	3.14	$190.15	0.21	$39.93	$21.58
	DTW	DEN	62	17.42	1.24	$75.07	0.21	$15.76	$22.86
	Combined Average		129	31.29	2.23	$134.84	0.21	$28.32	$25.28
20	DEN	BOS	56	33.63	2.48	$147.30	0.21	$30.93	$55.01
	BOS	DEN	24	101.65	7.62	$448.98	0.21	$94.29	$80.13
	Combined Average		80	54.04	4.02	$237.80	0.21	$49.94	$69.91
21	DEN	BWI	49	42.59	3.14	$186.67	0.21	$39.20	$42.22
	BWI	DEN	55	67.14	4.89	$292.43	0.21	$61.41	$126.96
	Combined Average		104	55.57	4.07	$242.60	0.21	$50.95	$97.40
22	DEN	ATL	119	37.61	2.69	$162.38	0.21	$34.10	$42.46
	ATL	DEN	115	41.11	2.96	$178.16	0.21	$37.41	$81.29
	Combined Average		234	39.33	2.82	$170.14	0.21	$35.73	$64.55

City Pair	Origin Airport	Destination Airport	Number of Flights Sampled	Average Fuel Savings (gal)	Average Time Savings (min)	Unscaled Cost Savings ($/flight)	Scaling Factor	Scaled Cost Savings ($/flight)	Std Dev Scaled Cost Savings ($/flight)
23	DFW	DTW	37	78.78	5.51	$336.58	0.21	$70.68	$54.84
	DTW	DFW	37	53.42	3.76	$228.88	0.21	$48.06	$38.48
	Combined Average		74	66.1	4.63	$282.73	0.21	$59.37	$48.70
24	DFW	BOS	41	96.74	7.02	$420.63	0.21	$88.33	$87.11
	BOS	DFW	53	64.85	4.73	$282.54	0.21	$59.33	$45.89
	Combined Average		94	78.76	5.73	$342.77	0.21	$71.98	$68.59
25	DFW	DCA	51	59.07	4.11	$251.95	0.21	$52.91	$75.68
	DCA	DFW	47	28.36	2.06	$123.24	0.21	$25.88	$41.25
	Combined Average		98	44.35	3.13	$190.22	0.21	$39.95	$63.08
26	EWR	ATL	32	20.59	1.35	$85.54	0.21	$17.96	$1.52
	ATL	EWR	26	56.15	3.85	$237.84	0.21	$49.95	$95.12
	Combined Average		58	36.53	2.47	$153.82	0.21	$32.30	$65.65
27	PHL	TPA	15	42.12	2.9	$178.58	0.21	$37.50	$29.06
	TPA	PHL	17	56.38	3.76	$235.82	0.21	$49.52	$33.86
	Combined Average		32	49.7	3.36	$208.99	0.21	$43.89	$32.26

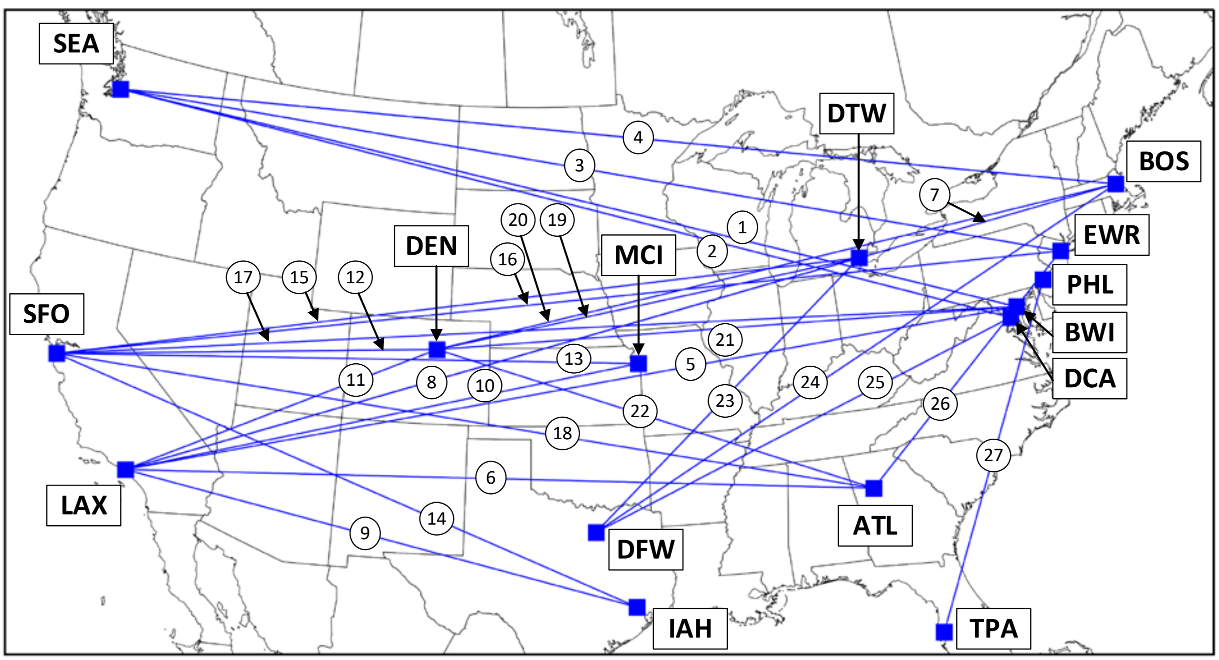

Figure 69. Sampled city pairs. Numbers in circles represent city pair numbers listed in Table 94.

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14. ABSTRACT

The NASA Traffic Aware Strategic Aircrew Requests (TASAR) concept offers onboard automation that advises the pilot of traffic compatible route modifications that would be beneficial to the flight. The Traffic Aware Planner (TAP) is the onboard automation component of TASAR. TAP was installed on three Alaska Airlines 737-900ER aircraft and used to conduct an operational evaluation of TASAR between July 24, 2018 and April 30, 2019.

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