Fuel Benefit from Optimal Trajectory Assignment on the North Atlantic Tracks

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This report is based on the Masters Thesis of Henry H. Tran submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology.

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by

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Abstract

The North Atlantic Tracks represent one of the highest density international traffic regions in the world. Due to the lack of high-resolution radar coverage over this region, the tracks are subject to more restrictive operational constraints than flights over the continental U.S. Recent initiatives to increase surveillance over the North Atlantic has motivated studies on the total benefit potential for increased surveillance over the tracks. One of the benefits of increased surveillance is increased accessibility of optimal altitude and speed operations over the track system. For a sample of 4033 flights over 12 days from 2014-2015, a fuel burn analysis was performed that calculates the fuel burn from optimal altitude, optimal speed and optimal track trajectories over the North Atlantic Tracks. These results were compared with calculated as-flown fuel burn in order to determine the benefit potential from optimal trajectories. Operation at optimal altitude and speed increased this benefit to 2.83% reduction potential in average fuel burn. Operation at optimal altitude alone, however, reduces the benefit potential to 1.24% reduction in average fuel burn. Optimal track assignment allows for a 3.20% reduction in average fuel burn. For the sample data, 45.1% of flights were unable to access their optimal altitude and speed due to separation requirements. Reduced separation up to 5 nautical miles can decrease the number of conflicts to 14.0%. Reducing the separation requirements both longitudinally and laterally can allow for increased accessibility of optimal altitudes, speeds and track configurations. Pilot decision support tools that increase awareness of aircraft fuel performance by integrating optimal altitude and speed configurations can also reduce aircraft fuel burn. The utility of such a tool is evaluated through a survey on pilot-decision making.

Acknowledgements

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Chapter 1
Motivation

The North Atlantic Tracks (NATs) represent one of the highest density oceanic traffic regions in the world. These tracks facilitate flights traveling between North America and Europe. These flights across the North Atlantic typically span greater distances than flights over the continental US, and thus require more fuel in order to travel from the origin to the destination. This airspace has special operational restrictions imposed on it due to the lack of RADAR surveillance over the region. These special operational restrictions cause aircraft operating within this region to operate at higher aircraft-to-aircraft separation distances.

For any individual flight, there is a combination of altitude, speed and routing that results in a minimum fuel burn. Operational constraints across the NATs, however, can result in flights operating at suboptimal altitudes, speeds and lateral routes. Uncertainty in aircraft position results in greater separation requirements for aircraft entering the North Atlantic Track system inhibiting the ability for any individual aircraft to access these more optimal trajectories, for doing so would cause a violation in the separation minima. Currently, there are initiatives to change these operational constraints in order to allow for increased flexibility in aircraft routing, altitude and speed trajectories. The first step in this process is to increase the level of surveillance available over the North Atlantic. Current systems, such as the Automatic Dependent Surveillance Contract (ADS-C) provide for low-resolution surveillance and data link between the aircraft and air traffic controller, although there are current initiatives to increase the reporting rate in order to increase surveillance resolution. With improved surveillance capability over the North Atlantic, flights will be able to access more efficient altitudes, speeds and lateral routes. The objective of this study is to quantify the benefits of optimal speed, altitude and routing assignments for flights across the NATs.

Chapter 2
Background

2.1 Aircraft Fuel Efficiency

Aircraft fuel efficiency is a function of many parameters. The weight of the aircraft, the winds encountered along the flight path, cruise speed, cruise altitude and aircraft all play a role in how much fuel is used during flight, along with other environmental and aircraft characteristics. A common metric used to define aircraft fuel efficiency is the specific-air-range (SAR). The SAR is a measure of the distance the aircraft flies per unit of fuel without any corrections for weather. This SAR is analogous to the miles-per-gallon metric that is commonly used to determine an automobile's fuel efficiency. For an aircraft, however, a correction must be made to account for wind and temperatures encountered along the flight. After the correction, the adjusted SAR is defined as the specific-ground-range (SGR), which is a metric used throughout this analysis as the aircraft fuel efficiency metric and corresponds to the distance over the ground traveled per unit of fuel. A common method of maximizing SGR (an in turn, maximizing fuel efficiency) is to fly at optimal altitudes and speeds. Figure 1 is a contour plot illustrating the instantaneous fuel efficiency of a typical narrow-body aircraft as a function of the cruise speed (in Mach) and altitude as a percentage of the maximum SGR achievable at the current aircraft configuration.

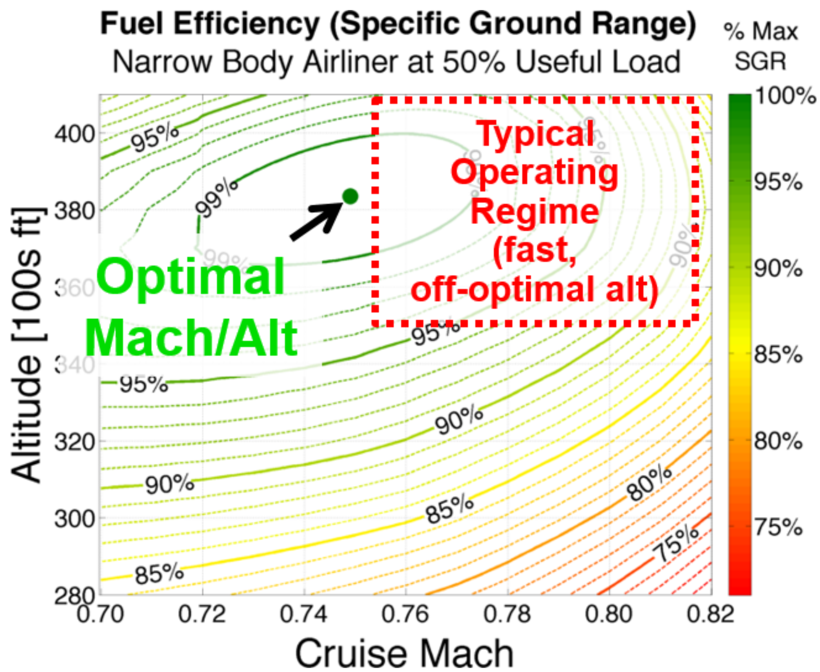

Figure 1: Fuel Efficiency (SGR) For a Typical Narrow Body Aircraft [1]

2.2 Current Altitude and Speed Optimization Methods

The typical operating regime for a flight is often above the optimal speed and off the optimal altitude, as shown by the region highlighted in the red in Figure 1. Although aircraft typically operate off fuel optimal speed, the optimization of a flight's altitude and speed is a multiobjective optimization process. When scheduling a flight and developing a flight plan, airlines will operate their aircraft at a speed that takes into consideration the costs of fuel and time related cost, such as hourly wages. As a result, the operating speed may be off the fuel optimal speed for that configuration due to these timing constraints. Consider the cost function for a flight considering fuel related cost and time related cost shown in Eq 1

$$TOC = (u_f) * (F_t) + (u_t) * (T_t) \quad \textbf{Eq 1}$$

Where TOC is the total operating cost, u_f is the unit cost of fuel, F_t is the total fuel used, u_t is unit cost of time and T_t is the total time. In short, Eq 1 simply takes the sum of the total fuel cost and the sum of the total time cost and the result is the total cost of a single flight. This also shows that simple minimization of fuel cost is not the only consideration when optimizing a flights altitude and speed. In order to minimize total fuel cost, a calculus approach is conducted by taking the derivative of Eq 1 with respect to distance and setting the result equal to zero. This derivation is shown as Eq 2.

$$0 = \frac{dF_t}{dx} + \frac{u_t}{u_f} * \left(\frac{dT_t}{dx}\right) = \frac{dF_t}{dx} + CI * \left(\frac{dT_t}{dx}\right) \quad \textbf{Eq 2}$$

The unit cost of time and fuel are not functions of distance, and thus are treated as constants and combined into a single constant CI. This constant is called the cost index and is an important metric that airlines use to balance the time related cost to the fuel related cost. It can be seen that the derivative of total fuel with respect to distance is the inverse of SGR, the metric defined earlier and the derivative of time with respect to distance is inverse of the current ground speed. This means that at any moment during an aircraft's flight, the SGR and cost index can be used to constrain the current aircraft ground speed.

When airlines plan their flights, they often define a cost index to operate at. Using a more complicated version Eq 2 that takes into account other cost sources, onboard flight computers can actually select a corresponding Mach that is computed using the cost index input. Figure 2 is an excerpt from a Boeing article describing the effects of cost index on cruise Mach selection. It can be seen that higher cost index settings correspond to higher cruise Mach. For Boeing aircraft, the cost index can range from 0-9999 with 0 corresponding to no time cost consideration and 9999 corresponding to maximum time cost consideration. This range of cost indices is unique to each airline and aircraft combination due to different units used and aircraft performance.

	CLIMB	CRUISE	DESCENT	ALTITUDE RECOMMENDATIONS
Cost Index 0	290/.778	.778	250	OPT 328, MAX 362, RECMD 310
Cost Index 9999	345/.847	.847	.819/334	OPT 268, MAX 268, RECMD 260
Cost Index 70	312/.794	.794	.80/313	OPT 327, MAX 363, RECMD 310

Figure 2: The Effects of Cost Index on Cruise Mach [1]

The cost index is capable of optimizing an aircraft's speed with considerations on fuel and time related cost, however, it does not optimize the aircraft's altitude profile. As mentioned before, aircraft fuel efficiency is also a function of altitude.

The fuel efficiency dependency on altitude is due to the fact that at different altitudes, the ambient air may change in temperature and density as well as the forecast winds. Since the aircraft fuel efficiency is a function of all these variables, specific combinations yield more efficient altitude and speeds than others. Current flight management systems (FMS) integrate forecasted atmospheric conditions and aircraft data in order to make a recommendation on a more efficient altitude. An example of this display is shown in Figure 3.

Figure 3: FMS Altitude Recommendation Display

As displayed above in Figure 3, the FMS computes the current optimal altitude as 36,400 feet (Flight Level 364 or FL364). In a real operational environment, however, this flight level is inaccessible due to the discrete available altitudes every 1000 feet and thus the recommended altitude is FL360.

In addition to speed and altitude, aircraft fuel efficiency is also dependent on the route that is chosen for a flight. The route that an aircraft flies determines what types of wind conditions are encountered as well as the total distance traveled. For this reason, routes are typically selected that simultaneously encounter desirable wind conditions as well as minimizing the distance required to the destination.

2.3 North Atlantic Tracks

The North Atlantic Tracks (NATs) are a system of flight routes across the northern Atlantic Ocean that facilitates traffic between Europe and North America. The tracks are spaced 1 degree apart laterally and stretch across the Northern portion of the Atlantic Ocean. The tracks are divided into two directions of flow, eastbound traffic and westbound traffic. The different directions of traffic are active at different periods of the day, with the eastbound tracks active at night during peak eastbound traffic hours and westbound tracks during the day so there is limited crossing flow. These tracks are designed such that the eastbound tracks are along the most favorable wind conditions available for the day. When the Jetstream is present along these eastbound tracks, the flights experience a strong tailwind, which is beneficial for fuel efficiency by reducing overall flight time. On westbound flights, the tracks are designed to avoid the strong headwinds thus reducing the time penalty of flying directly into the wind. The tracks are redesigned each day to capture these favorable wind conditions.

The entire track region is divided into 4 surveillance regions, the Gander Oceanic Airspace, Shanwick Oceanic Airspace, Reykjavik Oceanic Airspace and Santa Maria Ocean Airspace, however the NATs are typically within the Gander and Shanwick Airspaces exclusively. The Gander Oceanic Airspace covers the western half of the North Atlantic and the Shanwick Oceanic Airspace covers the eastern half of the North Atlantic. Aircraft that start from one side of the Atlantic to the other transition from one region to the other, and thus requires a handoff between control areas mid ocean. The separation of the oceanic region is shown in Figure 4 with the Gander and Shanwick regions highlighted.

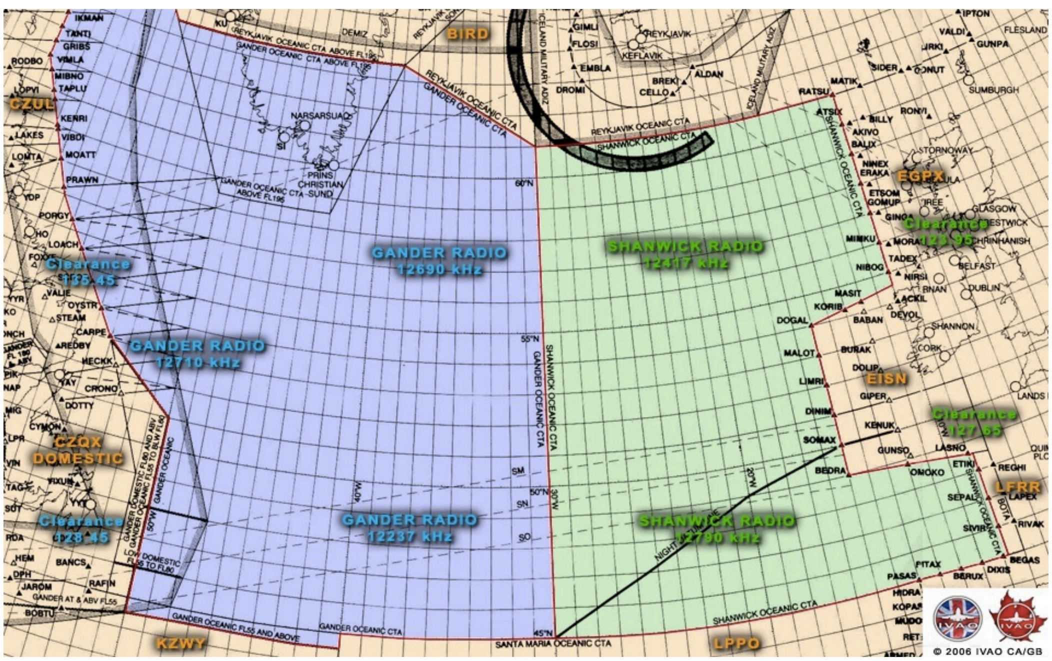

Figure 4: Gander and Shanwick Oceanic Airspaces [2]

Figure 5 shows what the Eastbound North Atlantic tracks look like on a particular day. The locations of the eastbound tracks are such that they are centered along the region of highest tailwinds, thus minimizing total flight time. Each of these tracks is typically offset laterally from one another by a minimum of 1-degree latitude, however on days with abnormal wind conditions these separations may be increased.

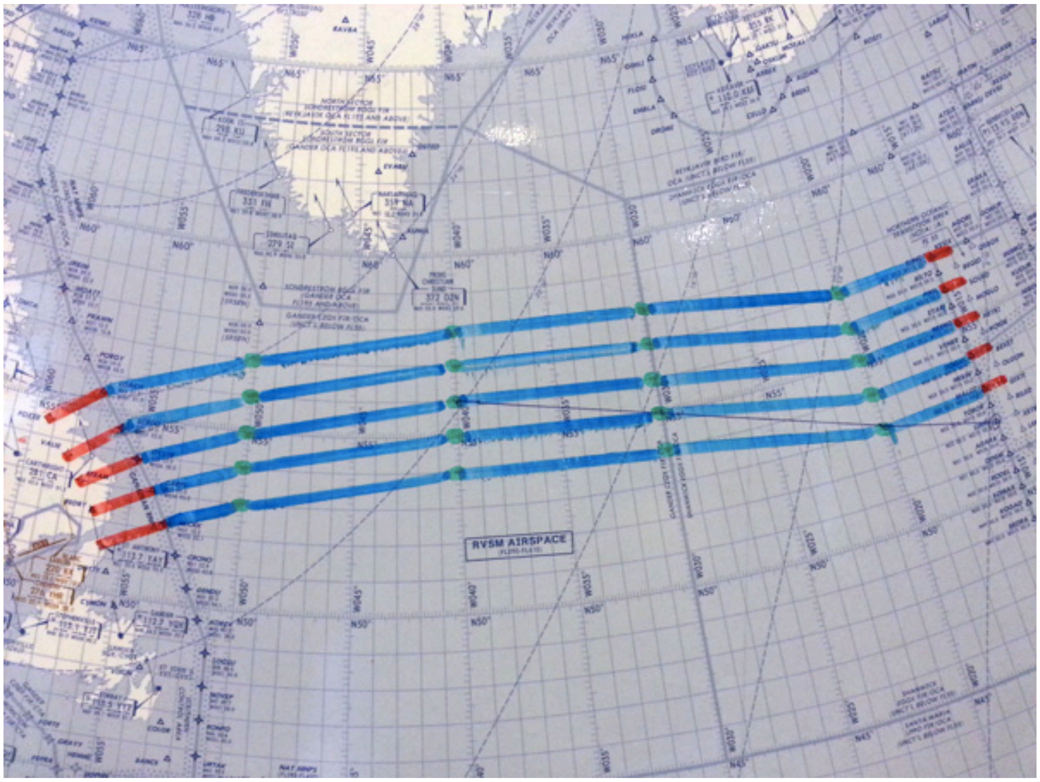

Figure 5: Eastbound North Atlantic Tracks Designed for 07/10/2013 [3]

The NATs, although represent a highly dense region of traffic, also has little to no RADAR surveillance. Due to this lack of surveillance, the position of any individual flight along the track has a greater uncertainty than for flights in regions of higher surveillance such as over U.S. domestic airspace. This uncertainty in position creates an operational constraint on how much traffic can be admitted into the tracks and which track they are assigned through increased separation requirements. The typical separation between aircraft in the track system is 10 minutes of entrail separation, which can result in distances as great as 100 nautical miles, 1-degree lateral separation, and 1000 feet separation in altitude. Compared to the separation standards in domestic US airspace (5-10 nautical miles entrail and laterally, 2000 feet separation in altitude for same direction flights), NATs separation is far greater due to the uncertainty in aircraft position. There are current initiatives to reduce the separation minima in the NATs to 23 nautical miles laterally and 5 minutes longitudinally however these reductions in separation currently cannot be implemented due to the lack of surveillance.

For flights entering the NATs, the traffic controller that is responsible for that region makes a track assignment for that flight. For any particular track, there are discrete and strict flight levels and Machs that can be assigned which must be maintained for the duration of the track. This is done through a grid-like representation as shown in Figure 6.

Figure 6: Bilateral Operations Resolution Grid (BORG) tool used for NAT assignment

The assignment grid highlights assignments that have no conflict (NOC), a conflict (CON) and a warning (WRN). Flight level and Mach assignments are labeled as conflicted if there is another aircraft in the airspace that may violate a safe separation with an aircraft at the selected assignment. As shown in Figure 6, this assignment grid is only applicable for the track labeled "X", with each track having a unique assignment grid based on the level of traffic assigned to that track. Flights that are assigned a flight level and Mach are expected to maintain that clearance for the duration of the flight that is within the NATs.

2.4 North Atlantic Track Selection

Although each flight is assigned a specific track, each flight has a track that is fuel optimal in terms of minimum distance and most favorable wind conditions. Northern routes are shorter in absolute distance, but also require additional distance to reach the entry point. For eastbound flights, tracks in the center of the system may have the most desirable wind conditions in terms of strongest tailwinds, but may not necessarily be the shortest distance. The track that is requested by a flight is usually selected based on which track offers a minimum fuel burn and thus takes into account favorable wind conditions and total distance simultaneously. The issue, however, is that the NATs may be designed such that only one or two of the tracks offer a highly favorable route in terms of weather conditions and distance traveled, thus prompting many flights to request the desirable tracks. This causes a capacity issue, as there is a limit to how many aircraft may operate simultaneously on one track while still maintaining a safe separation. As a result, North Atlantic tracks are typically designed such that no single track offers a significant fuel burn improvement over the next most fuel-efficient track. This can be thought of as "splitting" the most optimal routing into two adjacent tracks that still have lower fuel burn capability than other tracks, however, neither one is significantly "better" than the other. This is further explained in the results section.

Chapter 3

Approach

In order to quantify the benefits from altitude, speed and track optimization over the NATs, a framework that estimates cruise fuel burn was developed. The framework, as shown below Figure 7 requires a sample of flights across the North Atlantic. The sample data is then processed to generate high-resolution track trajectories. The high-resolution trajectories are then subject to a weight estimation model which is required to accurately estimate fuel burn. The high-resolution trajectory is then used to compute the weather conditions along the route using historical weather forecasts. The high-resolution trajectory, weight estimate and weather conditions are then all ingested in an aircraft performance model to incrementally compute the fuel burn along the entire track. The trajectory is also subject to a speed, altitude and track optimizer and the fuel among all the trajectories are compared in the results. Each element of Figure 7 is explained in more detail in the following sections.

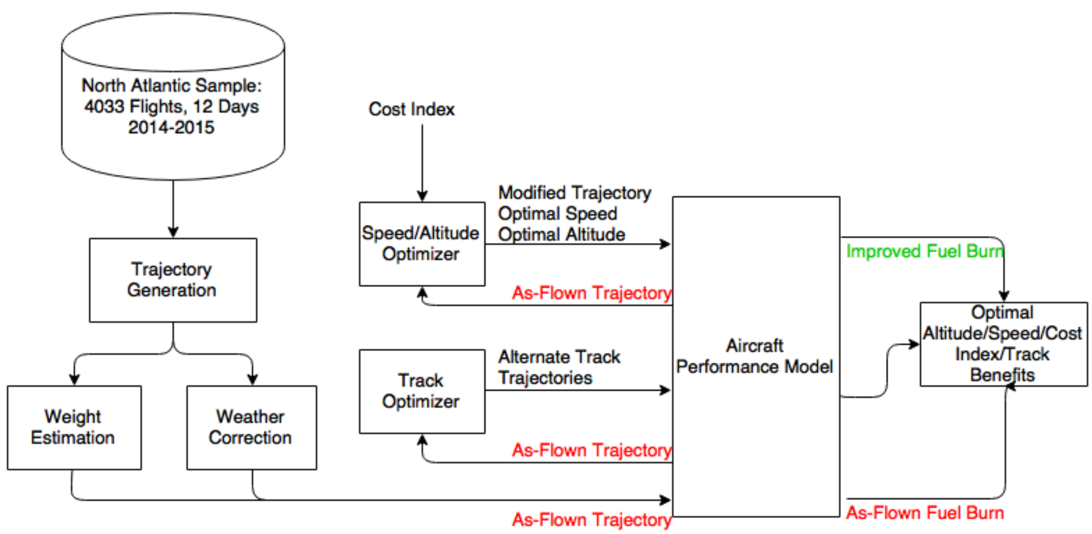

Figure 7: Methodology Diagram

3.1 North Atlantic Sample

In order to quantify the benefits from altitude, speed and track optimization over the NATs, a framework that estimates cruise fuel burn was used on a sample of data for 4033 flights taken over 12 days between 2014 and 2015 that represent all seasons of the year. The sample days are listed in Table 1.

Table 1: Sample Days

03/03/2014	06/09/2014	06/16/2014	09/08/2014	09/15/2014	12/08/2014
12/15/2014	03/25/2015	04/05/2015	04/26/2015	05/14/2015	05/25/2015

The data includes aircraft altitude, speed, lateral route and time. This data is provided for the Gander Oceanic Airspace and the Shanwick Oceanic Airspace, which is shown in Figure 4. The two sets of data are then stitched together to form a full lateral route over the North Atlantic tracks with corresponding altitude, speed and time.

3.2 Trajectory Generation

The provided data includes flight data for 12 sample days between 2014 and 2015. The data, however, is separated into two subsets. Since the NATs expand across two oceanic control areas, sets of data from both the Gander and Shanwick regions are required in order to fully define the NATs route, altitude and speed. The data set from the Gander Oceanic airspace consist of the flight's entire lateral route, aircraft type, origin, destination, direction, track assigned, Mach through the track, and altitude and crossing times for the 50W, 40W and 30W longitudinal crossings. The tracks, however, typically extend beyond the 30W crossing longitude, which is where the data from the Shanwick Oceanic airspace sample is used to fill in the gaps in the data. Excerpts from each set of data are shown below in Figure 8 and Figure 9.

Flight Route	Aircraf	Departu	Arrival	Dire	NA	Point of Entry Date anc	Point c
ELSIR 5000N05000W 5200N04000W 5300N03000W 5400N02000W DOGAL BEXET	GLF4	KPTK	EGGW	E		08Jan2015 0:01:00.000	
JOOPY 4900N05000W 5100N04000W 5300N03000W 5300N02000W MALOT GISTI	B77W	KEWR	VABB	E	S	08Jan2015 0:04:00.000	
6500N04000W 6300N05000W MAXAR	B77L	ELLX	KATL	W		08Jan2015 0:12:00.000	34000
RIKAL 5300N05000W 5700N04000W 5900N03000W 6000N02000W RATSU GUNPA	B763	KJFK	UUEE	E		08Jan2015 0:14:00.000	35000
JOOPY 4900N05000W 5100N04000W 5300N03000W 5300N02000W MALOT GISTI	B772	KEWR	LLBG	E	S	08Jan2015 0:15:00.000	36000
6500N05000W CLAVY	B77L	EDDF	KMEM	W		08Jan2015 0:21:00.000	
4400N05000W 4600N04000W 4800N03000W 4800N02000W 4800N01500W OMO	A346	KJFK	EDDF	E	X	08Jan2015 0:23:00.000	38000
RIKAL 5300N05000W 5500N04000W 5600N03000W 5600N02000W RESNO NETKI	B763	KATL	LFPG	E		08Jan2015 0:25:00.000	35000
NEEKO 5400N05000W 5700N04000W 5800N03000W 5700N02000W PIKIL SOVED	A333	KJFK	EHAM	E		08Jan2015 0:33:00.000	37000
6200N03000W 6200N04000W 6100N05000W SAVRY	B763	EGNX	KCVG	W		08Jan2015 0:34:00.000	34000

Figure 8: Gander Ocean Control Area Data

Date	Time	Callsign	A/Type	Direction	Departure	Destination	Speed	Flight Level	Track	RP1 Pos	RP1 Time	RP1 Level
3/1/14	0:05:00	TSO2222	B763	E	KJFK	UUWW	78	350		5100N04000	2325	350
3/1/14	0:14:04	AMX004	B788	W	LFPG	MMMX	84	360		BALIX	14	360
3/1/14	0:27:17	AIC126	B77W	E	KORD	VIDP	83	330	U	5100N04000	2349	320
3/1/14	0:46:14	UPS238	B763	W	EGSS	KSDF	80	340		ERAKA	46	340
3/1/14	0:53:01	JAF502	B788	E	MMUN	EBBR	84	410		4600N04000	9	390
3/1/14	0:55:34	DLH423	A346	E	KBOS	EDDF	80	370	W	4900N04000	15	370
3/1/14	1:02:00	UAL84	B772	E	KEWR	LLBG	82	350		4700N04000	8	330
3/1/14	1:03:50	AIC144	B77W	E	KEWR	VABB	83	320	V	5000N04000	25	320
3/1/14	1:04:00	UAL944	B772	E	KORD	EDDF	83	380	U	5100N04000	25	370
3/1/14	1:08:46	AFR345	B744	E	CYUL	LFPG	84	370	V	5000N04000	30	360
3/1/14	1:13:06	DLH401	B744	E	KJFK	EDDF	83	360	W	4900N04000	33	360
3/1/14	1:27:14	AFR023	B772	E	KJFK	LFPG	83	340	W	4900N04000	48	340
3/1/14	1:34:57	DAL28	B763	E	KATL	LFPG	78	360	W	4900N04000	53	360
3/1/14	1:35:55	DAL470	A333	E	KJFK	EHAM	80	390		5400N04000	57	380
3/1/14	1:39:00	TSO554	B744	E	MDPC	UUDD	84	350		4700N04000	51	330
3/1/14	1:42:00	TOM093	B763	E	MMUN	EGKK	80	370	Z	4600N04000	57	350
3/1/14	1:42:51	DAL252	B772	E	KDTW	EHAM	82	370		5500N04000	105	370
3/1/14	1:43:08	AZA60M	A332	E	KJFK	LIRF	80	400	W	4900N04000	102	380
3/1/14	1:44:02	LOT6204	B788	E	MDLR	EPWA	84	410		4200N04000	50	400
3/1/14	1:44:03	CGCDS	GLEX	E	CYUL	LFLS	85	410		5100N04000	104	410
3/1/14	1:45:16	CFG233	B763	E	MDPC	EDDF	79	360		4500N04000	58	350

Figure 9: Shanwick Ocean Control Area Data

Figure 10 shows the routes for the 4033 flights over the North Atlantic. The route data does not include domestic airspace data, and so the altitude and speed analysis only focuses on the section of a flight within the North Atlantic airspace.

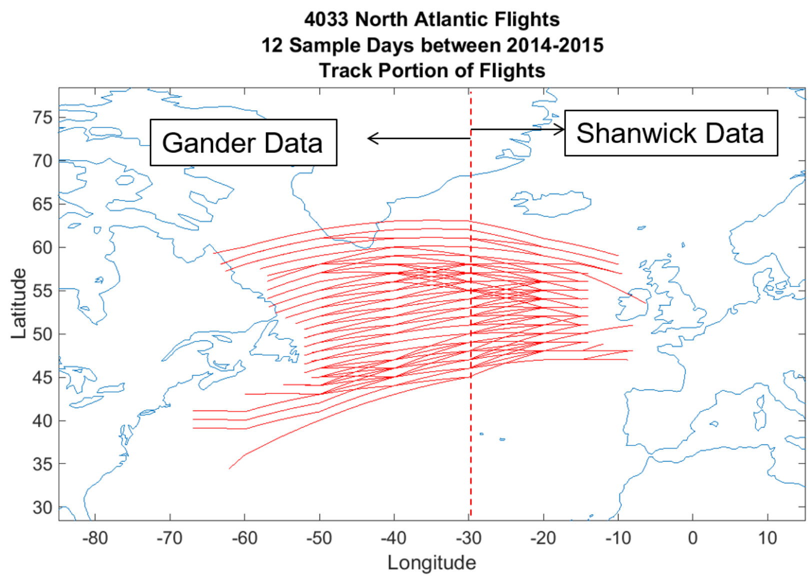

Figure 10: 12 Day Sample of 4033 Flights Over the NATs

After stitching together the two data sets, a set of five dimensional waypoints is generated for each flight using the available data at each recorded data point. Each waypoint represents a fix along the NATs and has a unique latitude, longitude, altitude, Mach and crossing time associated with it. This initial set of waypoints, however, are typically spaced 5-10 degrees apart longitudinally so the track data is not high enough in resolution in order to capture local wind effects and changes in instantaneous fuel efficiency, which is required in order to compute an accurate fuel burn estimate. Additional waypoints, therefore, are then generated by linearly interpolating between adjacent data waypoints in five dimensions. Each additional waypoint is generated such that the entire flight trajectory is segmented into a series of five dimensional waypoints that account for approximately one minute of flight time. After generating the higher resolution as-flown trajectory, additional alternate trajectories are generated using alternate track fixes provided by the publically available track definitions for the day in order to study the effects on improved track selection on fuel efficiency. The steps in the trajectory generation process are shown in Figure 11.

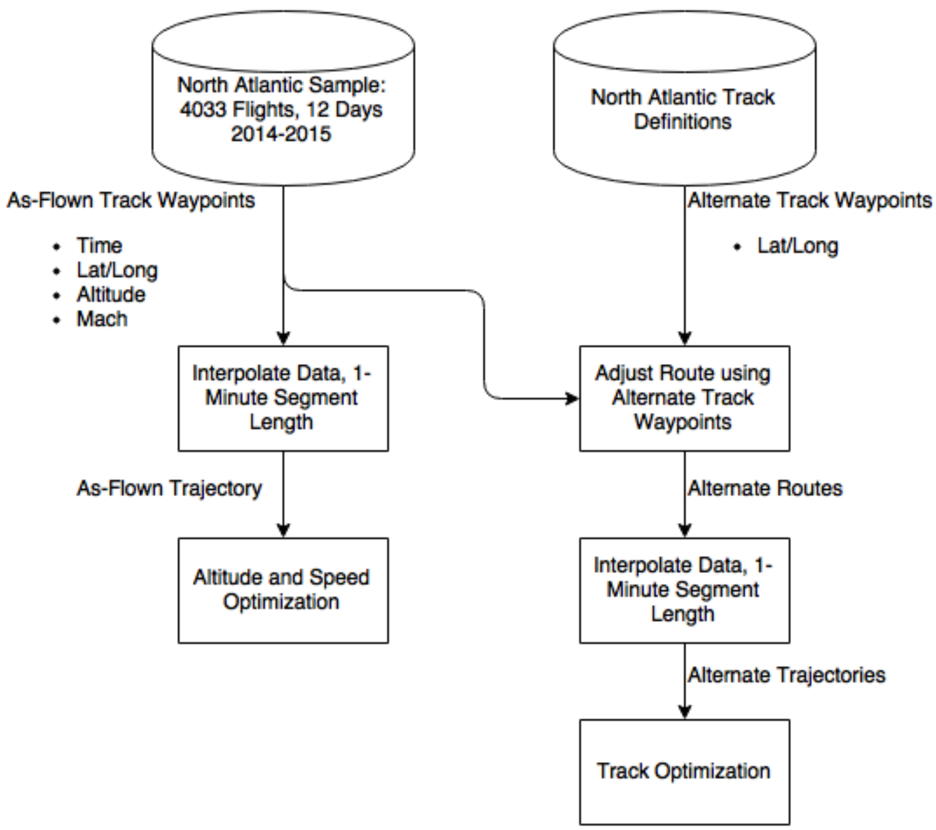

Figure 11: Trajectory Generation

3.2.1 Extended Trajectory Generation for Track Optimization Analysis

The available route data only exists for the flights trajectory within the North Atlantic Tracks, as shown in Figure 10. As a result, the analysis on optimal altitude and speed is only done for this region which isolates performance along the North Atlantic

Tracks from performance outside the track system. When looking at track optimization, however, analyzing only the North Atlantic region creates a unique problem that does not present itself with only optimizing altitude and speed. Since each track extends across the ocean and are bounded by the same longitudes, typically from 30W longitude to 50W longitude, the northernmost tracks are actually shorter in ground distance than the southern tracks due to the curvature of the Earth. As a result, fuel burn on a northern track is typically lower than that of a southern track primarily due to shorter distances traveled, even with weather conditions considered. This would imply that northern tracks are the most efficient in terms of track fuel burn, however, these northern tracks may also require greater travel distances by a flight from the origin airport to the entry point of the track system, as they are situated further north. If we performed an analysis on track fuel burn using only the available track data, the result would indicate that every flight was not assigned an optimal track, since the most optimal track is always the shortest one. In order to analyze the current efficiency of the track assignments, this ground distance effect must be considered and accounted for. To account for this, an extended trajectory is generated that includes great circle routes to and from the track from their origin and destination airports, thus penalizing the shorter, northern tracks by accounting for the additional distance required to reach these tracks. An example of this extended trajectory is shown below in Figure 12.

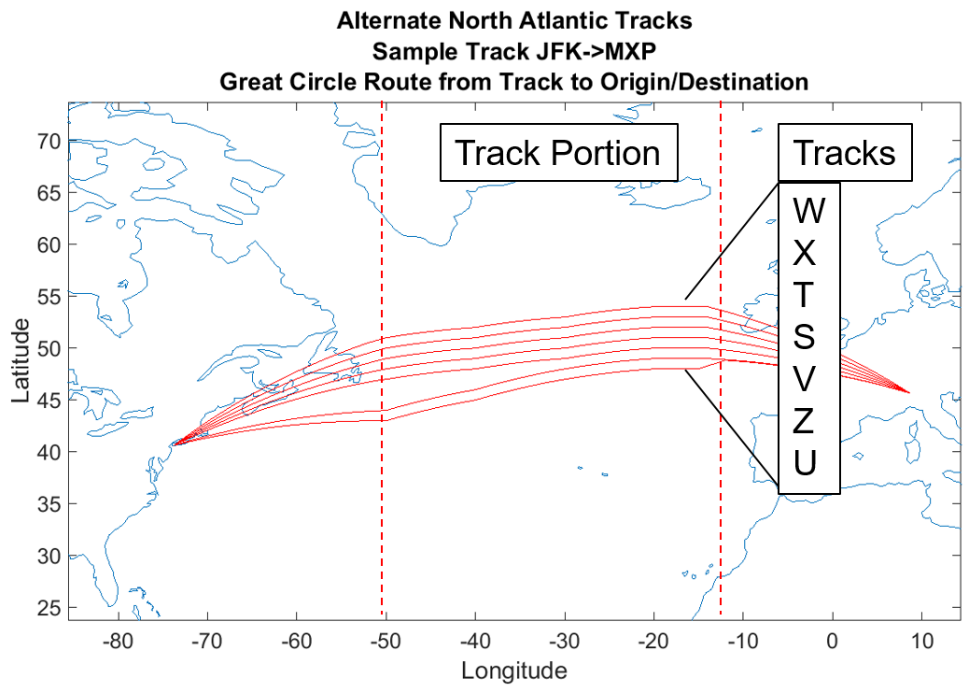

Figure 12: Alternate Track Concept Sample

For this particular flight from JFK to MXP, there are 7 tracks available for the day (Tracks W, X, T, S, V, Z, U). The northernmost track, track "W", is the shortest track in ground distance, but also requires the most travel time from origin to track entry due to its northern entry point position. The Gander and Shanwick surveillance data provide the track portion of the flight, whereas the region extending to the origin and destination is generated using great circle trajectories to and from the edges of the tracks. The altitude and speed on these extended portions of the flight are determined by the bounds of the track portion of the flight. This means that the altitude and speed at the edge of the track system is extended to the origin and destination airports for each flight. These extended trajectories are then subject to the same cruise fuel estimation framework, however, these trajectories are not optimized in altitude and speed in order to determine the effects on alternate track assignments on cruise fuel burn.

3.3 Weight Estimation

Aircraft fuel efficiency is sensitive to initial weight. Flights that are heavily loaded with fuel have much higher fuel benefit potential, as the relationship between fuel loaded and fuel consumed increases non-linearly. In order to estimate the initial weight, a weight regression model is generated based on historic data from three airlines and then correlated with the flight stage length using a best fit polynomial for each aircraft type. Figure 13 shows an example of the data available for the regression for a specific aircraft.

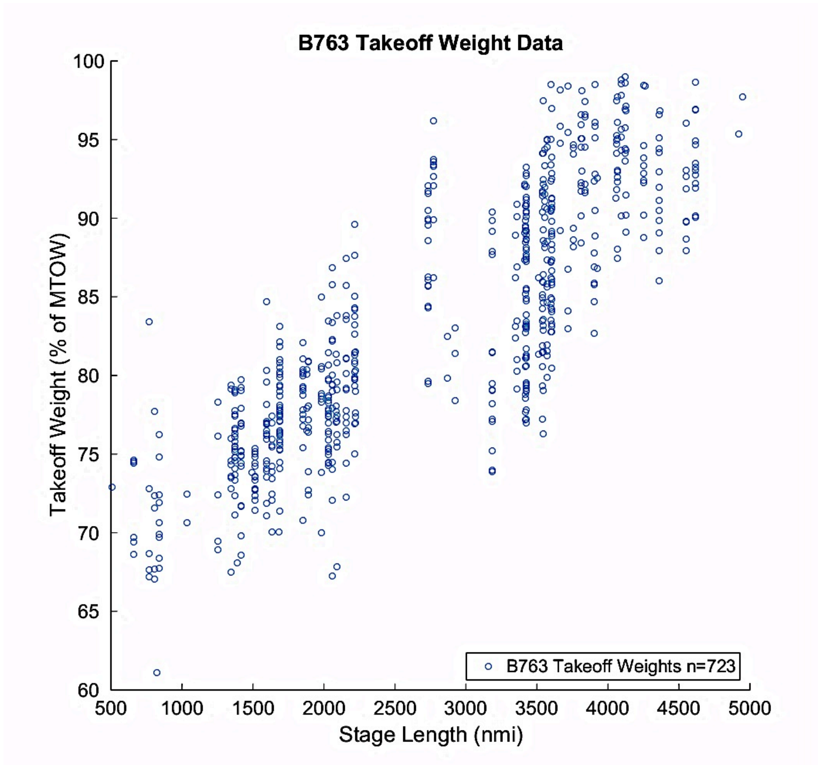

Figure 13: Weight Regression for B763 based on Stage Length

The data in Figure 13, however, only correlates the takeoff weight with the stage length. Since part of this analysis only focuses on fuel burn efficiency over the North Atlantic, additional steps are required to estimate the initial weight of an aircraft entering the track system. In all cases, there is a significant amount of fuel consumed in order to fly from the initial takeoff location to the entry point of the track system, which can be seen in Figure 14 as the great circle trajectories from the boundary of the track system to the origin and destination airports.

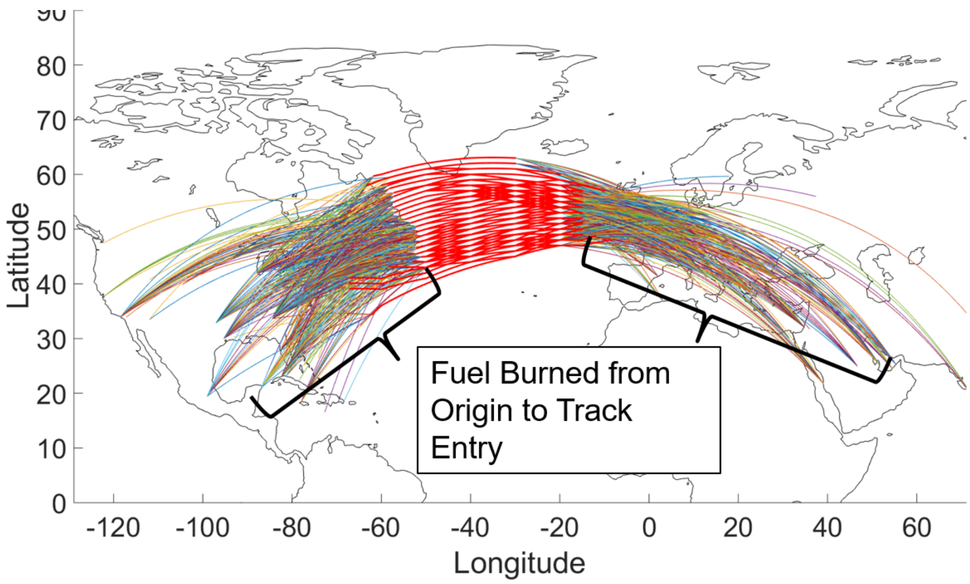

Figure 14: Distance from the Origin and Destination to the North Atlantic Tracks

To appropriately account for fuel burn from origin to track entry, the initial takeoff weight is scaled using an additional set of data on consumed fuel weight. Using the same aircraft weight data, this additional regression can be constructed that correlates the amount of fuel that is loaded with the stage length. Both the takeoff weight and fuel loading regressions are shown below in Figure 15.

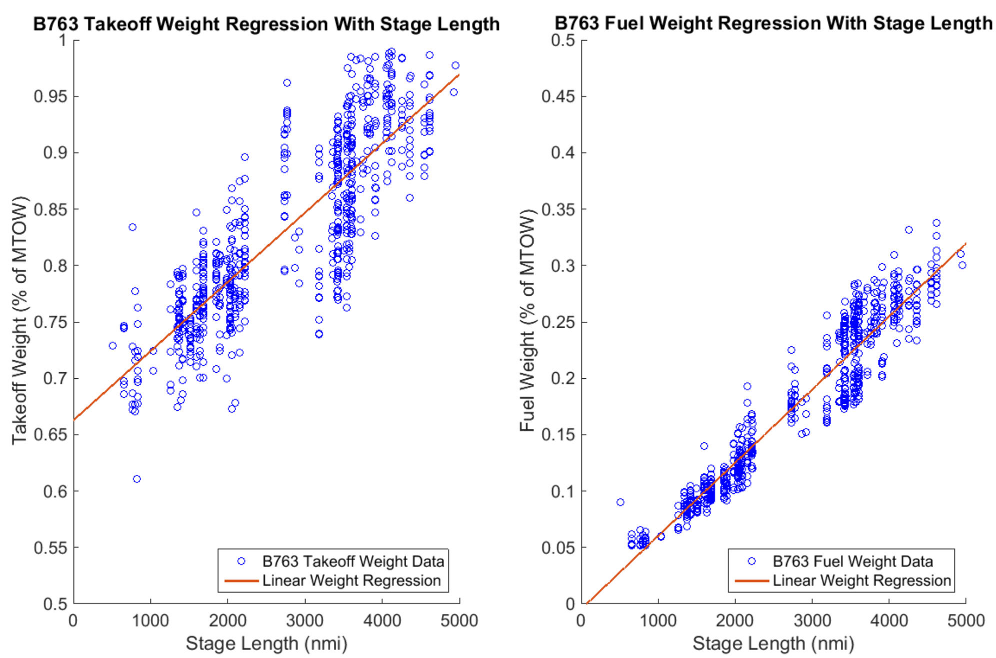

Figure 15: Takeoff and Fuel Weight Regressions with Total Stage Length

An approximate stage length for each sample flight can be calculated by computing the great circle distance from the origin to the track entry, the distance along the track, and then the track exit to the destination. Using the approximate stage length, an estimate for takeoff weight and fuel weight can be determined for each aircraft type using regressions shown above. The initial weight estimate for the track entry is then computed by scaling the fuel weight estimate and combining both estimates. The process is summarized below in Eq 3 where TOW is the takeoff weight estimate, FW is the fuel weight estimate, and the ranges correspond to the estimated remaining range in flight at the track entry and the estimated total stage length.

$$Track\ Entry\ Weight = (TOW_{est} - FW_{est}) + FW_{est} * \left(\frac{Range_{Remaining}}{Range_{total}}\right) \qquad \textbf{Eq 3}$$

The scaling of takeoff to track entry weight assumes that the aircraft has a constant fuel burn per unit distance, which is not true when considering changing wind fields. However, a weight sensitivity analysis shown in the results section will show that small variations from the estimated entry weight have only a minor effect on the possible fuel savings. Larger variations, however, have a significantly higher impact on possible fuel savings and will be discussed in later sections.

3.4 Weather Correction

Aircraft performance is also dependent on the encountered winds (The correction of SAR to SGR). Since lift is generated by the air flowing over the aircrafts wing, when a strong headwind is encountered, the actual ground speed of the aircraft is greatly reduced since the aircraft is flying “into the wind” but the wing experiences a much higher wind speed than that of the ground speed with a reverse process occurring when a tailwind is encountered. An example of a headwind configuration is shown below in Figure 16.

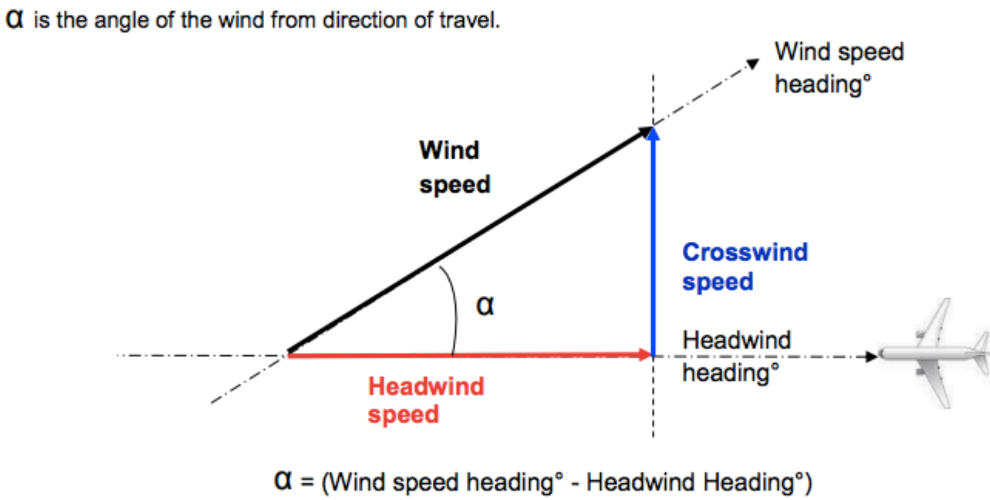

Figure 16: Aircraft Experiencing a headwind [4]

The distinction between a headwind and a tailwind is critically important to determining the performance of an aircraft because at different wind conditions, an aircraft can be operated at different speeds in order to compensate for these conditions. For example, when an aircraft experiences a strong tailwind, the aircraft can essentially ride the "current" and reduce its Mach, which may reduce fuel consumption while still maintaining on-time performance. The reverse case is also true for a strong headwind. When a strong headwind is encountered, the aircraft must operate at a higher Mach in order to maintain on-time performance or attempt to avoid these weather conditions. Winds experienced in the atmosphere determine whether or not the aircraft experiences a tailwind or a headwind and must be corrected in order to determine the actual ground speed.

The weather correction step takes the Global Forecast System gridded weather model and determines the winds that were encountered during the flight and matches them to the points along the flight in the high resolution trajectory generated in the previous step. The Global Forecast System spans the entire Earth and has a spatial resolution of 1-degree latitude, 1-degree longitude and has 26 available pressure altitudes with 100 millibar resolution. The temporal resolution of the model is 6 hours between update cycles. Shown in Figure 17 is a plot of the wind speed from the gridded weather model superimposed on a map of the North Atlantic region. There is a unique model for each day, time and altitude for the forecast winds.

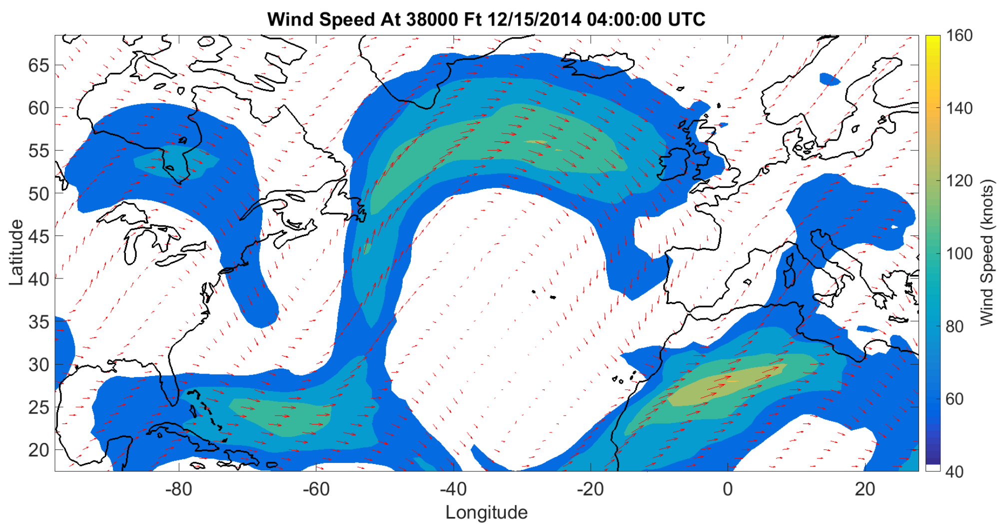

Figure 17: Global Forecast System Wind Speed at 38,000 feet on 12/15/2014 04:00:00 UTC

For this particular altitude and time, there is a very clear Jetstream across the north Atlantic from the North American side to the European side. This illustrates why the design of the North Atlantic Tracks is dependent on the weather conditions for the day as mentioned in the previous sections.

Using a five dimensional linear interpolation in space, time and speed, the weather conditions along the flights trajectory at each waypoint can be determined. The wind at each point is then used to correct the airspeed to the ground speed, which is then used to compute the aircraft SGR.

3.5 Aircraft Performance Model

Once the initial trajectory is fully defined, the weather conditions computed and the weight is estimated, an aircraft performance model is used to compute the SGR at each incremental waypoint along the trajectory. For this analysis, the Lissys Piano-X aircraft performance model was used. This model includes performance models for over 5000 commercial aircraft and can compute SGR for the aircraft along the trajectory given the altitude, speed, weight and weather conditions. The computed SGR is then assumed constant over the minute-long interval and is used to compute the fuel burn for the flight at that incremental segment. The weight estimation of the aircraft is then updated to account for the fuel that was consumed and the process is repeated for each minute-long segment in the flight's trajectory. When the fuel burn has been computed for each segment along the trajectory, the total fuel burn is calculated by taking the sum of the all the segment fuel burns. The steps in this process are shown below in Figure 18.

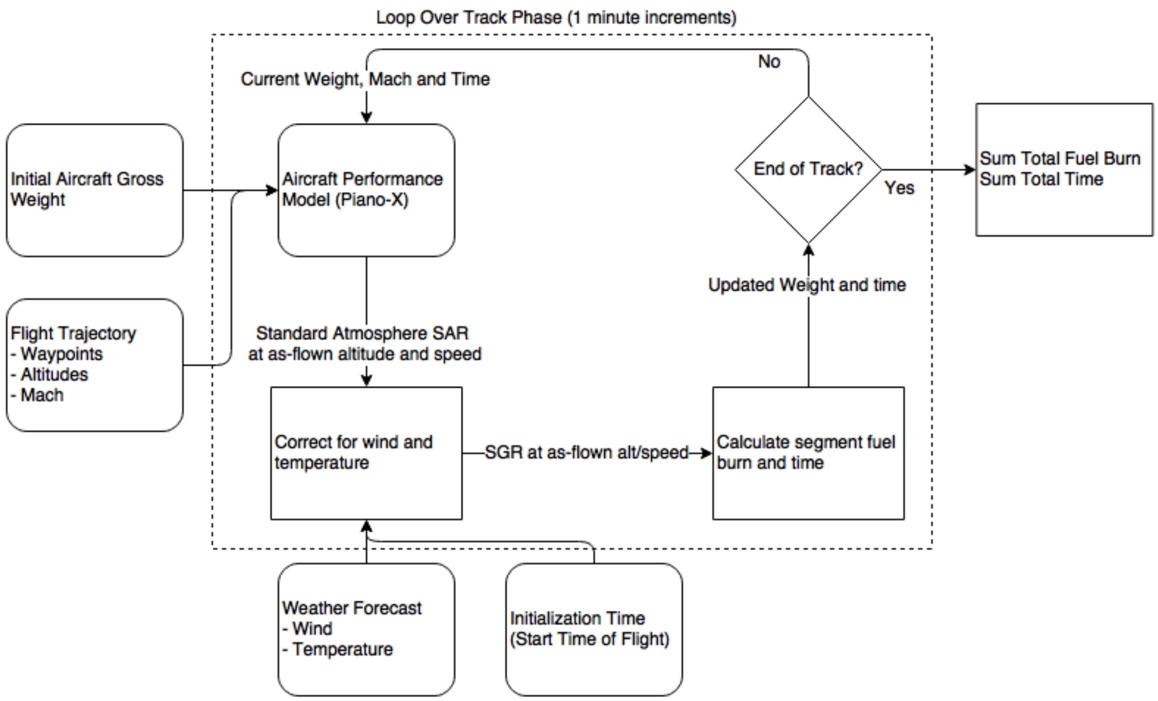

Figure 18: Computing Estimated Track Fuel Burn

3.6 Track Optimizer

In the trajectory generation step, alternate trajectories were generated for each flight using all the available tracks for the day. Figure 12 shows an example of the alternate tracks that were generated for a specific flight. Using the aircraft performance model and the wind forecasts, the fuel burn for each alternate trajectory was computed using the as-flown altitude and speed. The fuel burn for each is then compared with the as-flown fuel burn to determine the amount of fuel benefit possible from more efficient track assignments.

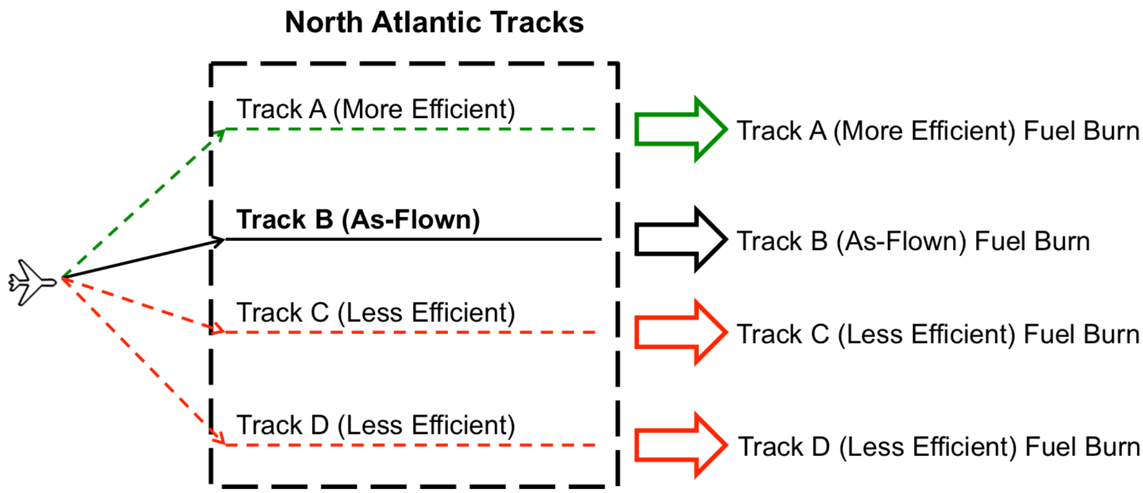

Figure 19: Track Optimization Concept

3.7 Speed/Altitude Optimizer

Once the aircraft as-flown fuel burn has been computed, the trajectory is then subject to an optimization process that can optimize either speed or altitude. The optimization is done by maximizing the SGR, the metric used to evaluate fuel efficiency, at each minute-long segment in the as-flown trajectory. Using the aircraft performance model used to compute as-flown fuel burn and the atmospheric conditions, a table of segment SGR values for multiple combinations of altitude and Mach can be generated, resulting in a set of values that can be visualized as a three dimensional surface shown in Figure 20.

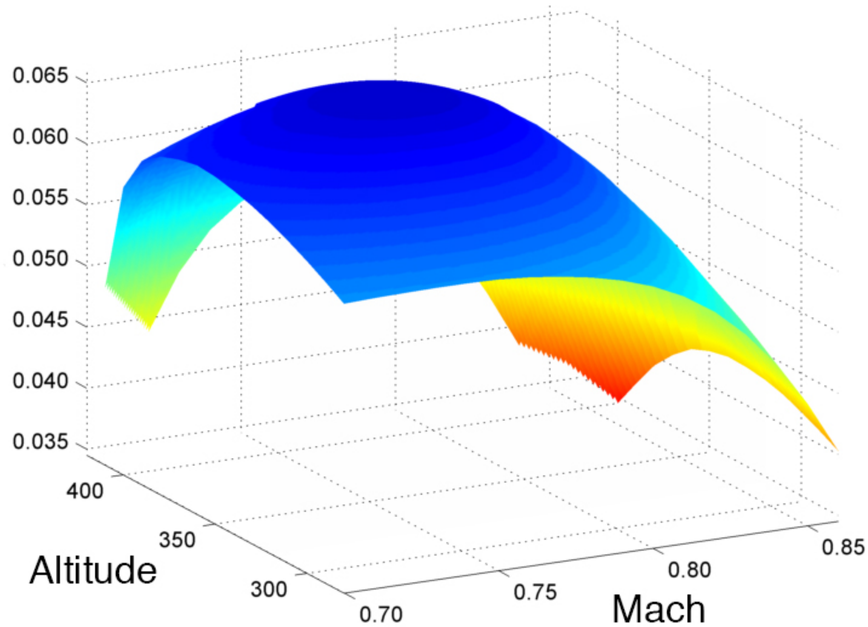

Figure 20: Instantaneous fuel efficiency surface (SGR) as a function of altitude and speed, accounting for weather [5]

The maximum SGR for the surface corresponds to the most optimal altitude and Mach that was available for that minute interval. For each minute long interval in the flight, a surface like that in Figure 20 can be generated for all possible configurations of Mach and altitude. By strictly maximizing the SGR at each minute long segment, the aircraft's truly fuel optimal Mach and altitude can be determined. This optimization, however, results in trajectories that require changes in Mach and altitude at each minute-long segment, as each surface is unique for each segment due to continuously changing aircraft weight and atmospheric conditions. These "true" optimal trajectories may result in altitude changes of 100 feet and continuous accelerations and decelerations in speed every minute along the flight. In a real air traffic environment, however, the trajectory of an aircraft is not assigned continuously along the flight every minute and the resolution of available clearances is not as high as this analysis assumes. In practice, altitudes are assigned in 1000-foot increments and are maintained for a period of time that represents a level segment in flight. For this reason, there are constraints placed on the optimization method in order to accurately represent the level of benefit in a real traffic environment. These constraints restrict changes in trajectory to 10 minute level segments, meaning changes in trajectory must maintain the current altitude and speed for at least 10 minutes before performing another change. The altitude is also restricted to 1000-foot step climb increments, which is what is available to aircraft in a real traffic environment.

The optimization first considers a scenario when the flight is given the flexibility to operate at their as-flown Mach, preserving the desired relationship between cost of time and cost of fuel, but a vertical trajectory with the flexibility to perform 1000-foot step climbs. The 1000-foot step climbs allow the aircraft to achieve more optimal altitudes as the flight goes on, which has a negligible impact on total flight time. Optimizing the altitude and constraining the Mach to the as-flown Mach allows for the reduction of the SGR surface into an SGR curve, shown below in Figure 21. The maximum of this curve results in the constrained optimal altitude at that minute interval of the flight. Repeating this process along each interval of the flight yields the constrained optimal altitude SGR along the flights entire trajectory. This process is then repeated with a fixed altitude in order to determine the constrained optimal Mach SGR.

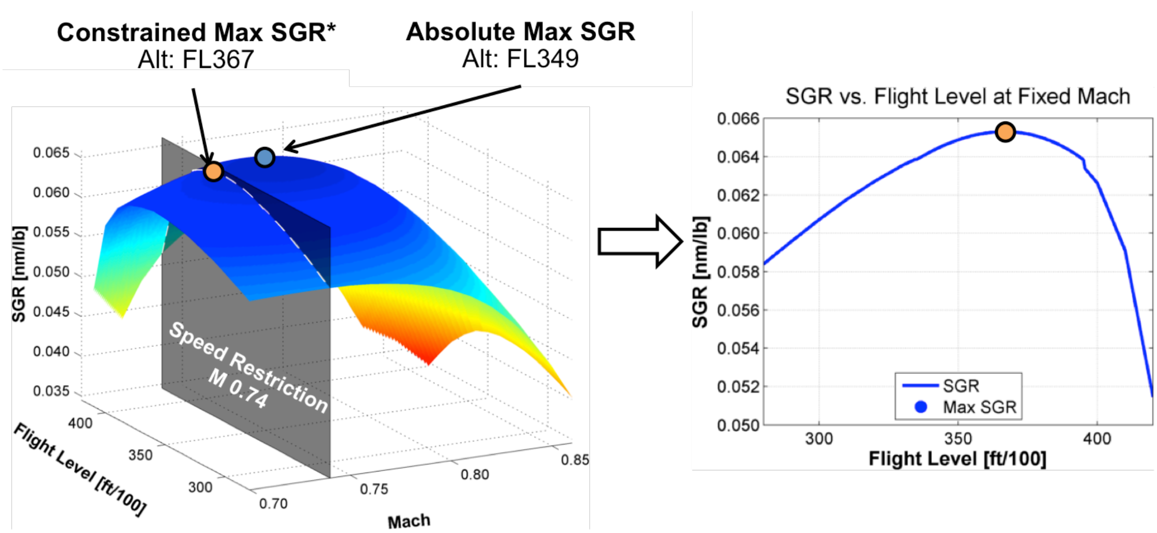

Figure 21: Reduction of SGR Surface to Fixed Mach SGR Curve

By taking the curve from Figure 21 for each minute-long segment of flight, a visualization was constructed that illustrated the en-route fuel performance over the entire track segment for an example flight shown below in Figure 22.

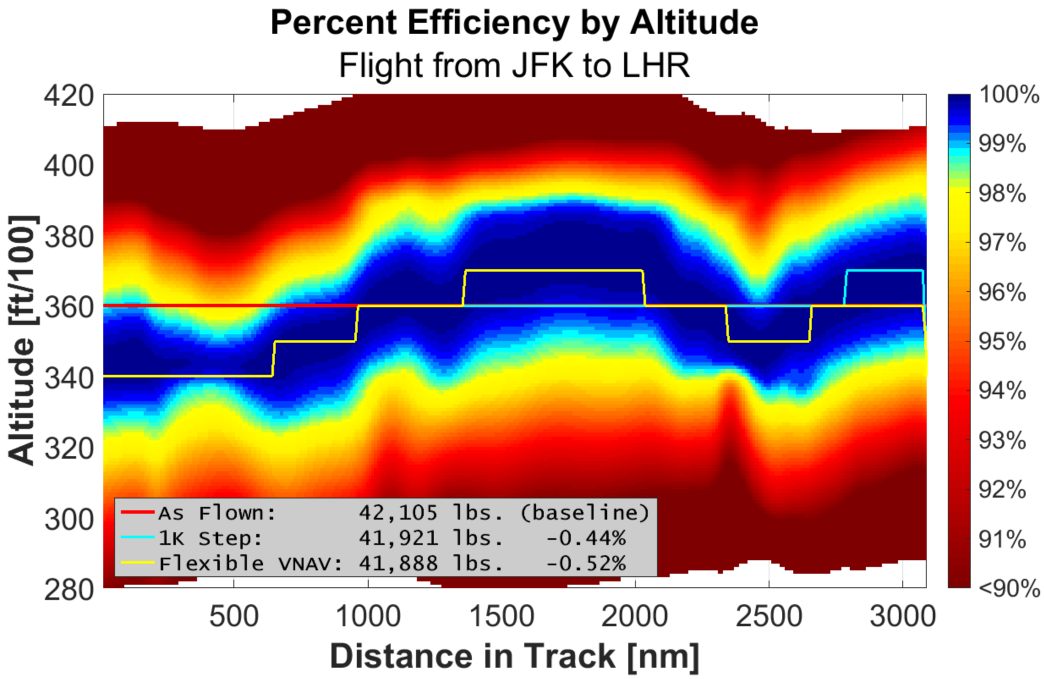

Figure 22: En-route Fuel Efficiency [5]

Figure 22 shades the regions by level of efficiency in terms of percentage of maximum possible SGR. The region that is shaded blue represents the most efficient vertical trajectory that could have performed by this specific flight along its cruise trajectory. This region, further referred to as the "high-efficiency tunnel", continuously changes along the cruise phase of flight. Although this high-efficiency tunnel represents the maximum benefit possible, it is operationally infeasible to perform this type of vertical trajectory since in a real air traffic scenario, altitudes are assigned in 1000-foot increments. Shown overlaid on the high-efficiency tunnel is an example of a vertical trajectory that is constrained to discrete 1000-foot increments. This feasible trajectory was generated using Dijkstra's shortest path algorithm that constrains available altitudes to levels that would be accessible in a real traffic environment with the option to perform various step climb and descent methods [6]. As shown by Figure 22, constraining the optimal vertical trajectory to 1000-foot step climbs improves fuel performance by 0.44%. Additionally, there is also the "flexible VNAV" option for trajectories shown above that also allow for simultaneous climbs and descents, however this type of trajectory typically only offers small improvements from a simple 1000-foot step climb with only a small increase in fuel benefit to 0.52%. For the remainder of this analysis, the results from optimal altitude trajectories are presented for the 1000-foot step climb cases. In later sections, this visualization is discussed for its possible operational application to tactical decision making.

Optimization of the speed is done after altitude optimization by allowing for a cost index input, resulting in a trajectory that is more fuel efficient in terms Mach. For a truly fuel optimal speed, the cost index is set to zero, which maximizes the SGR at each minute interval. This process is then repeated multiple times for alternate cost indices to analyze the result of increasing focus on time related costs. When combined with the altitude optimization done in the previous steps, the resulting trajectory is more efficient in terms of Mach and altitude.

Chapter 4

Results

4.1 Fuel Benefit Pool From Optimal Altitude and Speed

For each flight, the fuel benefit is presented in percentage of possible track fuel that could have been saved through optimal altitude and optimal speeds. The maximum possible fuel benefit for any flight is a scenario where the vertical trajectory is optimized for feasible step climbs operating at the fuel optimal Mach. For the sample of data, this refers to a trajectory that allows for 1000-foot step climbs while also operating at minimum cost index of zero. This results in a trajectory that is simultaneously more efficient in terms of altitude and speed. For each individual flight, there is a percentage of track fuel that can be reduced through this more efficient trajectory. The distribution of this possible fuel benefit is shown in Figure 23.

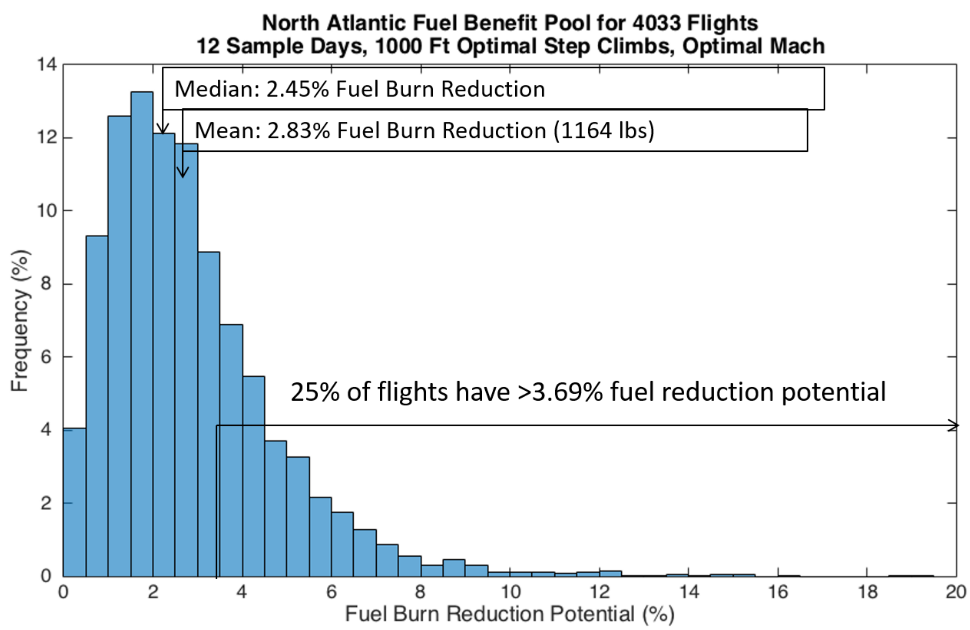

Figure 23: Fuel Benefit for Optimal 1000-Foot Step Climb Altitude and Optimal Speed

For the sample of 4033 flights, the average reduction in track fuel possible is 2.83% (1116 lbs). The total sum of all the fuel benefit possible in terms of absolute magnitude is 4,502,000 pounds of fuel. This reduction in fuel possible, however, is only for the portion of the flight that is within the North Atlantic tracks and does not include possible fuel benefits from optimal altitude and speeds for the regions that extend outside the North Atlantic region. For the worst performing quarter of flights (the flights that have the most benefit available), the fuel benefit possible exceeds 3.96% (1422 lbs).

4.2 High Fuel Benefit Cases

As mentioned in the previous section, 25% of the analyzed flights have fuel reduction potential that exceeds 3.96%. These flights are defined as inefficient flights, and the cause for their inefficiency may be due to operating far off optimal altitude or speed. Comparing the difference between entry altitude and entry Mach with optimal altitude and optimal Mach shows that the worst performing quartile of flights typically operates farther off their optimal trajectory than that of the entire set. This distribution is shown in Figure 24, with negative values indicating that the as-flown trajectory was either higher or faster than the optimal. Each plot is a histogram that shows the difference between the as-flown clearance and the optimal clearance.

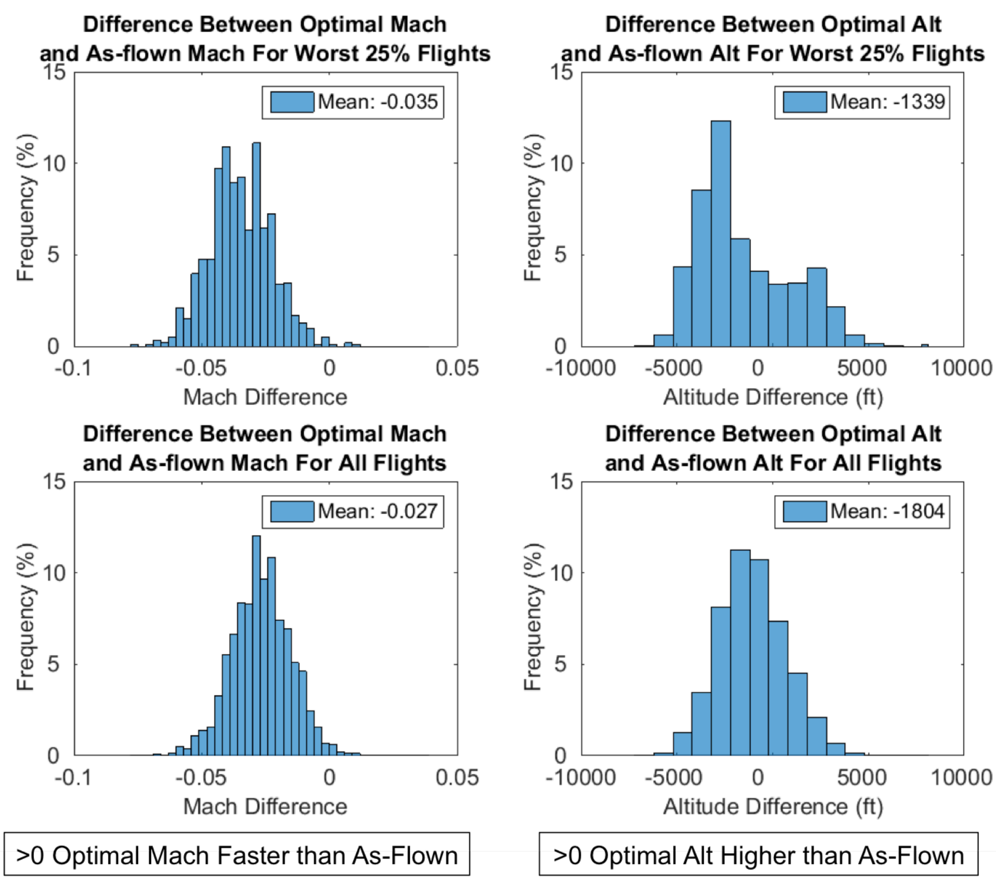

Figure 24: Difference in Mach and Altitude at entry for Inefficient Flights and Total Flights

As shown in Figure 24, the inefficient flights, on average, operate 0.008 Mach faster than the total distribution of flights and also operate 465 feet higher than the total distribution of flights. The cause of the discrepancy in the top is further investigated below by investigating the worst performing flights (the flights with the most benefit available). Table 2 is a table of the 10 worst performing flights.

Table 2: 10 Worst Performing Flights

Aircraft Type	Origin	Destination	Est. Stage Length (NM)	Fuel Benefit (%)	Entry Mach Difference	Entry Altitude Difference
B773	CYYZ	EDDM	3664	11.54	-0.035	-4000
B77L	LSGG	CYUL	3219	11.76	-0.008	-5000
B77L	CYYZ	EGLL	3181	12.69	-0.028	-5000
B77L	CYUL	LSGG	3206	12.74	-0.033	-5000
B77L	EGLL	KDTW	3293	13.11	-0.021	-5000
B773	KJFK	LFPG	3193	13.31	-0.025	-5000
B764	LIRF	KEWR	3868	13.81	-0.059	-6000
B773	CYYZ	EGLL	3117	14.17	-0.021	-5000
B773	EGLL	CYUL	2877	15.14	-0.034	-7000
B77L	CYYZ	EGLL	3118	16.01	-0.040	-6000

Shown in Table 2, the flights with the most benefit available are typically operated by Boeing 777 model aircraft. This aircraft is the second heaviest aircraft in production by Boeing, only smaller than the Boeing 747 model of aircraft. Surprisingly, flights operating the 747 model aircraft do not show up within the worst performing flights, indicating that the level of benefit available for these worst performing flights is more than just aircraft size dependent. This may be caused by increased emphasis on fuel efficiency for heavy aircraft, as the impact on inefficient altitude and speed for larger aircraft is much larger than for smaller aircraft. For these high benefit cases, the aircraft are operating very far off optimal altitude and operating at speeds much faster than their optimal Mach, in some cases 7000 feet above optimal altitude and 0.059 Mach faster than their optimal Mach at the entry point of the tracks.

4.3 Cost Index Constraints

Airlines typically do not operate at the minimum fuel burn speed. Entering the North Atlantic tracks, flights are assigned a Mach number that is typically not the fuel optimal speed, as shown by Figure 24 by the discrepancy in the average and distribution of the optimal and assigned Mach clearances. This Mach is assigned with consideration of other traffic in the area and with what is requested in the aircraft's flight plan. The Mach assigned, therefore, is selected with some consideration on timing constraints for each airline. In order to analyze the effects of alternate cost index settings and speeds on the available fuel benefit, an initial analysis was done to determine the possible fuel benefit for flights that operated at their as-flown Mach, but were allowed the flexibility to perform 1000-foot step climbs freely. The result of this analysis is shown below in Figure 25.

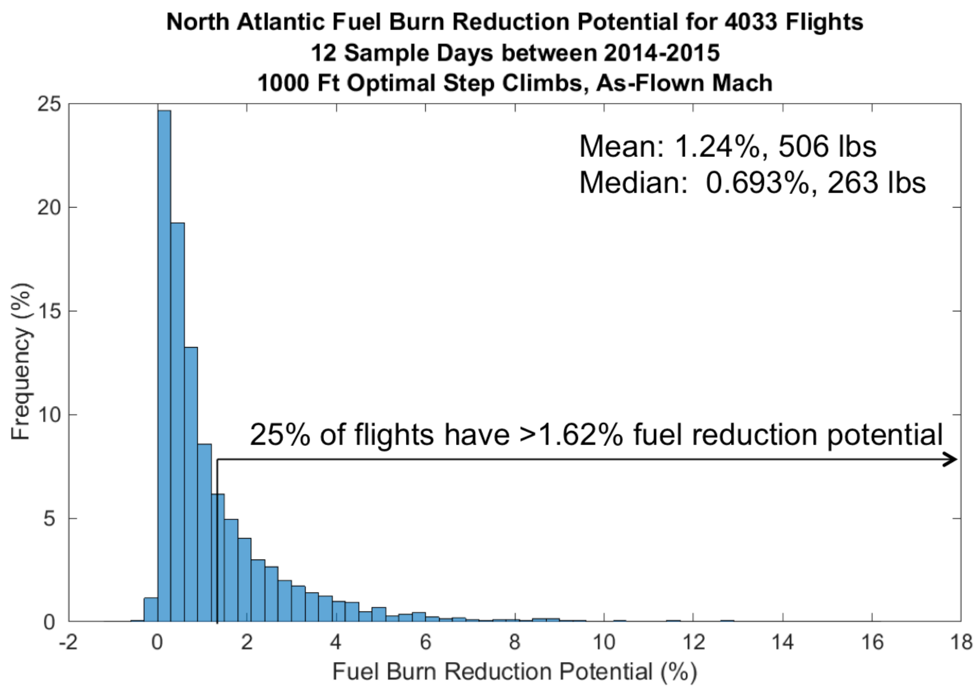

Figure 25: Fuel benefit from 1000-foot optimal step climb and as-flown Mach

The maximum fuel benefit shown before indicates a 2.83% average fuel benefit possible, however, when the speed is fixed to the as-flown Mach, the average available fuel benefit drops to 1.24%, with the benefit originating from more optimal altitudes only. Although there is still opportunity to decrease fuel burn through more efficient altitudes, more than half of the fuel inefficiency is directly caused by operating far off the optimal speed due to time related costs.

As a next step in the analysis, the optimization algorithm constrained each aircraft to operate at their as-flown altitude, but enforced a global cost index to determine the effect on fuel efficiency. This causes the fuel benefit pool to decrease, but also decreases the amount of track flight time. The results from this analysis are shown in Table 3.

Table 3: Effect of Cost Index on Fuel Benefit and flight time

Cost Index	Fuel Benefit Pool (%)	Change in As-Flown Flight time (min) (>0 indicates decrease in time)
CI=0	1.32	-5.09
CI=25	1.20	-3.53
CI=50	0.91	-2.30
CI=75	0.54	-1.30
CI=100	0.13	-0.50
CI=150	-0.84	0.84
CI=200	-1.69	1.67
CI=300	-4.03	3.40

When each aircraft operates at its fuel optimal Mach at their as-flown altitude, the available fuel benefit is 1.32%. One can also see that on average, flights across the North Atlantic are typically operating at a back-calculated cost index of approximately 100, since this cost index offers the smallest non-negative fuel benefit. When considering operating at a high cost index of 300, the average decreases in track flight time from a minimum cost index is 8.49 minutes with an average fuel penalty of 5.35%.

4.4 Accessibility of Optimal Altitude and Speed

The previous analysis indicates that there is a maximum average fuel benefit of 2.83% for flights operating in the North Atlantic. This analysis, however, does not take into consideration if the optimal altitude and speed is available without separation conflicts. Since the NAT airspace lacks high resolution surveillance, separation standards are much greater than for domestic flights. This increased separation can result in scenarios where aircraft are forced to operate at sub optimal altitudes and speeds in order to comply with these separation standards. An example of how these minimum separation standards can affect an aircraft's ability to operate at optimal altitude is shown in Figure 26.

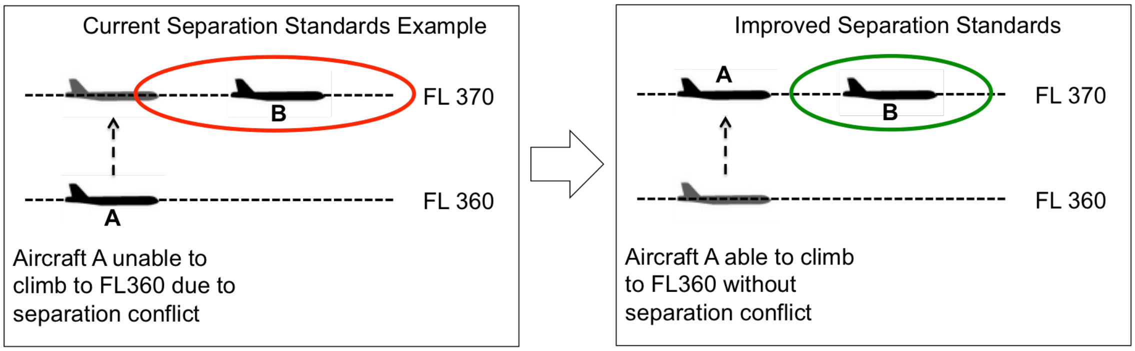

Figure 26: How separation standards can prevent operating at optimal altitude

Currently, there is an initiative to increase surveillance on the NATs with the hope that there will be benefits toward increased flexibility and predictability over this region. With this increased surveillance, separation standards can be reduced from 10-minute separation to 25, 15, or even 5 nautical mile separation. In order to determine what the amount of accessible benefit there is, a simulation was conducted that allowed each aircraft to operate at their optimal altitude and Mach within the track system and the number of conflicts was determined. The criteria that determined whether a conflict arose is whether or not a user defined minimum separation was violated. For aircraft that were conflicted, the available benefit from optimal altitude and speed was ignored to simulate a scenario where traffic prevented that flight from accessing their more efficient trajectory. The result of this analysis is shown in Figure 27.

Separation Minima	Number of Separation Conflicts with Optimal Trajectory	Fuel benefit pool
10 Minute Separation (current standard, ~60 NMI)	1818 (45.1%) flights conflicted	2.51M lbs Fuel
23 NMI Separation	1287 (31.9%) flights conflicted	3.17M lbs Fuel
15 NMI Separation	842 (20.9%) flights conflicted	3.57M lbs Fuel
5 NMI Separation	578 (14.0%) flights conflicted	3.93M lbs Fuel

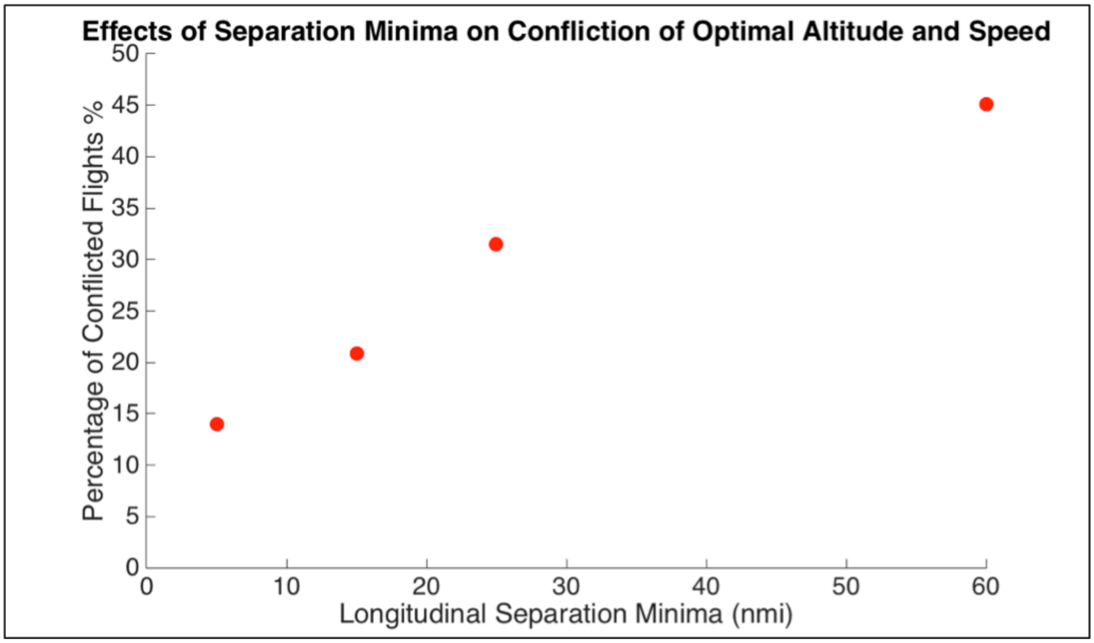

Figure 27: Effects of Separation Minima on Available Fuel Benefit

With the current separation standards of 10 minutes, 45.1% of the sample was unable to operate at their optimal Mach and altitude due to a separation violation. Current initiatives, however, are proposing a reduction of the separation standard to 23 nautical miles, which will reduce the number of traffic conflicts from 45.1% to 31.9% and increasing the benefit pool from 2.51 million pounds of fuel to 3.17 million pounds of fuel. This reduction in the number of conflicts due to decreased separation minima, however, only applies to a longitudinal conflict. This means that for flights operating on the same track, a conflict is when an aircraft is violating the minimum separation from either in front of the aircraft or behind the aircraft. Since the North Atlantic tracks have multiple options for lateral route, there is also a degree in flexibility that allows for flights to achieve optimal altitude and speed but on a different track, which is explored in the next section.

4.5 Fuel Benefit Pool from Optimal Track Assignment

The fuel benefit from optimal track assignment is presented as the percentage of total flight fuel that could have been saved from more efficient track assignment. Unlike the results from optimal altitude and speed, the track fuel benefit from optimal track assignment cannot be isolated from the reduction in total flight fuel benefit due to the effects on varying track distances and location. The results from this analysis are shown below in Figure 28.

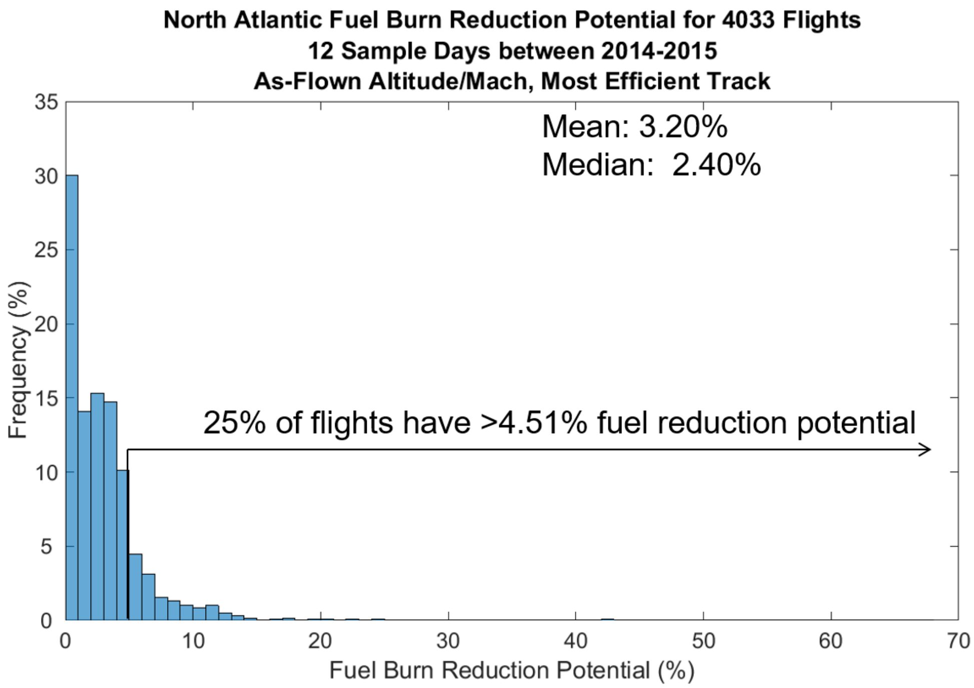

Figure 28: Fuel benefit from Fuel Efficient Track Assignment

Through more efficient selection of tracks, flights can find an average benefit of 3.20% in total flight fuel, with the upper quartile of flights having benefits that exceed 4.51%. Of the 4033 flights analyzed, however, 480 flights (12%) were already operating on their optimal track in terms of fuel burn. The remaining 3553 flights were assigned tracks that were not fuel optimal, which is a result of the capacity limitations on the track that were discussed previously. These capacity limitations severely limit a flights ability to not only capture optimal altitude and speed configurations, but also prevent them from accessing the benefits from optimal track assignments.

4.6 Reduced Lateral Separation on the North Atlantic Tracks

The premise behind the analysis on optimal altitude and speed was that with improved surveillance, separation minima could be reduced, allowing for the opportunity for aircraft to access their optimal altitude and speed configurations. Under this premise, the next step in the analysis was to consider how reduced lateral separation could allow for increased accessibility in optimal trajectories.

Shown above, there is a 3.20% fuel benefit in optimal track assignments. With the current system, however, desirable tracks may reach their maximum capacity and force other aircraft to fly on tracks that are less efficient. Even the longest of tracks at a fixed altitude and speed can only accommodate up to 10-20 flights at a time based on the necessary separation requirements. The analysis on optimal track assignment also shows that 88% of flights along the North Atlantic were assigned tracks that were not fuel optimal. Analyzing the results from the analysis on optimal altitude and speed shows that 45.1% of the sample would have experienced separation conflicts if they were to operate at their optimal altitude and Mach using the current separation standard.

By switching to a reduced lateral separation track system, there would be more tracks available to distribute the system traffic load. A concept of how reduced lateral separation works is shown in Figure 29. Reduced Lateral Separation Standards (RLAT) would result in a reduced number of aircraft on any single track. Since the number of aircraft on any track would decrease, there would be a decreased chance of separation conflicts arising, allowing for more flights to operate at their optimal altitude and speed. The move to reduced lateral separation would also allow for increased accessibility of the 3.20% fuel burn potential from optimal track assignment, as aircraft are now more likely to get assigned tracks with more favorable wind conditions simply due to the fact that there would be more tracks available and less traffic to generate separation conflicts on any single track.

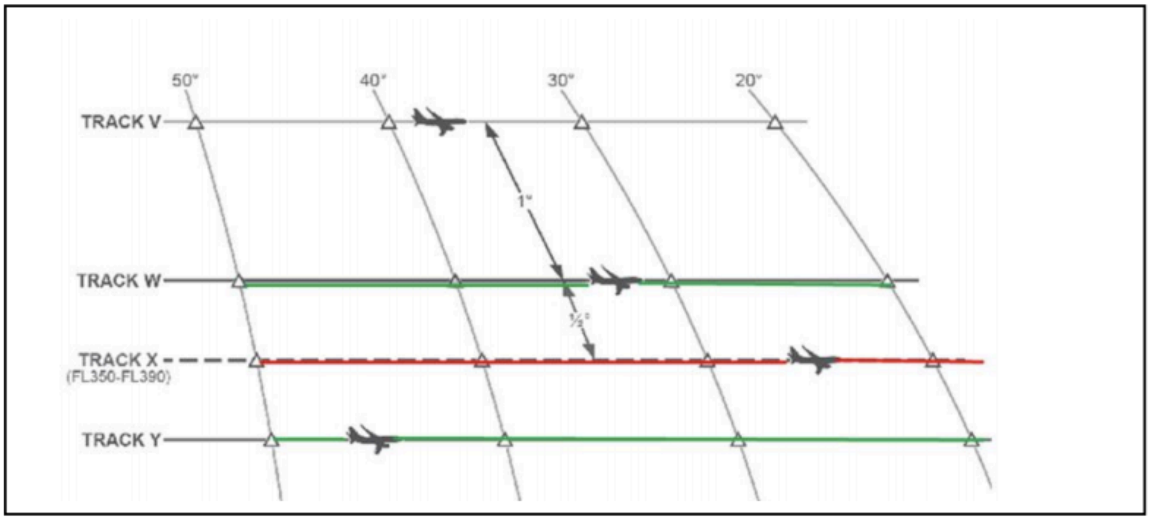

Figure 29: Reduced Lateral Separation Concept [8]

Reduced lateral separation has already been implemented in the North Atlantic tracks on a limited scale. For any day in which reduced lateral tracks are available, a pair of two non-reduced lateral tracks are converted into three reduced lateral tracks; each separated by half a degree latitude. Aircraft equipped with the technology required to operate on these reduced separated tracks have the ability to choose between three tracks with the benefit of operating in a lower traffic environment, thus allowing for operation at more efficient altitudes and speeds.

Chapter 5
Decision Support Tools

Computing the possible benefit from optimal vertical and lateral trajectories yielded a benefit pool of 2.83% possible reduction in fuel from fuel-efficient vertical trajectories and 3.20% from more fuel-efficient lateral routing through improved track selection. These benefits, however, are currently not accessible in the current North Atlantic Track structure and surveillance capabilities. Benefits from improved track assignment are currently inaccessible due to capacity constraints on the tracks. With improved surveillance, the capacity of a single track can be increased since aircraft the position of each aircraft would be known with greater certainty, reducing the size of the safe separation distances. This reduction in separation minima can allow for each flight to access more efficient vertical and lateral trajectories. With more altitudes and speeds available for assignment, the next step was to implement a method to take the cruise altitude and speed optimization algorithm and apply it to a real operational environment. These applications include implementing the altitude and speed optimization algorithms in a prototype electronic flight bag (EFB) application that can be used by pilots to get real time information on their current aircraft fuel and schedule performance.

5.1 Pilot Decision Support Tools

An analysis on optimal altitude and speed prompted the hypothesis that a possible cause for inefficient vertical trajectories may be caused by lack of performance information provided to the pilots. Figure 3 shows what is available to pilots in terms of altitude efficiency. This display is from the FMS and integrates the internal weather forecast and aircraft performance to recommend an optimal altitude for the current aircraft configuration. Combined with the cruise speed performance display shown in Figure 30, pilots are given some information of efficient altitude and speed trajectories. These displays, however, do not immediately associate fuel-efficient trajectories with the direct impact on fuel and also provide little information on the current and future airspace environment.

Figure 30: FMS Cruise Speed Performance Display [9]

Figure 22 shown before is a visualization of fuel performance along the cruise phase of a single flight. This visualization, accompanied by the optimization algorithm outputs, allows for not only a direct comparison between as-flown estimated fuel burn and estimated fuel burn after optimal vertical trajectories, but also shows the future aircraft fuel efficiency environment as an “optimal altitude tunnel.” This analysis prompted the question of whether or not pilots could utilize the information in this visualization to make improved tactical decisions on fuel-efficient altitudes and speeds. This visualization could be implemented in an electronic flight bag (EFB) as a pilot decision support tool.

In order to implement the visualization in Figure 22 in an electronic flight bag, a vertical situation display was conceptualized using research from previous studies. Vakil in 1996 proposed a design for an electronic vertical situation display, which is shown below in Figure 31 [10].

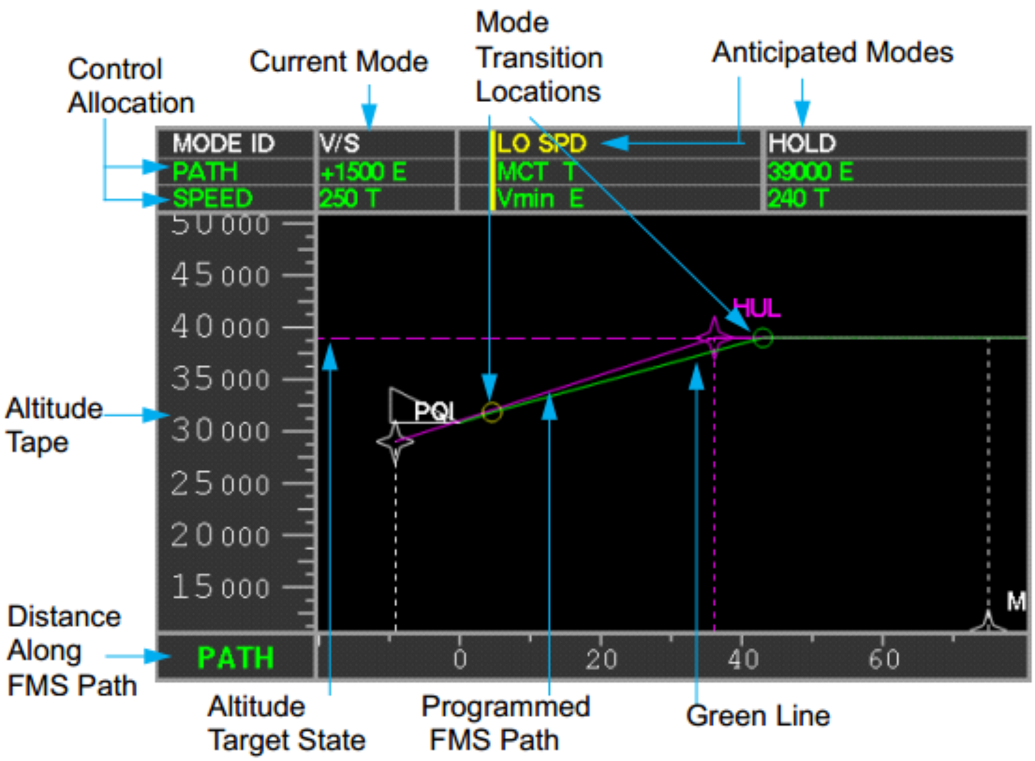

Figure 31: Concept Electronic Vertical Situation Display [10]

The concept electronic vertical situation display in Figure 31 along with current flight instrumentation available to pilots was used as a model to generate a prototype tool that implemented the cruise altitude and speed optimization framework. Key aspects of the display such as altitude clearances and color schemes were selected in order to main consistency with other flight instrumentation. Pilots familiar with current aircraft instrumentation were consulted in order to ensure that there was no inconsistency between the concept prototype tool and available flight instrumentation. The final concept of the prototype tool is shown below in Figure 32.

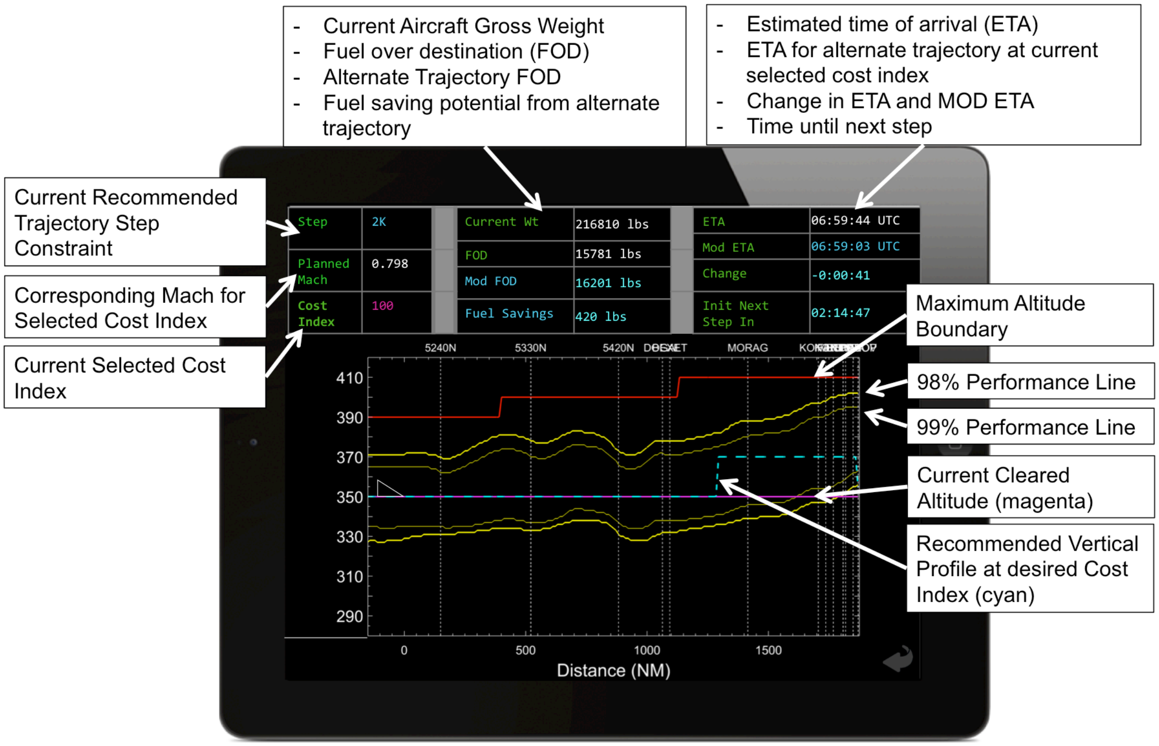

Figure 32: Visualization Implemented in Pilot Decision Support Tool Concept

With the additional display, pilots would be more aware of the current fuel and schedule performance of the aircraft but also what the forecasted performance is in the form of an en-route fuel efficiency display. This tool would allow pilots to quickly evaluate the impact of alternate speeds and altitudes through a direct interaction with the touch-screen display, which can be used to select more efficient trajectories or evaluating the impact of deviations for traffic or turbulence. The "optimal altitude tunnel" allows the pilot to immediately assess the overall trend of fuel optimal altitude and allows for more negotiation with ATC in order to achieve more desirable trajectories.

Chapter 6
Evaluation of Decision Support Tools

Using the prototype tool proposed in the previous section, the next step was to evaluate how the addition of this tool would affect pilot decision making during flight. This evaluation was done as a web-based survey where pilots are presented with in-flight situations and were asked to make a decision with and without the prototype tool. The hypothesis behind this study is that with increased awareness of current aircraft performance, the pilot would feel more empowered to request changes in their trajectory that would benefit their aircraft fuel and schedule performance.

6.1 Study Design Methodology

The study is a scenario-based evaluation targeted toward airline pilots. Each scenario places the subject in a simulated flight deck environment mid-flight. The pilot is provided with conventional flight documentation and is prompted to make a decision on their altitude and speed. The scenarios themselves are designed such that they are able to allow for testable situational awareness. The premise behind testable situational awareness is that a subject, when fully aware of their surrounds, would always make the same “correct” decision [11]. In this evaluation, the “correct” decision is defined as the fuel minimizing decision that also avoids turbulence and maintains schedule performance. The hypothesis of this study, is that when aided by the prototype tool, the subjects will be more likely to be situationally aware and make the “correct” decision.

For the evaluation, each pilot is presented with eight scenarios, each consisting of unique flight documentation that would be used to make tactical decisions on speed and altitude. For each pilot, the order and presence of the prototype tool is randomly generated, with the presence of the tool being the independent variable of the study. In order to account for the learning process, two populations are created; one where the first half of the scenarios are presented with the prototype tool and one where the first half of the scenarios are not presented with the tool. The remaining scenarios are then presented with or without the tool depending on whether or not the subject has seen it in the first half of the scenarios. In total, each pilot is shown 4 scenarios with the tool, and 4 scenarios without the tool. The order of each set of 4 is randomly generated, as well as the order of when the tool is shown (first 4 or second 4 scenarios).

The scenarios created for the study represent real-world scenarios that could happen during any flight. Within each scenario is a unique event that prompts the subject to make a decision on their altitude or speed. A list of the scenarios is shown below in Table 4.

Table 4: Scenario Descriptions

#	Description	Situationally Aware Decision
1	**Weight Limited Climb Into Turbulence** A climb is indicated in the flight plan, however, there is a report that there is moderate turbulence at that flight level as well as the current flight level. The aircraft is currently too heavy to climb over this flight level.	**Descend below the turbulence or slow to penetration speed** In doing so, the aircraft takes a heavy fuel penalty, however the ride is smooth. Slowing ensures better penetration through turbulence
2	**Efficient Climb Due to Difference in Weight** Aircraft loaded significantly less fuel on takeoff making the current flight plan obsolete.	**Perform a step climb** Since the aircraft is lighter and there is no indication of turbulence, the pilot should pursue reduced fuel burn by performing a step climb.
3	**Weather Forecast Motivated Descent** A weather forecast update has been issued. This weather forecast indicates more efficient tailwinds at lower flight levels.	**Perform step descent** The flight plan suggest maintaining current altitude, however the new weather forecast makes the filed flight plan inaccurate
4	**Climb into Turbulence** Climb into turbulence is in the flight plan. No turbulence at current altitude	**Maintain current altitude or slow to penetration speed** In doing so, the aircraft takes a fuel penalty, however the ride is smooth. Slowing ensures better penetration through turbulence
5	**Early Arrival** Flight departs the origin 20 minutes early and is still expected to arrive 20 minutes early	**Reduce Mach Number** Since the flight is scheduled to arrive early, slowing down to meet the scheduled in time is the correct decision. Slowing down will also improve fuel burn
6	**ATC Cleared Slow Due to Traffic** There is traffic ahead operating at a very slow Mach number. ATC sees a separation conflict occurring and so they clear the flight to a very slow Mach number as well	**Perform a Step Climb Immediately** By performing a step climb immediately, the aircraft takes a minor fuel penalty, however the pilot can maintain schedule performance by avoiding the slow traffic ahead
7	**Small Savings Potential Due to Weight Difference** Aircraft is loaded with slightly less fuel on takeoff.	**Maintain current altitude** Although the prototype tool indicates a step climb as being more fuel efficient, the level of benefit is negligible
8	**Tool and Flight Plan Indicate Same Trajectory** No deviation from flight plans	**No deviation from the flight plan** The prototype tool and the flight plan will both read the same recommendations

Each scenario is accompanied by unique flight documentation, such as a flight plan, weather forecasts, fuel planning slips and aircraft performance guidelines. Within each scenario, the subject is placed at key moments in the flight where they are asked to make a decision on their altitude and speed through a textual description of the aircraft environment. An example of this scenario description is shown below in Figure 33.

Scenario Description

You are operating a 757-200 from YYZ-FRA approaching 52N 40W North Atlantic Crossing.
You are currently in the North Atlantic Track System on Track W (TUDEP 52/50 53/40 54/30 55/20 RESNO)
You are cleared at FL 350 at Mach 0.80.
You departed with 3046 pounds less payload than planned.

- **Plan Takeoff Weight**: 235844 lbs
- **Actual Takeoff Weight**: 232798 lbs
- **Current Weight**: 211200 lbs

The map below shows the current location of your aircraft along the route in the flight plan.

Figure 33: Scenario Page Format. Textual Description

Each scenario is also accompanied by a unique aircraft type and route type based on real world flight routes. The route type is either a domestic flight or an international flight. Both types of flights were used as part of the study because flights operating domestically and internationally have unique operating environments and restrictions. For example, domestic flights are restricted to 2000-foot flight level increments whereas North Atlantic flights are free to operate at 1000-foot flight level increments. Since each of these types of routes are also operated by different types aircraft, performance guidelines are provided for aircraft representative of the traffic mix for those types of routes. The routes and aircraft types used in the study are shown below in Table 5.

Table 5: Routes and Aircraft Types

Origin-Destination	Route Type	Aircraft Type
ATL-SEA	Domestic	Boeing 737-700
JFK-LHR	Oceanic, North Atlantic	Boeing 757-800
YYZ-FRA	Oceanic, North Atlantic	Boeing 757-800

Additional demographic information is collected before presenting the scenarios. This demographic information includes the pilot's aircraft certifications, hours of flight time as pilot in command, and the type of training they received. The subjects are also introduced to the prototype tool in order to familiarize themselves with the functionality and usability of the tool. Once they understand the tool, they are presented with the scenarios described before. A storyboard representation of the entire evaluation is shown below in Figure 34.

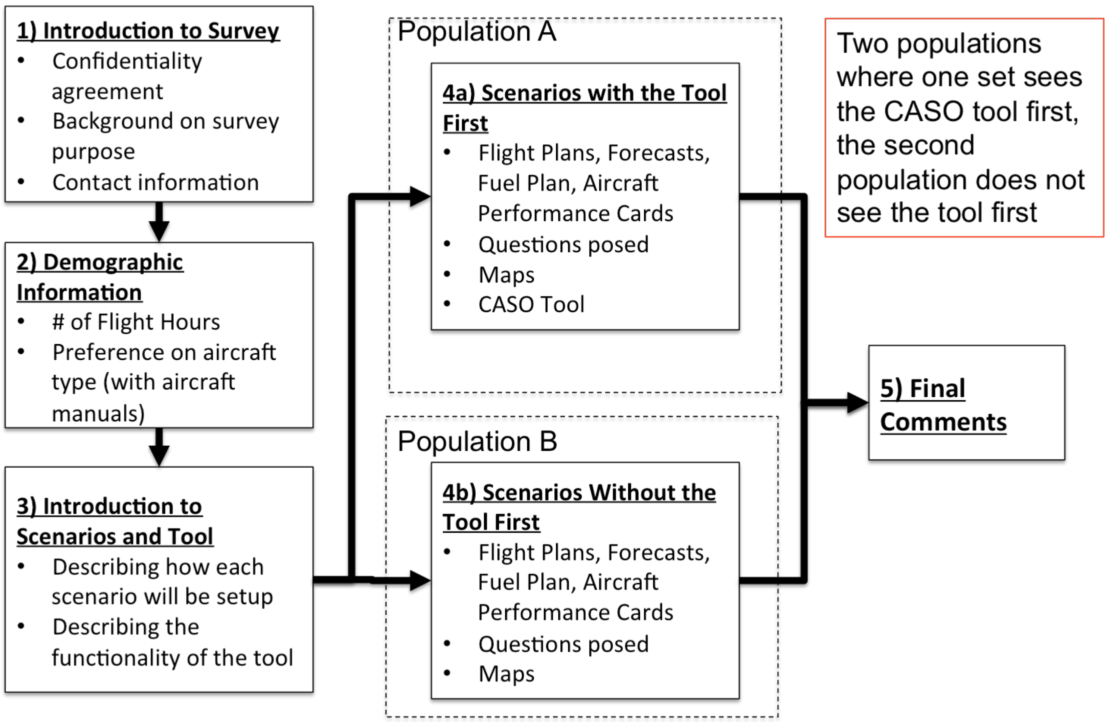

Figure 34: Pilot Decision Support Tool Evaluation Storyboard

6.2 Feedback Structure

For each scenario, there is a series of questions that are posed that are standard across each scenario. The set of standard questions are listed below in Table 6. The questions posed are presented next to the scenario itself to allow the subjects to review all the additional documentation before responding. An example excerpt of the format of a single scenario is shown in Figure 33 and Figure 35.

Table 6: Standard Questions

Question	Answer Selections
Would you request a change in Speed/Mach?	Request Increase in Speed Request Decrease in Speed Maintain Current Mach
Would you request a change in altitude?	Request Increase in Speed Request Decrease in Speed Maintain Current Mach
If you are requesting changes in your altitude or speed, when would you request this change to be executed?	Immediately Later *Text Entry: When?*
Describe any additional actions that you would take.	*Free Response*
What motivated this decision? Explain your reasoning.	*Free Response*
Is there any additional information that would aid this decision?	*Free Response*

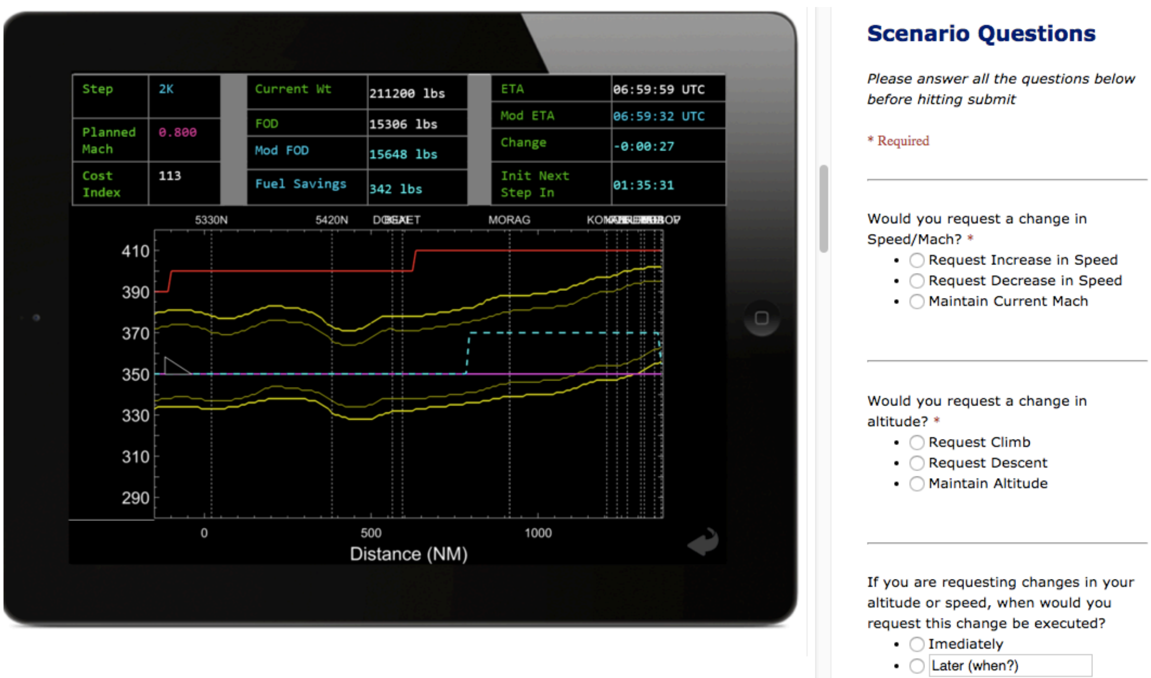

Figure 35: Scenario Page Format. Prototype Tool Display

The objective questions regarding the changes in speed and altitude are used to gauge whether or not the pilot made the "correct" (situationally aware) decision. The free response questions help to determine the motivation behind the decision, and will be used to help design future studies involving the decision support tool.

Unseen in Figure 35 are the additional supporting documentation that is provided for each scenario. These documents include the flight plan for the scenario, fuel planning slip, weather forecast and aircraft performance guidelines. These documents can be found in the Appendix for convenience.

At the end of the evaluation, there is also a place for general feedback on the tool display such as additional requested features or improved user interface. The set of feedback questions are shown below in Table 7. A sample of the end-survey feedback form is shown below in Figure 36.

Table 7: Feedback Questions

Question
Would you use this app during a normal flight? Why/Why not?
Overall, how easy is it to interpret the display? How can we improve this?
What additional features would you like to see?
Is there any other feedback that you would like to provide?

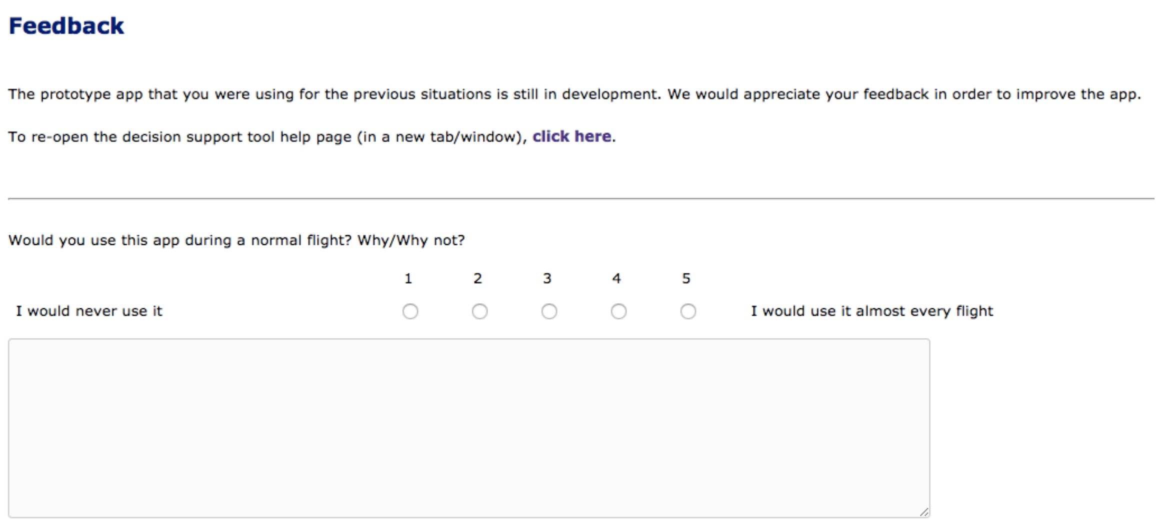

Figure 36: End-survey Feedback Form

6.3 Preliminary Results

The survey has been released and preliminary results have been recorded. Five pilots represented the pool of preliminary responders that completed the survey. Two of these subjects only have seven of the eight scenario responses recorded, due to a technical malfunction with the web recording system. Table 8 summarizes the qualifications of these five pilots.

Table 8: Response Demographics

Normal Type of Operation	Normal Role	Flight Hours	Types of Aircraft Certified On
Both Domestic U.S. and International	Captain	17000	Airbus A300/310, Airbus A320 family, Boeing 757, Boeing 767, McDonnell Douglas MD-11, McDonnell Douglas MD-80/MD-90
Domestic U.S.	Captain	2500	Airbus A320 family
Domestic U.S.	First Officer	3500	Airbus A320 family, McDonnell Douglas DC-10, McDonnell Douglas MD-80/MD-90
Both Domestic U.S. and International	First Officer	3000	Airbus A320 family, Bombadier CRJ
Both Domestic U.S. and International	Captain	12000	Boeing 737, Boeing 757, Boeing 767, Boeing 777, McDonnell Douglas DC-9, McDonnell Douglas MD-80/MD-90

From Table 8, it is clear that these responses include both Domestic US and International pilots with varying degrees of experience, who are type certified on a variety of aircraft.

Due to the random assignment of the scenario order, the number of responses to each scenario with and without the app is not equal. The responses in each category are summarized in Table 9. There were two responses that were not recorded due to a technical error with the web recording system, one each for scenarios 3 and 6.

Table 9: Breakdown of Responses

		Altitude Responses		Speed Responses	
#	Description	Situationally Aware Without App	Situationally Aware With App	Situationally Aware Without App	Situationally Aware With App
1	**Weight Limited Climb Into Turbulence**	3/3	1/2	3/3	1/2
2	**Efficient Climb Due to Difference in Weight**	0/1	2/4	1/1	4/4
3	**Weather Forecast Motivated Descent**	0/3	1/1	3/3	1/1
4	**Climb into Turbulence**	1/2	2/3	2/2	2/3
5	**Early Arrival**	4/4	1/1	1/4	1/1
6	**ATC Cleared Slow Due to Traffic**	0/1	3/3	0/1	3/3
7	**Small Savings Potential Due to Weight Difference**	1/1	4/4	1/1	4/4
8	**Tool and Flight Plan Recommend Same Trajectory**	4/4	1/1	4/4	1/1
	Total	**13/19**	**15/19**	**15/19**	**17/19**

Based on the limited sample, the app appears to have a minor effect on pilot decision-making. Situationally aware decisions regarding both speed and altitude were made more often when the tool was present than when it was not with 32 out of 38 situationally aware responses with the app, compared to 28 out of 38 without the app. The responses vary by scenario.

The free responses in Scenario 6, where the aircraft is cleared at a slow Mach number due to traffic, indicate an increase in situational awareness. In this scenario, pilots recognized that there is the option to perform a step climb earlier than in the flight plan in order to avoid taking a schedule penalty due to the speed restriction imposed by ATC. For each subject where the tool was present in scenario 6, the situationally aware decision on altitude and speed was made while the pilot without the tool made the decision to maintain the present altitude even under the speed restriction. Below are comments that indicate that the subjects were situationally aware.

"Flt plan calls for 360 and .80M so you can climb and get above speed bump traffic and get normal speed."

"Will changing altitude eliminate the traffic conflict? If so, climb and return to planned Mach"

"Can a reroute or climb to 350 get me around traffic?"

The Mach number and altitude decisions in Scenarios 2 and 3 are consistent with what would be expected; in Scenario 2, the aircraft weight is different from what is filed on the flight plan, while the weight is able to be updated in the app. Similarly, Scenario 3 incorporated updated weather conditions in the app that only impact cruise altitude. Since the only way in which the tool differs from the flight plan is in altitude, the only difference in decision-making should be regarding the altitude decision. The responses indicate increased situational awareness in the altitude category, while all of the pilots followed the planned Mach number as expected.

Scenario 5, with the aircraft earlier than scheduled, only incorporates a difference regarding Mach number. The optimal altitude profile is consistent between the flight plan and the EFB tool, so all pilots should correctly select their altitude trajectory. This is consistent with the results. The situational awareness is tested regarding Mach number; the situationally aware decision is to slow down and save fuel, which these preliminary results indicate is clearer when the app is present. In the free response section, the decision support tool was indicated as the reason for slowing down when it was present; when it was not, the pilot indicated that the decision to slow down was because "SEA is traditionally gate constrained" and a decrease in speed would allow the flight to arrive on schedule.

Scenarios 1 and 4, both of which involve climbs into turbulence, indicate that the app has little or no impact on decisions regarding altitude or speed when turbulence is involved. In these scenarios, the situationally aware decision can take one of two forms: either the pilot makes an altitude adjustment to avoid all reported turbulence while maintaining their speed, or the pilot slows to turbulence penetration speed and may or may not make an altitude change in order to find a less turbulent flight level. Both are considered situationally aware because in both cases, the pilot has taken actions that indicate that they are conscious of the turbulence. For all the responses that make the situationally aware decision on altitude without the app in scenario 1, the pilots indicated that the motivating factor in the decision was ride quality without any mention of fuel penalty.

The last two scenarios closely matched the flight plan and the decision support tool to one another; Scenario 7 offered two situationally aware options: either climb and take a small fuel savings, or maintain the current altitude since the fuel savings are minimal. Only one of the responses with the tool took advantage of this fuel savings, while the others maintained the Mach and altitude for which they were cleared. In both scenarios, the flight plan provides a situationally aware decision; therefore the results show that even the pilots without the app were capable of determining the situationally aware response.

In the event that maintaining altitude or speed is the correct decision, it is unclear why the pilots chose to do so. This could have been motivated by either the pilot's awareness that the app or flight plan recommended them to maintain altitude, or the pilot is simply maintaining altitude due to the fact that nothing prompted them otherwise.

As a whole, pilots were more likely to choose the best option regarding speed than regarding altitude (32 total situationally aware speed selections, compared to only 28 situationally aware altitude selections). This is due in part to the design of the survey, as only two of the eight scenarios were clearly meant to elicit a change in speed. The tool also generally has some positive effect on pilot decision-making. All five pilots made more situationally aware decisions with the app than they made without it. This indicates that the decision support tool has some operational utility in this limited sample.

Chapter 7
Conclusions

The purpose of this study was to quantify the fuel benefit potential over the North Atlantic Tracks from optimal altitude, speed and track assignments. This analysis used a sample set of 4033 flights that operated within the North Atlantic Tracks over 12 days that span all seasons in a year. Combining the Global Forecast System weather model, the PianoX aircraft performance tools and airline weight data, an estimate of track fuel burn was determined. The trajectory for each of the 4033 flights was then optimized and the track fuel burn was estimated for these optimal trajectories and compared with the original trajectories. The result from this analysis indicates that there is a 2.83% track fuel saving potential from optimal altitude and speed and a 3.20% fuel saving potential from optimal track assignments.

The fuel savings from optimal altitude and speed are currently inaccessible due to the minimum separation requirements over the NATs. Simulating an environment where all aircraft are allowed to operate at their optimal altitude and speed results in 54.9% of flights violating the current separation minima. There are current initiatives to reduce longitudinal separation from 10-minute separation to a fixed 23 nautical mile separation. With a 23 nautical mile fixed separation distance, only 31.9% of flights will be unable to achieve optimal altitude and speed.

The tracks on the current system are separated by 1-degree latitude. This level of separation results in flights being unable to access optimal tracks due to the traffic constraints on the optimal track. Performing an analysis on optimal track assignment indicates that 88% of flights were assigned tracks that were sub-optimal. The analysis on optimal altitude and speed indicates that 45.1% of flights were unable to access optimal trajectories due to separation conflicts. With reduced lateral separation, aircraft will be more capable of accessing tracks closer to the optimal track. This reduction in lateral separation distributes the traffic entering the system among more tracks, and thus reduces traffic on any individual track. This apparent reduction in traffic will also allow for increased accessibility of the fuel burn reduction potential since there will be less aircraft on any individual track to generate separation conflicts.

Through the study on optimal altitude and speed, pilot decision support tools were hypothesized and created using visualizations from the analysis and previous research efforts. Consultation with airline pilots and research on current flight instrumentation was used to model the prototype tool. The prototype is evaluated for its impact on tactical pilot decision-making on altitude and speed. A web-based approach that placed subjects in flight deck environments is being conducted in order to study these effects. The study evaluates the pilot's situational awareness with or without the presence of the prototype tool. Preliminary results indicate that the decision support tool has some operational utility.

Appendix

```
142044 EGGXZOZX
(NAT-1/2 TRACKS FLS 310/390 INCLUSIVE
FEB 15/1130Z TO FEB 15/1900Z
PART ONE OF TWO PARTS-
A ERAKA 60/20 62/30 62/40 61/50 SAVRY        → Track A
EAST LVLS NIL
WEST LVLS 310 320 330 350 360 370
EUR RTS WEST NIL
NAR NIL -
B GOMUP 59/20 61/30 61/40 60/50 URTAK        → Track B
EAST LVLS NIL
WEST LVLS 310 320 330 350 360 370 380 390
EUR RTS WEST NIL
NAR NIL -
C SUNOT 58/20 60/30 60/40 59/50 AVUTI        → Track C
EAST LVLS NIL
WEST LVLS 310 320 330 350 360 370 380 390
EUR RTS WEST NIL
NAR NIL -
D PIKIL 57/20 59/30 59/40 58/50 DORYY        → Track D
EAST LVLS NIL
WEST LVLS 310 320 330 340 350 360 370 380 390
EUR RTS WEST NIL
NAR NIL -
E RESNO 56/20 58/30 58/40 57/50 HOIST        → Track E
EAST LVLS NIL
WEST LVLS 310 320 330 340 350 360 370 380 390
EUR RTS WEST NIL
NAR NIL -
END OF PART ONE OF TWO PARTS)
```

Figure 37: Track Definition Format

B752 KJFK -> EGGL

TO		LAT	LONG	MACH	MAG. COURSE	GRND SPD (KT)	TEMP DEV (F)
IDENT	FL	DIST REM. (NMI)	TOTAL TIME (HH:MM)	TOTAL BURN (LBS)	MAG. HEADING	TRUE AIRSPD (KT)	WIND (°/KT)

-- BEGIN FLIGHT PLAN EXCERPT --

ACK		N41.28	W070.03	800	058°	438	-05
ACK	33	2915	00:23	3339	066°	463	350/068
KANNI		N42.63	W067.00	800	065°	434	-02
KANNI	33	2754	00:45	6380	072°	464	090/060
PORTI		N46.50	W052.00	800	069°	475	+02
PORTI	35	2072	02:15	18242	073°	462	320/031
N47W050		N47.00	W050.00	800	078°	470	+02
4750N	35	1992	02:25	19535	084°	462	330/052
N48W040		N48.00	W040.00	800	078°	481	+13
4840N	35	1581	03:16	25947	080°	469	320/019
N49W030		N49.00	W030.00	800	086°	461	+08
4930N	37	1170	04:08	32290	077°	463	000/076
N49W020		N49.00	W020.00	800	071°	464	+04
4920N	37	0778	05:00	38324	068°	461	000/029
SOMAX		N50.00	W015.00	800	090°	461	+04
SOMAX	37	0576	05:26	41306	089°	461	350/008
ATSUR		N50.00	W014.00	800	066°	460	+04
ATSUR	37	0536	05:31	41907	066°	461	330/006
EVRIN		N51.78	W006.56	800	094°	447	+02
EVRIN	39	0235	06:11	46401	098°	460	080/035
NEKAP		N51.73	W005.29	800	095°	451	+01
NEKAP	39	0185	06:17	47147	100°	459	080/041
ABDUK		N51.64	W003.80	800	096°	447	+01
ABDUK	39	0134	06:24	47900	102°	459	070/049
NUMPO		N51.61	W003.28	800	102°	447	+01
NUMPO	39	0113	06:27	48203	108°	459	070/051
OKESI		N51.44	W002.06	800	103°	449	+00
OKESI	39	0062	06:34	48952	109°	459	070/052
BEDEK		N51.37	W001.56	800	103°	448	-00
BEDEK	39	0042	06:36	49259	110°	459	070/054
NIGIT		N51.31	W001.17	800	091°	444	-00
NIGIT	39	0031	06:38	49413	097°	459	070/054
D273L		N51.31	W000.77	800	048°	412	-03
D273L	35	0011	06:41	49725	052°	459	070/054

-- END FLIGHT PLAN EXCERPT --

Figure 38: Sample Flight Plan for Web-based Evaluation

Pressure Altitude 1000 Ft	Std Temp °C	Cruise Speed Mach	Buffet Margin Limited		Engine Thrust Limited		
			1.3 G Smooth Air to Moderate Turbulence	1.5 G Moderate Turbulence and greater	Temp Deviation from ISA - °C		
					+ 10 and Colder	+ 15	+ 20
41	-56	0.84	179000	155000	159000	150000	140000
		0.82	189000	164000	165000	179000	171000
		0.80	192000	166000	199000	193000	186000
		0.79	192000	166000	201000	196000	189000
		0.78	191000	166000	203000	198000	191000
40	-56	0.84	188000	163000	168000	159000	148000
		0.82	198000	172000	195000	168000	180000
		0.80	201000	175000	209000	203000	196000
		0.79	202000	175000	212000	207000	200000
		0.78	201000	174000	213000	207000	201000
39	-56	0.84	197000	171000	177000	168000	157000
		0.82	208000	180000	205000	199000	190000
		0.80	211000	183000	220000	214000	207000
		0.79	211000	183000	223000	217000	210000
		0.78	211000	183000	224000	219000	212000
38	-56	0.84	207000	179000	187000	177000	166000
		0.82	215000	189000	210000	209000	201000
		0.80	222000	192000	231000	225000	215000
		0.79	222000	192000	234000	229000	222000
		0.78	221000	192000	236000	231000	223000
37	-56	0.84	217000	188000	198000	188000	176000
		0.82	229000	198000	228000	221000	212000
		0.80	233000	202000	244000	237000	230000
		0.79	233000	202000	247000	241000	234000
		0.78	232000	201000	248000	243000	235000
36	-56	0.84	228000	198000	209000	198000	187000
		0.82	240000	208000	240000	233000	224000
		0.80	224000	212000	256000	250000	243000
		0.79	224000	212000	260000	254000	246000
		0.78	243000	211000	261000	256000	248000
35	-54	0.84	239000	207000	216000	205000	192000
		0.82	252000	218000	250000	242000	232000
		0.80	256000	222000	267000	260000	252000
		0.79	256000	222000	271000	254000	256000
		0.78	255000	221000	273000	256000	258000
34	-52	0.84	251000	217000	223000	205000	196000
		0.82	264000	229000	260000	242000	239000
		0.80	269000	233000	278000	260000	261000
		0.79	269000	233000	282000	264000	265000
		0.78	268000	232000	284000	266000	267000
33	-50	0.84	263000	228000	229000	211000	199000
		0.82	277000	240000	269000	251000	245000
		0.80	281000	244000	289000	270000	169000
		0.79	282000	244000	293000	275000	274000
		0.78	281000	243000	295000	277000	275000
32	-48	0.84	275000	239000	235000	215000	200000
		0.82	290000	251000	278000	259000	251000
		0.80	295000	256000	300000	280000	276000
		0.79	295000	256000	304000	284000	282000
		0.78	294000	255000	306000	286000	284000
31	-46	0.84	288000	250000	241000	220000	200000
		0.82	304000	263000	287000	266000	255000
		0.80	309000	268000	310000	290000	284000
		0.79	309000	268000	315000	294000	290000
		0.78	308000	267000	317000	298000	293000

Figure 39: Sample Aircraft Maximum Altitude Capability For Web-Based Evaluation

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