Aircraft En-Route Performance Considering Winds-Aloft

Philip R. Thomas[1]

and

Timothy T. Takahashi[2]

Arizona State University, Tempe, AZ, 85281, USA

In this paper, we analyze mission performance with real-world winds-aloft models. We compare flight with the wind, against the wind to flight in still air to determine the effects of winds upon mission fuel economy. We analyze commercial flight profiles using a conventional narrow-body-transport model (reminiscent of an Airbus *A320*), and a more hypothetical "high-altitude" capable aircraft. These models document the effects of winds aloft on en-route cruise performance. We demonstrate how radically the optimal mission profiles change in the presence of winds aloft, and how dependent the best cruise altitude is on the aircraft heading. Aircraft with flight capability above FL400 appear to provide improved performance in flight against the winds without compromising performance in other flight regimes.

I. Introduction

TRADITIONAL Aircraft Design textbooks present aircraft performance representative of flight in still-winds on standard-day conditions even though real-world conditions may vary widely. [1][2][3][4] In flight operations, pilots are expected to take-off, land and fly en-route at temperatures that deviate as much as (or even more than) +/- 30°C from the temperature-altitude profile published as the standard reference altitude. [5][6] As a consequence of these real-world conditions, aircraft flight manuals (see references [7], [8] and [9] for example) publish climb and en-route performance estimates at standard as well as non-standard temperature conditions; see Figure 1, overleaf.

But what of winds aloft?

Traditional flight manuals [7][8][9] present takeoff, landing and initial climb performance as a function of reported headwind. Beard & Takahashi [10] demonstrated how much obstacle clearance capability can be impacted the choice of flap-retraction altitude but noted that the traditional concept of applying a factored airport reported headwind [11] to the departure air-phase performance many miles from the runway seemed to over simplify the real-world problem.

Once aircraft climb beyond 1,500-ft AGL, traditional aircraft performance methods [12] and manuals [7][8][9] distill en-route performance into a concept of an aircraft that flies an "equivalent still air distance." That is, we model the aircraft as if it flew through still air; and consider en-route performance in terms of fuel-consumed per still-air-nautical mile flown. Flight planning services to assist dispatch compute ESAD based upon seasonal and real-time winds and nominal flight speeds. [13][14]

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[1] M.S. Candidate, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85287. Member AIAA

[2] Professor of Practice, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85287. Associate Fellow AIAA.

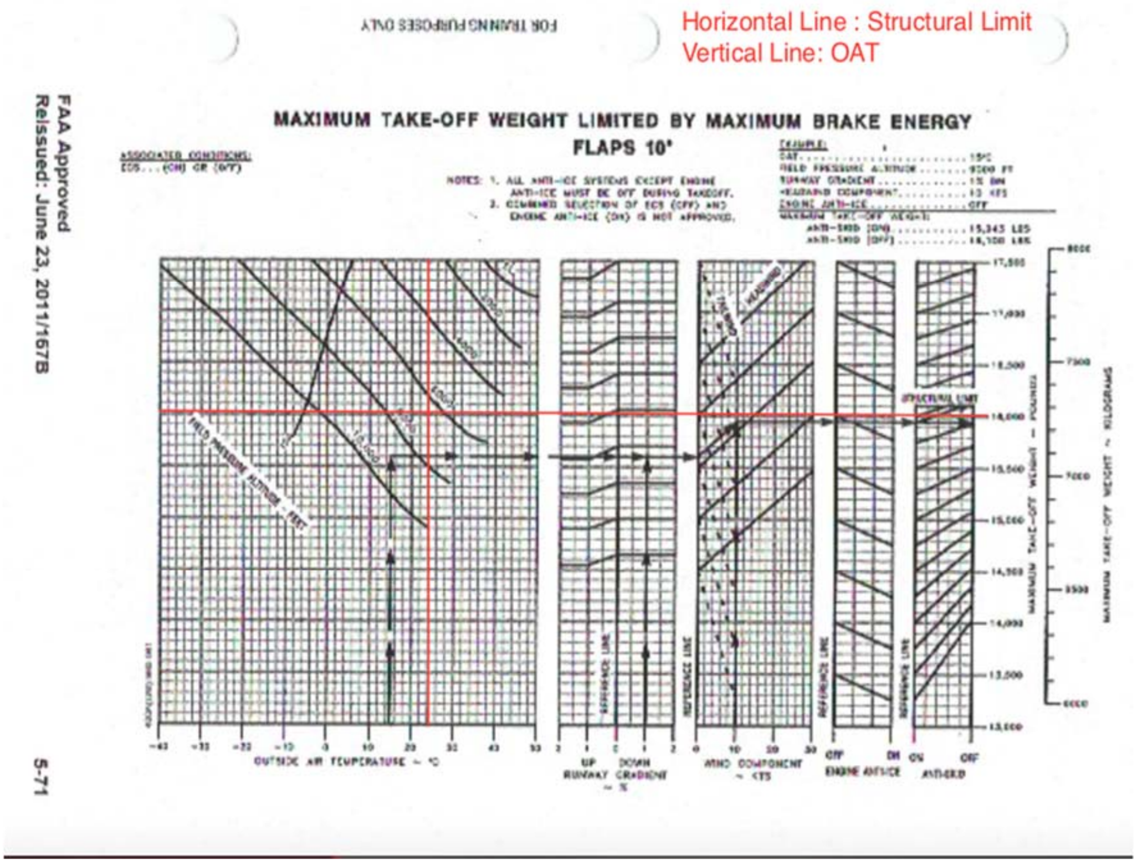


FIGURE 1 - Example Flight Manual Data Showing performance as a function of airfield temperature & altitude as well as airfield reported surface winds [9]

The Department of Atmospheric Science at the University of Wyoming maintains a web-site [15] with a comprehensive historical collection of real-time winds aloft data derived out of telemetry obtained from sounding balloon launches. Twice a day, every day of the year, the United States National Weather Service – part of NOAA, the National Oceanic and Atmospheric Administration - releases 92 weather balloons; see Figure 2. [16] These balloon flights last for around 2 hours; they can drift as far as 125 miles from launch and can ascend to an altitude over 100,000 ft. (about 20 miles). They carry radiosondes that transmit pressure, temperature and relative humidity information during the ascent. By tracking the position of the radiosonde, the National Weather Service can infer the wind speed and wind direction. This website contains this flight data in a consolidated database.

Interrogating this database for any particular date and place, we can see how the winds aloft vary in direction and magnitude; see Figure 3, overleaf. Here, for example, we see wind conditions for Upton, NY

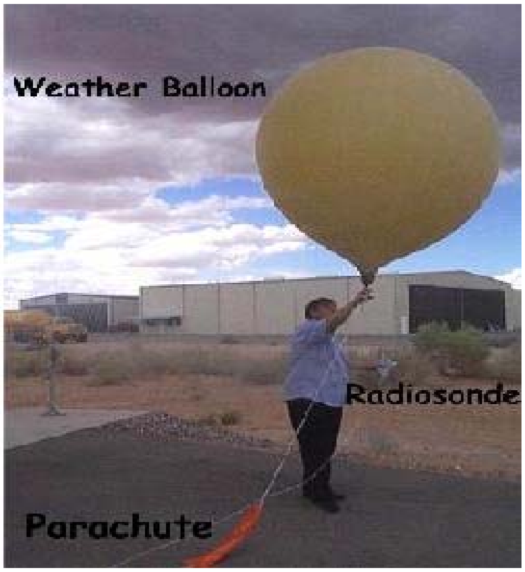


FIGURE 2 - Example NOAA/NWS Radiosonde weather balloon [16]

(OKX) which shows the absolute wind speed and wind direction averaged over the months of January, April, and August 2018. The winds aloft are significant and will clearly impact aircraft performance. Depending upon its flight altitude and direction, aircraft operations and performance may be helped or hindered by the jet-stream winds. From these plots we can see that the jet-stream peaks at ~39,000-ft altitude, with speeds varying from 40 – 80 knots at maximum; this is right in the range where typical transport category aircraft operate. For altitudes less than 60,000-ft, the winds aloft almost uniformly come from the west (~260-deg).

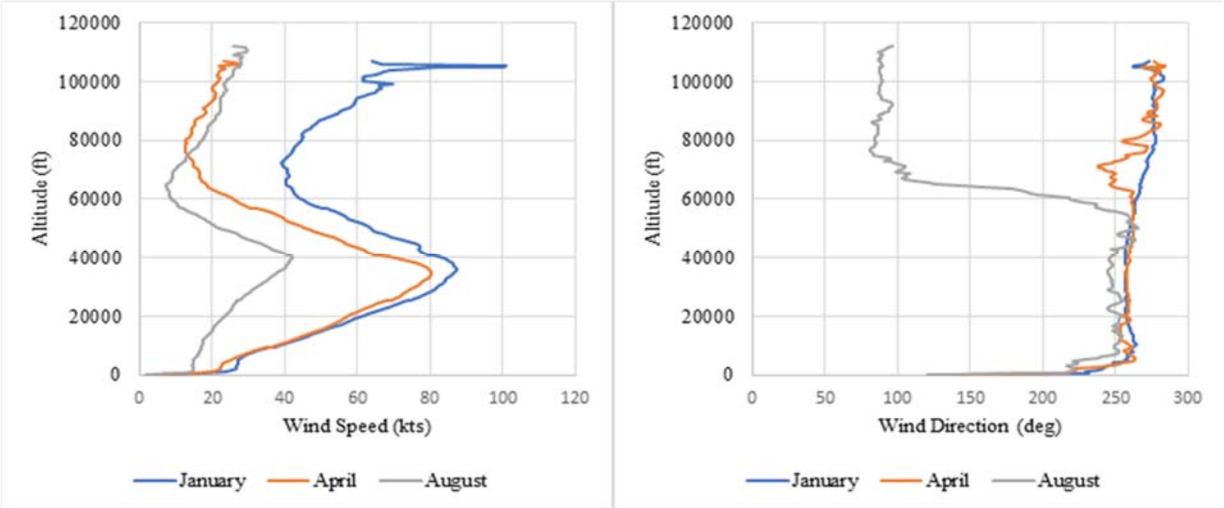


FIGURE 3 - Winds Aloft Profile for Upton, New York (OKX Station) taken during 2018. Wind direction is based on where the winds are coming from. Compass reference (0-deg is Compass North). [15]

The implications of this are immediate: if a pilot were to fly west (on a heading around 260), the pilot should avoid the jet-stream by either flying above or below the maximum wind speed point. If flying to the east (on a heading around 80), a pilot could take maximal advantage of the Jet-stream by flying at the altitude of peak tailwind.

To date, we have seen little open-literature discussion as to how to best strategize the selection of best-cruise-altitude under real-world winds for existing aircraft and even less discussion as to how to design an aircraft for operation under such conditions.

In this paper, we incorporate real-world meteorological data into point-performance [15] and mission-performance [16][17] simulations to show how much winds aloft can impact both the conceptual design and the operational performance of aircraft. Since aircraft flight performance is such a multi-faceted problem (a function of aircraft configuration and specification as well as weight, speed, altitude as well as the environmental conditions – temperature and winds aloft), we will study the problem from the perspective of an airline operating aircraft over realistic routes with aircraft of varying capability.

II. Methodology

Since weather patterns change across geographical locations and time periods, it was necessary to limit the weather data for our initial studies. For this work, we will only look at the effects of winds with altitude along the East Coast of the United States. The time frame was restricted to January 2018.

The University of Wyoming's Atmospheric Sounding database provided the winds-aloft data used to develop the wind model shown here. [15]

To determine the effect of atmospheric winds upon the mission performance of aircraft, we will consider that the operator could fly one of two commercial transport aircraft.

To represent the current state-of-the art, we modelled a conventionally configured narrow-body transport reminiscent of an Airbus *A320* CEO. The Airbus *A320* is a widely used transport-category aircraft that is known to fly in multiple routes with multiple operators over the East Coast. This makes it an ideal candidate for determining the effects of winds upon its fuel economy.

We developed the aerodynamic and propulsive model using *EDET* [18] and *NPSS* [19] respectively.

These models were refined and calibrated to closely reverse-engineered published *A320* flight performance by Beard [22] and has been validated through its use in subsequent publications. [23]

Looking closely at the *A320*'s performance characteristics, we note that it has a certified flight ceiling of 39,800-ft. [26] However, we can see from Figure 3 that the maximum winds from the jet-stream can occur near this altitude. Thus, the *A320* has little ability to climb above the jet-stream, which prevents us from any understanding of the impact of flight at higher altitudes.

In order to understand how higher-altitude flight is impacted by weather conditions, we also chose to utilize the *Aeris*: a student-developed 70-passenger regional aircraft with a flight ceiling of 50,000-ft [17][25] This aircraft was designed to maximize still-air fuel efficiency via high-altitude flight, and thus is expected to have optimal fuel-burn at cruise at or near FL500 for most missions.

For both the *A320* and the *Aeris*, two missions were simulated: 1) a regional mission of ~450-nm, and 2) a domestic flight along the length of the East Coast. The regional mission was a notional flight between Boston-Logan International Airport (KBOS Boston, MA) and Washington-Dulles International Airport (KIAD Washington D.C.). The domestic flight represents operations between Boston-Logan

FIGURE 4 - University of Wyoming Atmospheric Sounding Station Map for the Continental USA [15]

FIGURE 5 – Aircraft Basis for Study. a) Airbus *A320* CEO, b and c) *AERIS* [25]

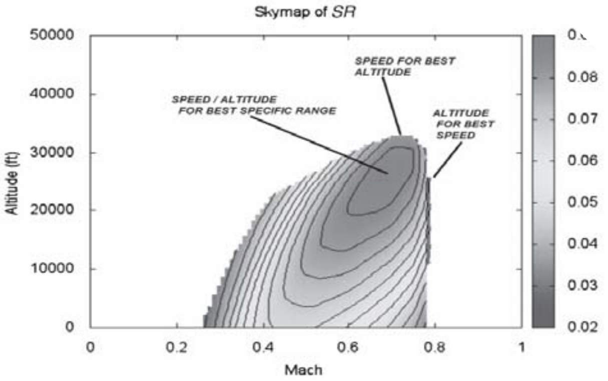
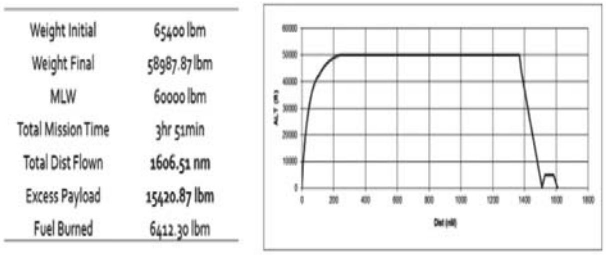


FIGURE 6 – Point Performance Skymap Tool [16]



Weight Initial	65400 lbm
Weight Final	58987.87 lbm
MLW	60000 lbm
Total Mission Time	3hr 51min
Total Dist Flown	1606.51 nm
Excess Payload	15420.87 lbm
Fuel Burned	6412.30 lbm

FIGURE 7 – Nominal Mission Profile for Point-Mass Simulation [17]

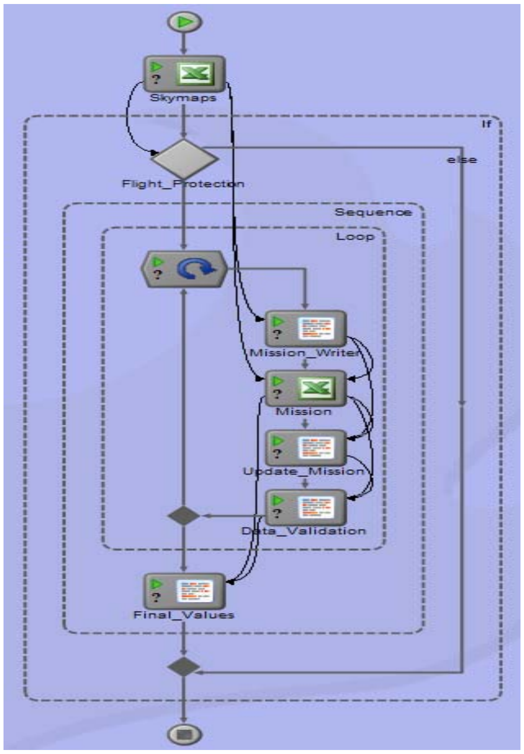


FIGURE 8 - Model-Center mission simulation model.

International Airport (KBOS) and Jacksonville International Airport (KJAX).

For each of the missions, we ran three variations: 1) flight in still air, 2) flight from the origin to destination with winds, and 3) a return flight from destination to origin with winds.

III. Simulation Methodology

We utilize two different approaches to study en-route performance: using a point-performance energy-maneuverability "skymap" (see Figure 6) [17][18] and through a time-step integration point-mass "Mission" simulation (see Figure 7) [19] code.

The *Skymaps* tool processes five-column tabular propulsion data, tabular drag polars at a user specified weight. The tool computes flight performance parameters such as aerodynamic performance efficiency *M(L/D)*, indicated and true airspeed, *CL*, *CD* at trimmed conditions, rate-of-climb (*ROC*) as well as fuel flow and specific range (*SR*) for steady-level flight.

Specific range is an efficiency metric factor that symbolizes the nautical miles flown per pound fuel burned. The maximum specific range value should occur at the overall aircraft's design altitude and Mach. In addition to aerodynamics and propulsion cycle, the *SR* depends on the flight weight (*W*) and the effective headwind.

The strategy in designing and operating fuel-efficient aircraft comes from understanding how we can maximize the specific range. If we consider the Brequet Equation: $R = (V / TSFC) (L/D) \ln(Wi/Wf)$, we can see that flight at peak $V(L/D)$ should provide the maximum range of the aircraft. [20][21] When we consider en-route winds, the V term in $V(L/D)$ is the effective ground speed in the presence of winds, not the true airspeed encountered by the airframe. In other words, $V = VKTAS - V_{HEADWIND}$.

We will also study the performance using a point-mass-simulation mission performance tool that "flies" the aircraft from takeoff to touchdown; see Figure 7. This code computes the credit distance flown and fuel burned as it "flies" the aircraft through a mission. It utilizes the same aerodynamics data, five-column data as the point performance code. In addition it follows a flight profile governed by a control file which can explicitly command the aircraft to accelerate, decelerate, maintain constant altitude flight, and climbs or descend at either constant KIAS or Mach.

Both of these models have been enhanced to consider the effects of winds aloft.

We performed our studies using these two simulations interconnected using the *ModelCenter* program (see Figure 8, above). [28]

The coupled multi-disciplinary model begins with a user-specified cruise altitude, flight direction, and takeoff weight. It exercises the point-performance code (*Skymaps*) with the given aircraft's engine and aerodynamic database in the context with a still-winds aloft context. From this program, we obtain the maximum cruise Mach number that corresponds to a 99% best specific-range at the specified altitude. A validation check is also performed at this step to ensure that the aircraft can actually fly at the specified altitude. If there is no data (aircraft cannot fly at the altitude), the whole run is set as invalid.

Once we determine the cruise Mach number, we initiate a mission convergence loop. The loop begins with a mission generator which writes a basic mission with cruise parameters given by the desired travel distance, cruise altitude, and cruise Mach number. As the aircraft flies the mission, it will overfly typical IFR routing waypoints – change its heading and encounter varying winds. For example, between KBOS and KIAD, we will use the en-route winds model from Upton, NY. But between KBOS and KJAX, we will use the en-route winds model from Upton, NY (OKX), Wallops Island, VA (WAL), Newport, NC (MHX) and Charleston, SC (CHS); refer back to Figure 4 to see the location of these sounding measurements. The mission itself also includes a 45-minute hold after the landing segment to simulate extra fuel-reserves necessary for emergency situations as required by 14 CFR § 21.639 [29] Once we define this mission, the simulation computes the total fuel used, the total distance traveled, and the total mission time.

The travel distance from the mission program is then compared to the travel distance required by the mission. If the difference is greater than 5-nM, an update module edits the cruise segment distance in the mission file to better converge the total travel distance. This sequence of mission writing, execution, and updating is looped until the travel convergence requirement is satisfied.

Further data validation is performed to ensure that the landing weight is less than the maximum landing weight (MLW) of the given aircraft, the effective payload is non-negative, the aircraft has enough fuel to make the required mission, and that the aircraft can climb to and descend from its cruise altitude rapidly enough to still make the required distance. If any of these are not satisfied, the mission is non-operational and thus the data is invalidated.

For the purposes of this paper, we studied *A320* operations for all three mission variants (no winds, into the winds, against the winds) at varying take-off weights from 115,000-lbm to 150,000-lbm and cruise altitudes varying from 25,000-ft (FL250) to 40,000-ft (FL400). Similarly, we examined the *Aeris* at take-off weights from 48,000-lbm to 61,600-lbm and cruise altitudes from 25,000-ft (FL250) to 50,000-ft (FL500).

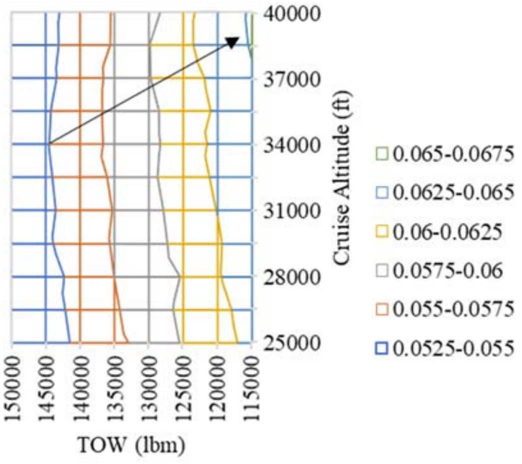


FIGURE 9 - *A320* Mission Specific Range vs Altitude and TOW for Boston, MA (KBOS) to Washington D.C. (KIAD) (with winds) with arrow indicating *best SR* trend.

IV. Results

In order to understand the effects of the jet-stream upon aircraft performance on short-haul flights, we performed mission simulations of the Airbus *A320* and *Aeris* aircraft flying the route of Boston International (KBOS) to Washington-Dulles (KIAD). This route is approximately 450-nM in length, constituting a "regional" flight. Flights from Boston to Washington are primarily against the winds, while flights from Washington to Boston are primarily with the winds.

A. *A320* Regional Flight

Figure 9 shows the mission specific range of the Airbus *A320* flying with winds-aloft (from Upton NY) from Boston (KBOS) to Washington-Dulles (KIAD).

An important aspect that can be seen is that the change in specific range over altitude for a given aircraft takeoff-weight is fairly small, although a larger gradient is produced as the aircraft gets lighter. We do see the trend that the specific range increases as weight decreases. This is to be expected as lower aircraft weights result in lower induced drag overall throughout the flight, and thus better fuel efficiency.

Despite the small gradients, we can still see an interesting trend arise where the best cruise altitude increases with decreasing weight. At 115,000-lbm (near empty), the aircraft wants to fly at its ceiling of ~40,000-ft to maximize its specific range. At 150,000-lbm (near full), the aircraft wants to fly at ~33,000-ft (FL330).

Figure 10 shows the mission specific range for the same flight, but without winds as a "winds-neutral" case.

We can see that the maximum specific range point has shifted towards lower altitudes at lower weight but has had little change for higher takeoff weights. This suggests that the impact of winds-aloft is most dominant on lower-weight flights.

There is also a net-benefit in terms of the total specific ranges. Since the aircraft is not flying into the winds, the fuel efficiency improves substantially, with a maximum specific range of ~0.075 nm/lbm compared to the with-winds case maximum specific range of only ~0.0675 nm/lbm. This yields a nearly 10% increase in maximum specific range.

Figure 11 shows the mission specific range for the flight from Washington-Dulles (KIAD) to Boston (KBOS) with winds. As we fly with the winds, the total specific ranges increase further.

However, we can also see a major shift in terms of the best specific range altitude. At low weights, the best altitude is found at nearly 34,000-ft (FL340), while at the heaviest weight the best altitude is at ~32,000-ft (FL320). The intermediary weights also appear to have a similar *best SR* altitude as the lightweight case. The low-weight case altitudes diverge significantly from the with-winds model, which showed that the best specific ranges were found at the absolute highest altitude for the lowest weights.

This change in altitude shows the dominating effect of the jet-stream. As we fly with the jet-stream, the net speed gain overtakes the drag reductions and fuel efficiency improvements gained from flying at higher altitudes.

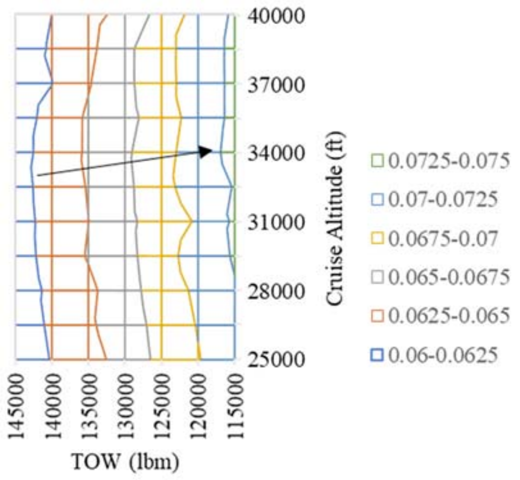


FIGURE 10 - *A320* Mission Specific Range vs Altitude and TOW between Boston, MA (KBOS) and Washington D.C. (KIAD) (with no winds) Arrow indicates best *SR* trend.

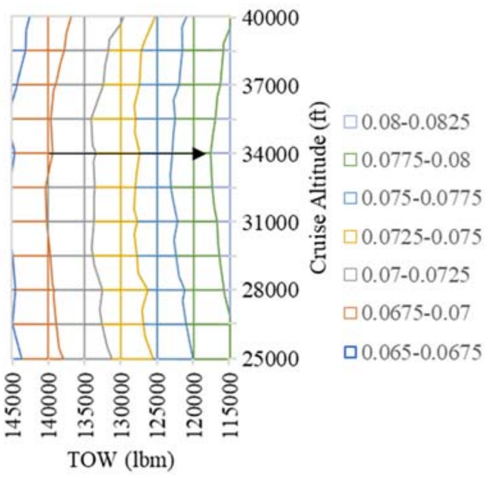


FIGURE 11 - *A320* Mission Specific Range vs Altitude and TOW for Washington D.C. (KIAD) to Boston, MA (KBOS). Arrow indicates best *SR* trend.

Although the specific range of the aircraft appears to have a large variability when winds are involved, the specific range only affects the fuel economy and not the overall economy of the aircraft. The overall economy of the aircraft is heavily decided by the payload for each flight, and thus we need to consider the payload capacity as well as the specific range.

From the specific range plots, we can glean an understanding of the payload and overall economy trends. Higher TOWs correspond to higher payloads, and from this perspective we see that the altitude trends of maximizing the specific range is highly muted for the *A320*. When considering the highest payload capacity, the aircraft wants to fly at ~34,000-ft for each mission regardless of the winds.

Even in the with-winds case, we can see that the *A320* cannot climb to high altitudes at higher TOWs. This suggests that the Airbus *A320* has insufficient thrust and is riding close to buffet under these conditions. Since the *A320* is resistant to even minor changes in flight altitude at high TOWs, this suggests that the payloads corresponding to these TOWs result in the aircraft flying into drag rise, and thus any gain in increased altitude is overshadowed by the massive rise in drag.

B. *Aeris* Regional Flight

The changing altitudes of the *A320* best specific range begs the question as to whether even higher altitudes are more effective. The *Aeris* was used as a test-bed, as it was designed for cruise at 50,000-ft, which is significantly higher than the typical Airbus *A320* cruise altitude. In doing so, the *Aeris* would cruise at its maximum certified ceiling.

However, because it cruises at a higher altitude, it may take longer for the *Aeris* to get to its cruise altitude. This establishes the question as to whether it will be able to make cruise altitude for regional flights, and whether it would even be useful considering how short the cruise section would be.

Figure 12 shows the mission specific range for the Boston to Washington-Dulles flight with winds aloft. Due to the short overall stage length of this regional flight, the maximum altitude the *Aeris* could attain was 45,000-ft. If we were to climb to 50,000-ft we would overshoot the target distance even with no level cruise segment.

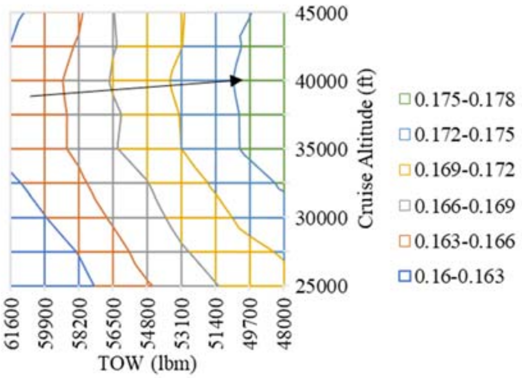


FIGURE 12 - *Aeris* Mission Specific Range vs Altitude and TOW from Boston, MA (KBOS) to Washington D.C. (KIAD) (with winds). Arrow indicates best *SR* trend.

Curiously, we can see that the best cruise altitude for specific range for the *Aeris* is at 40,000-ft (FL400) at low weights, reducing to ~37,000-ft at high weights. This seems to break the trend seen by the *A320* where the aircraft wants to fly as high as possible at low weights flying against the winds. However, because the cruise period is reduced at higher altitudes (as the ascent and descent phases increase in length), the aircraft's actual time at altitude is significantly diminished, and thus we develop slightly worse specific ranges. However, the chart still suggests that the optimal mission for the *Aeris* uses a very small cruise window and is largely dominated by the climb and descent phases.

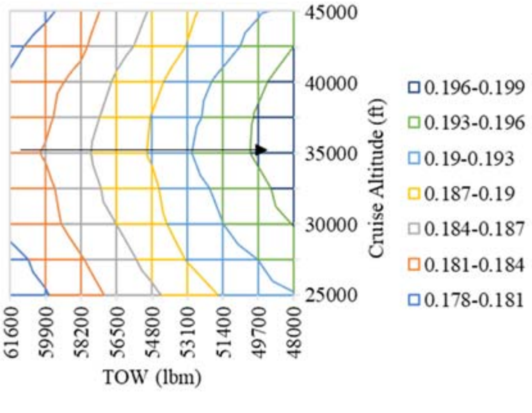


FIGURE 13 - *Aeris* Mission Specific Range vs Altitude and TOW between Boston, MA (KBOS) and Washington D.C. (KIAD) (without winds). Arrow indicates best *SR* trend

Figure 13 shows the mission specific range for the Boston to Washington-Dulles flight with no winds. With no winds, we can see that the maximum specific range cruise altitude decreases dramatically to only ~35,000-ft (FL350) for all weights. Without winds, the

Aeris favors a longer cruise phase of flight to maximize the specific range.

When looking at Figure 12 against Figure 13, we can see that the appearance of the jet-stream radically changes the perspective of the mission. The *Aeris* finds that it is beneficial to spend much more time climbing above the maximum jet-stream point to achieve higher cruise altitudes even for short hop flights.

It appears that the going against the jet-stream still creates an incentive for the *Aeris* to fly higher, however the limitations of the regional mission begin to affect the specific range at higher altitudes.

Figure 14 shows the mission specific range for the Washington-Dulles to Boston flight. From this chart, we can see that the best specific range point is lowered even further at only ~33,000-ft (FL330). This follows the trend seen in the *A320*, where flying with the winds results in better specific ranges at lower altitudes.

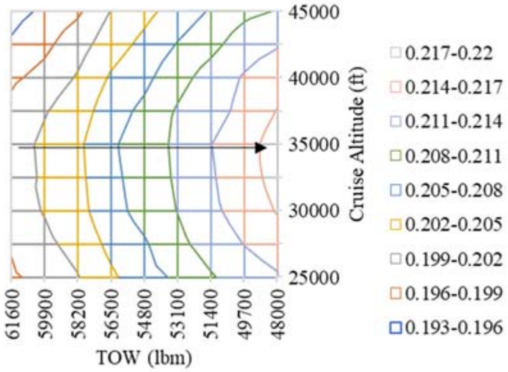


FIGURE 14 - *Aeris* Mission Specific Range vs Altitude and TOW from Washington D.C. (KIAD) to Boston, MA (KBOS) (with winds) Arrow indicates best *SR* trend

If we consider the same overall economy perspective as the *A320* with the *Aeris*, we can see that a different story starts to emerge with how the *Aeris* handles the winds even at high payload loading. When flying with the winds, we can see that the *Aeris* prefers flight altitudes of around 38,000-ft at high TOWs. In flight against the winds, the *Aeris* flies at a lower altitude of 35,000-ft.

It appears that the design of the *Aeris* is such that it does not feel the same induced drag "cliff" that the *A320* has at high TOWs. Thus, the *Aeris* has a better ability to climb into the jet-stream when flying with the winds even on a very short flight. This suggests that the *Aeris* has a better ability to maneuver itself with respect to the winds than the *A320*.

C. *A320* Domestic Flight

To determine the effects of winds along a longer mission (and therefore a longer cruise period), we simulated the flight of both the *A320* and the *Aeris* from Boston to Jacksonville, Florida (KBOS to KJAX).

As this flight covers more territory, the mission uses a series of wind profiles along the east coast to better simulate the effects of changing wind conditions upon the aircraft. Although the changes are not drastic, the differences in wind speed magnitudes and directions still impact the performance of the aircraft and thus must be tracked to provide accurate results. Our route passes over five sounding stations: OKX (Upton, NY), WAL (Wallops Island, VA), MHX (Newport, NC), CHS (Charleston, SC), and JAX (Jacksonville, FL). Their respective January 2018 monthly average wind profiles can be seen in Figure 15.

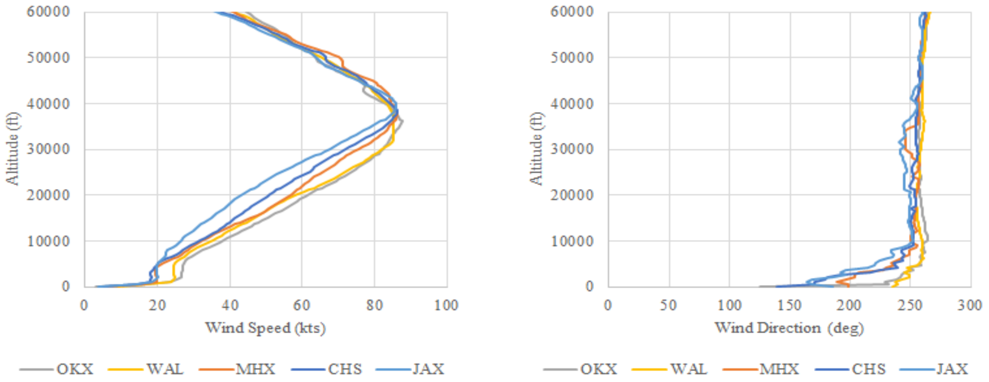


FIGURE 15 - January 2018 Monthly Average Altitude vs Wind Speed and Direction for Sounding Stations

The specific range plot vs altitude and takeoff-weight for the mission from Boston, MA (KBOS) to Jacksonville, FL (KJAX) with winds can be seen in Figure 16. We can immediately see a large difference in the best specific range altitude at this longer mission as compared to the regional mission in part A.

For the *A320* at very lightweight cases, it is clear that the aircraft wants to fly at high altitudes. However, as the weight increases, the best specific range altitude drops more rapidly than in the regional case, from 40,000-ft to 34,000-ft. Note that the top-left corner is invalid (as the aircraft is too heavy to fly at the altitude) and hence blacked-out.

However, we can also see that the specific ranges appear to “straighten” shortly after the *best SR* altitude is reached. This suggests that the consequences of flying above the *best SR* altitude are far less impactful than flying below it. Thus, when flying against the winds, it appears that one would want to tailor the mission to an altitude at or above that which yields the *best SR*.

The no-winds case can be seen in Figure 17. Here we see that the best specific range altitude appears to have shifted higher somewhat for light and moderate weight cases. Whereas flying against the winds at 145,000-lbm had an optimum at 35,000-ft, without winds the best altitude is around 37,000-ft.

The return trip specific ranges from Jacksonville to Boston with winds is plotted in Figure 18. From this, we can see that the *best SR* altitude is now virtually unchanged for all weights, holding at around 37,000-ft. Looking back at Figure 15, we can see that the maximum wind speeds also follow around the same altitude. Thus, the speed boost obtained from the jet-stream overcomes the increased induced drag of flight at high altitudes and high weights, making it most economical to fly at the jet-stream altitude for nearly all weights.

Looking at all three cases, we can see the trend: when we fly with the wind, the aircraft wants to fly at the altitude corresponding to maximum wind speed. This is not particularly surprising, as a tailwind only adds to the speed of the aircraft without requiring extra thrust or fuel consumption.

However, as we begin flying against the winds, the aircraft is confronted with a unique dilemma. This time, flying against the core of the Jet-stream yields a net decrease in speed, and thus a large decrease in specific range. To combat this, the aircraft can fly either above or below the jet-stream to reduce effective headwind.

Flying above the core of the jet-stream has the benefit of less-dense air and thus less skin-friction drag. However, this requires the aircraft to be lighter in order

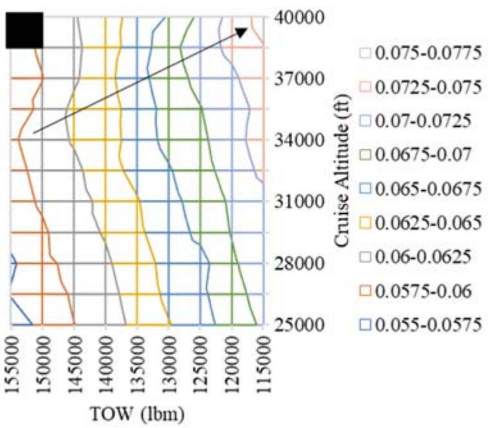


FIGURE 16 - *A320* Mission Specific Range vs Altitude and TOW for KBOS to KJAX with winds. Arrow indicates best *SR* trend

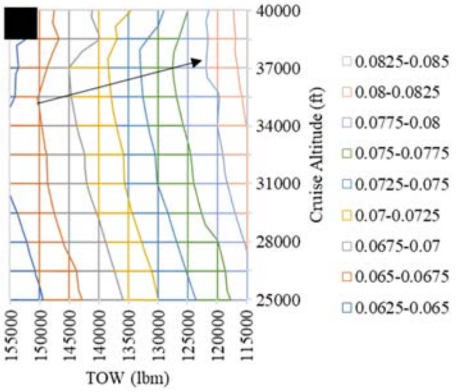


FIGURE 17 - *A320* Mission Specific Range vs Altitude and TOW between KBOS and KJAX. Still winds. Arrow indicates best *SR* trend.

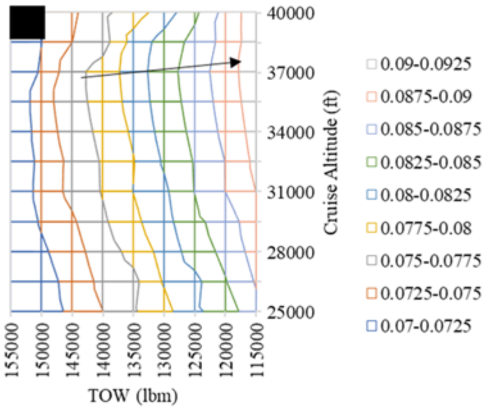


FIGURE 18 - *A320* Mission Specific Range vs Altitude and Take-off Weight for KJAX to KBOS with winds. Arrow indicates best *SR* trend

to sustain lift at these altitudes, and heavier aircraft may encounter drag rise and buffet onset. At heavier weights, the aircraft is forced to fly at lower altitudes. This results in the sharper altitude gradient as seen in Figure 16.

As discussed in the regional flight section, the overall economy trends can be determined by looking at the *best SR* corresponding to maximum TOWs (and thus maximum payloads). From the domestic specific range plots, we can see that even with a longer cruise period the *A320* is still resistant to altitude changes in the presence of winds at high TOWs.

This result further supports the drag-rise problem as seen in the regional flight section. For all studied conditions (flight with winds, in neutral winds, and against winds) the *A320*'s best overall economy altitude is found at ~34,000-ft. It appears that even when under the effect of winds for a longer period of time, the increased induced drag still overshadows the effect of winds for the Airbus *A320*. Thus, it appears that, when heavily loaded, the *A320* will see little change in its optimum cruise altitude no matter the winds aloft. As the load gets lighter and lighter, however, we will see greater variance in the optimum cruise altitude for the *A320*.

D. *Aeris* Domestic Flight

The trends seen by the *A320* domestic flight create curious intricacies for dispatch, as the direction of flight along with the cruise altitude and takeoff-weight of the aircraft make large differences in the overall fuel economy of the mission. Considering how much the aircraft wants to fly at higher altitudes, this leads to the question as to what the trends look like for an aircraft that can fly at higher altitudes. Thus, the same scenario was performed for the *Aeris*.

The Boston to Jacksonville case can be seen in Figure 19. From this plot we can see that the aircraft wants to fly at the maximum altitude of 50,000-ft at all TOWs. Note that the bottom-right corner is invalid as it yields a negative payload and is thus blacked-out.

This counteracts the trend initially seen by the *A320* mission, where the *best SR* altitude increases as we decrease the TOW. However, because the *Aeris* is capable of flying at 50,000-ft for nearly all takeoff weights, it bypasses the altitude dilemma found by the *A320*. When flying against the winds, the *Aeris* will always prefer to fly at maximum altitude to decrease the negative wind speeds.

The no-winds case can be seen in Figure 20. From this, we can see that the aircraft still wants to fly as high as possible for all takeoff weights, however the decrease in SR with decreasing altitude is much shallower than in the winds-aloft case. This indicates that the presence of the jet-stream creates a very large negative effect on the SR of the aircraft, making it much more sensitive to altitude changes than if no winds were present.

Finally, the Jacksonville to Boston with-winds case can be seen in Figure 21. From this figure, we can see an immediate difference in the best specific range point as compared to the no-winds and against-winds cases. When flying with the winds, the *Aeris* (like the *A320*) wants to fly near the altitude of maximum wind speed. However, because the *Aeris* has a much higher

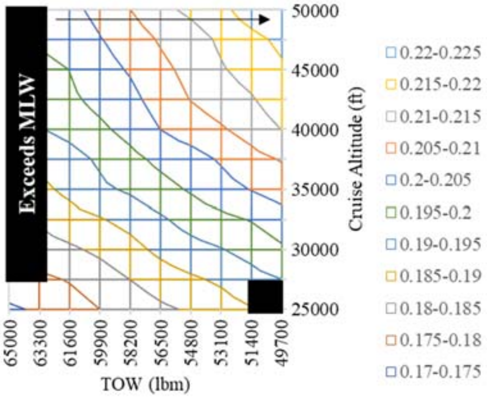


FIGURE 19 - *Aeris* Mission Specific Range vs Altitude and Take-off Weight for KBOS to KJAX with winds. Arrow indicates best *SR* trend

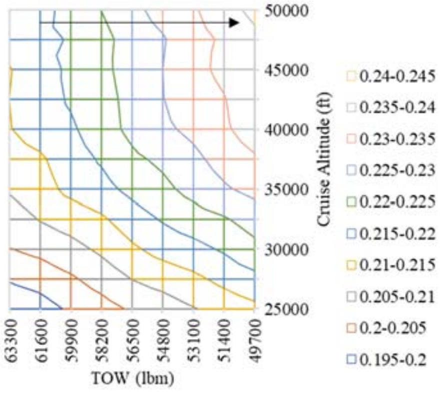


FIGURE 20 - *Aeris* Mission Specific Range vs Altitude and Take-off Weight between KBOS and KJAX in still air. Arrow indicates best *SR* trend.

altitude capability and a much higher no-wind *best SR* altitude, the *Aeris* wants to fly slightly higher than the *A320* with a cruise point of ~40,000-ft.

When looking from the perspective of the overall economy of the *Aeris*, the optimum flight altitude at high TOWs changes remarkably depending on the direction of flight. When flying against the winds (figure 19), the *Aeris* wants to fly at its design cruise altitude of 50,000-ft. The specific range curve shows that the jet-stream at 40,000-ft causes sharp reductions in fuel economy with reductions in altitude, and thus the *Aeris* is incentivized to fly as high above the jet-stream as it can.

However, when flying with the jet-stream (figure 21), we can see that the *Aeris* prefers to fly far below its design cruise altitude in order to fly close to the core of the jet-stream. This results in a massive 10,000-ft reduction in flight altitude at high TOWs.

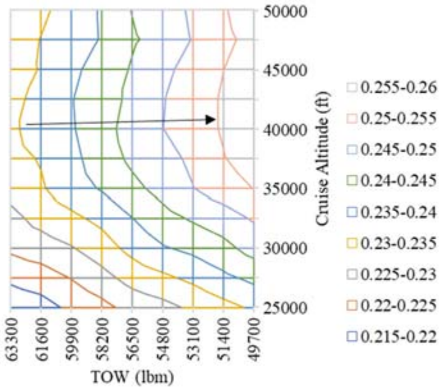


FIGURE 21 - *Aeris* Mission Specific Range vs Altitude and Take-off Weight for KJAX to KBOS with winds. Arrow indicates best *SR* trend.

It appears that the *Aeris* has the opposite condition of the Airbus *A320*, where the *Aeris* will end up flying severely below its design cruise altitude (and thus its design lift coefficient) in order to gain speed by flying closer to the core of the winds. The strategy employed by the *Aeris* is one that its design cruise condition is optimized to fly high above the jet-stream, allowing it to fly at its design point when flying against the winds and under neutral winds conditions. However, when flying with the winds the *Aeris* can naturally fly at lower altitudes to maximize its speed potential. Thus, the *Aeris* presents a much more dynamic interplay in its cruise altitude with winds than the *A320*.

V. Conclusion

The presence of winds has a major impact upon the optimal cruise altitude of an aircraft. The jet-stream in particular creates a major dilemma for aircraft operations as the highest winds are often found at altitudes near normal cruise points. Flying against the jet-stream has been shown to have a detrimental effect of 10% or more on the specific range of an aircraft, while flying with the jet-stream yields significant fuel savings. However, the altitudes at which aircraft want to fly is highly dependent upon the weight of the aircraft as well, and thus creates yet another dimension to the problem.

In this work, we demonstrate that the optimal cruise altitude is not static but is highly dependent upon which direction the aircraft flies relative to the winds aloft. For current transport-category aircraft (mostly limited to 40,000-ft operations), flying into the winds highlights issues with buffet-boundaries and thrust lapse rates: at low weights, the aircraft can fly at high altitudes – the aircraft should fly as high above the jet-stream as it can. However, as we increase the weight, the restricted ceiling leads to dramatic changes in optimal altitudes: heavy-weight flights prefer to fly below the jet-stream even if light-weight flights can fly above the core.

When flying with the winds, nearly all aircraft find that the speed gain from flying with the jet-stream yields the optimal result. This also results in a softening of the specific range gradient in regards to altitude, where increasing altitude above the jet-stream yields little change in the specific range of the aircraft. At low weights, the aircraft can fly at higher altitudes (and thus less dimensional drag from a thinner atmosphere), however with decreased speed gains and thus the overall specific range is not heavily affected.

Both of these events differ from when the aircraft is flying in winds-neutral, which is shown to be (as expected) a middle-ground between flying against the winds and flying with the winds. The specific range gradients are not as dramatic as when flying against the winds, however there is still a significant altitude impact throughout the whole flight envelope.

These effects are somewhat muddied for short-range regional flights, as a more significant amount of time is spent in the climb and descent portions and thus the cruise gain is minimized. Despite this, we can still see the impact of winds upon these flights. With enough altitude capability and a low enough weight, an aircraft might find it beneficial when flying against the winds to simply “power through” the jet-stream in climb up to a higher altitude and immediately descend (as can be seen with the *Aeris* in Figure 9). Although a longer cruise portion can be gained from flying at a lower altitude, the cruise is offset by increased detrimental winds.

From an operational standpoint, it is clear that the presence of winds yields a major effect on the economy of a flight. However, because the winds might change in both direction and magnitude over the geography of a mission, optimal results can only be developed if the mission is designed with current weather in mind. Therefore, airlines and aircraft operators might find serious economic benefit to developing flight plans based upon tracking real-time weather over the course of their flight.

From a design standpoint, high-altitude flight is incentivized when dealing with winds-aloft especially when regarding the overall economy of a mission rather than a simple fuel economy. The Airbus *A320* showed that its high-payload flights were very resistant to changes in cruise altitude in the presence of winds, while the *Aeris* showed great variation in its cruise altitude even at maximum payload capacity.

Higher altitude capability provides aircraft more maneuvering room around the jet-stream and is coupled with the tendency of aircraft to have better fuel economy overall at higher-altitude flight. Flight capability above 40,000-ft allows aircraft to bypass much of the jet-stream impact by flying above the jet-stream and eliminates much of the drag-fight that can be seen from the *A320* model. Higher-altitude capabilities could also help alleviate airspace congestion when flying with the winds as well, as the *Aeris* has shown that an aircraft can have a much wider range of altitudes with similar specific ranges in Figure 21.

From this first look at the effect of fuel and mission economy with winds has given us much reason to delve further into understanding the interactions between aircraft mission economies and flight with the winds. A more comprehensive look at the mission economies of the *A320* and the *Aeris* is currently being researched, along with the development of a more comprehensive atmospheric-aloft model with better geographical interpolation and the inclusion of temperature deviations. From this research, we hope to better understand the nuances underlying the optimization of current aircraft mission economies through the real-world atmosphere, along with a better understanding of how we should approach the atmosphere when designing and developing future aircraft.

Due to the highly variable nature of winds-aloft models, we also recommend that further research be applied in studying aircraft missions at different geographic locations and different seasons. Because the data in this paper is derived from the east coast on January 2018, the total scope of the winds-aloft models is limited and begs for more development as to different locations in the world and in how the optimal cruise altitude may change on a seasonal, monthly, or even daily basis.

VI. Acknowledgements

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[29] 14 C.F.R. § 121.639 "Fuel Supply: All Domestic Operations," 2019. ("No person may dispatch or take off an airplane unless it has enough fuel - (a) To fly to the airport to which it is dispatched; (b) Thereafter, to fly to and land at the most distant alternate airport (where required) for the a rport to which dispatched; and (c) Thereafter, to fly for 45 minutes at normal cruising fuel consumption or, for certificate holders who are authorized to conduct day VFR operations in their operations specifications and who are operating nontransport category airplanes type certificated after December 31, 1964, to fly for 30 minutes at normal cruising fuel consumption for day VFR operations.")