How to Soar Above the Competition – Design Strategies to Improve Airliner Operating Economics in Real Weather

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Many modern aircraft are derived from older airframes with larger engines and increased payload capacity on the same wing of the original airframe. However, we are rapidly approaching the payload limit that these classical airframes can handle; this may motivate a need for novel aircraft designs in the future. This provides opportunity to revisit and perhaps revamp classical aircraft design methods based on a more modern understanding of aircraft performance combined with increased computational power. Current aircraft design uses a "deviation method" from the standard atmosphere to inform decisions on the design of aircraft. However, this provides a fundamentally limited view of how aircraft actually interact with real-world conditions given that atmospheric properties change over time and geographic location. This paper analyzes the performance of two aircraft with radically different design philosophies in the presence of real-world atmospheric conditions. The Airbus *A320* is used to quantify traditional aircraft design techniques, and a hypothetical high-altitude regional jet, the *Aeris*, is used to contrast against the Airbus *A320* providing insight into how different design philosophies develop different strategies and performance characteristics in the presence of real-world conditions. From this analysis, a better understanding of real-world aircraft interaction with the atmosphere can be obtained and used to inform future design.

I. Introduction

AS ECONOMIC COMPETITION SOARS in the aviation industry, aircraft designers are constantly challenged to develop aircraft with increasing economic efficiency. This is oftentimes at odds with the real cost of aircraft design and production, where the development of a clean-sheet aircraft can be a decade long process. [1] To mitigate these costs, modern aircraft designers have adopted a philosophy of "retrofitting" existing airframes with increased payload capacity to provide better operational economics. [2][3] This process of retrofitting existing airframes has historically come with a number of benefits: reduced development costs, reduced certification costs, and reduced training costs for aircraft operators.

However, recently it appears that this process of increasing the flight economics of an aircraft by adding payload capacity has reached a peak with modern airframes. The Boeing 737 MAX debacle highlights this issue: the desire to squeeze ever more payload capacity out of the original airframe has turned a stable aircraft [4] into one with supposed fundamental aerodynamic instability that needs computer-driven stability augmentation for "safe" operation. [5][6] As current airframes are reaching their maximum capabilities in terms of total payload capacity, the question again arises as to whether it is time to revisit aircraft design and perhaps adopt a new design philosophy to provide improved operational economy.

One of the primary factors that has so far been untouched in aircraft design is the performance of aircraft in real-world atmospheric conditions. Modern aircraft design approaches the variance in real-world atmospheric conditions using deviations from a "standard atmosphere" model. [7][8] Through this method, aircraft performance and flight properties can be directly analyzed via temperature deviations from the standard atmosphere model. However, static temperature deviations are often used for flight mission simulation, when real-world flight encompasses a very dynamic relationship between pressure altitude,

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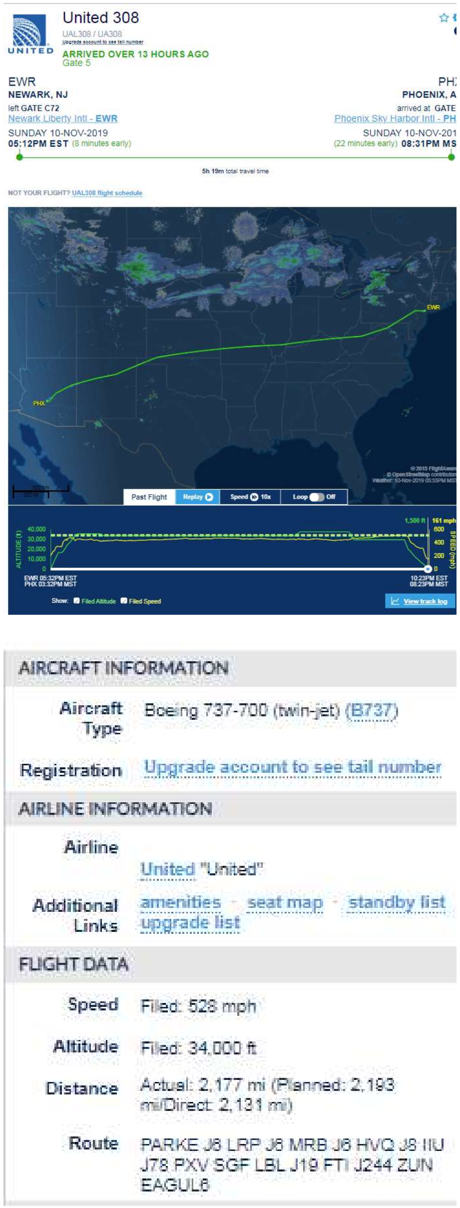
temperature deviation, geographic location, and time-of-flight. [8][9] The dynamic properties of real-world atmospheric conditions are thus left out of traditional aircraft design and analysis.

Furthermore, the presence of winds-aloft can establish major differences in the performance of aircraft and their optimal cruise altitudes depending on the time of flight and lateral flight path taken. High wind magnitudes can often be found at the core of the "jet-stream" which occurs at altitudes around 40,000-ft (FL400) [8][9]. Modern commercial transport struggle to make it to this altitude due to their increased payload capacity from their original design.

When an airline dispatch operator plans a commercial flight, the operator must abide by 14 CFR § 91 and 121 regulations [10].



United 308
UAL308 / UA308
Upgrade account to see tail number
ARRIVED OVER 13 HOURS AGO
Gate 5

EWR
NEWARK, NJ
left GATE C72
Newark Liberty Intl - EWR
SUNDAY 10-NOV-2019
05:12PM EST (8 minutes early)

PH
PHOENIX, A
arrived at GATE
Phoenix Sky Harbor Intl - PH
SUNDAY 10-NOV-201
(22 minutes early) 08:31PM MS

5h 19m total travel time

NOT YOUR FLIGHT? UAL308 flight schedule

AIRCRAFT INFORMATION	
Aircraft Type	Boeing 737-700 (twin-jet) (B737)
Registration	Upgrade account to see tail number
AIRLINE INFORMATION	
Airline	United "United"
Additional Links	amenities · seat map · standby list · upgrade list
FLIGHT DATA	
Speed	Filed: 528 mph
Altitude	Filed: 34,000 ft
Distance	Actual: 2,177 mi (Planned: 2,193 mi/Direct: 2,131 mi)
Route	PARKE J6 LRP J6 MRB J6 HVQ J8 IIU J78 PXV SGF LBL J19 FTI J244 ZUN EAGUL6

FIGURE 1 – example IFR flight plan followed by actual flight trace from flightaware.com [17]

Dispatch must ensure that a flight depart at a weight suitable for a critical-engine failure during the takeoff process (see 14 CFR § 121.189 [11]), enroute flight that can avoid terrain under normal and engine-inoperative conditions (see 14 CFR § 121.191 [12]) and land at a scheduled destination airport at a planned arrival weight with an adequate ability to stop within the available runway length (see 14 CFR § 121.195 [13]). Aircraft dispatch with reserve fuel to reach an alternate airport with long runways suitable to accommodate an aircraft landing at its planned arrival weight with impaired braking capability and no-reverse thrust (see 14 CFR § 121.197 [14]).

Dispatch computes fuel-load, takeoff and arrival weights based upon a flight plan filed with air traffic control under the purview of 14 CFR 91.169 [15] – the IFR Flight Plan. The IFR flight plan requires the operator to disclose the aircraft identification number (flight number and tail number), the proposed point and time of departure and arrival, the route (this typically begins with a standard instrument departure (SID), followed by a variety of waypoints connected by formal airways, and ends with a standard terminal arrival (STAR) [16]. The flight plan presently declares a single proposed flight level and true airspeed (based upon standard day conditions). This sort of information can be found on services like *flightaware.com* [17].

Consider the flight shown in FIGURE 1. Dispatch scheduled this B737-700 was scheduled to fly from Newark (KEWR) to Phoenix (KPHX) beginning with the PARKE standard instrument departure, then overflying navaids such as Lancaster, PA (LRP), Liberal, KS (LBL) and Zuni Mesa, NM (ZUN) to eventually join the EAGUL6 standard terminal arrival into Phoenix. The declared flight level was FL340 and speed was 528 mph (which works out to Mach 0.79 when referencing the standard atmosphere). This ground (and seasonally adjusted "equivalent still air distance) would pump prime the "handbook" calculations used to estimate fuel burn.

In reality, the aircraft flew at different altitudes as it encountered differing winds and environments on its actual journey. We can see from *flightaware.com*, that the planned ground track was 2,192 miles but the actual flown ground track was slightly shorter: 2,177 miles. Air traffic control cleared the pilots for an initial cruise at FL360, stepping down to FL340 over West Virginia. Near Liberal, KS the aircraft climbed up to FL390 only to encounter light-chop just east of Albuquerque. Pilots descended to FL340 and flew this altitude until instructed by ATC to descend to follow the speed / altitude targets for the standard terminal arrival.

Thus, we see that a nuanced consideration of flight altitude should occur when designing a new aircraft. When flying in the direction of the winds, it is desirable to fly as close to the core of the jet-stream as possible, however when flying against the winds it is desirable to fly far from the jet-stream. The question thus arises: is it better to fly above the jet-stream or below the jet-stream from an aircraft design perspective? And behind these issues lies an implicit question, to what magnitude should an aircraft be able to change its altitude to account for winds and temperature deviations along a route?

This paper examines the performance of an *A320* against a hypothetical regional jet, the *Aeris*, to determine the effect of real-world atmospheric conditions upon their respective performance. From this analysis, we can glean insight into the differences in their design philosophies and how they interact with real-world conditions. This can advise future aircraft design with a better understanding of how aircraft interact with real-world atmospheric conditions and how to design aircraft to optimize their performance under these conditions.

II. Aircraft Performance Model

The classical aircraft model studied in this paper is the Airbus *A320* (FIGURE 2). The *A320* is a staple of the United States domestic market, widely used for narrow-body flights for operators including JetBlue, United, Spirit, Delta, Allegiant, Alaska, and American Airlines [18]. Operators of the *A320* follow the design philosophy laid out in the beginning of this paper: interiors have been reconfigured to increase seating capacity. In 1999, United Airlines operated A320s with a 12F/132Y interior [19]; today they operate the same aircraft with a 12F/42Y+/96Y interior (a gain of 6 seats). [20] The change in interiors is even more evident when we compare American Airlines A321 fleet: the ex-US Airways A321s were delivered with a 16F/165Y interior, the latest A321neo operate with a 20F/47Y+/129Y interior (a gain of 15 seats). [20] Note that the A320 and A321 share a common wing: United's older A320s were delivered to a 170,000-lbm Maximum Takeoff Weight standard; American's latest A321neo's are delivered to a 213,800-lbm standard. [21] Thus, the wing loading at maximum takeoff weight has increased more than 35% as the product line evolved.

FIGURE 2: Airbus A320 [22]

FIGURE 3: Aeris [23]

In contrast, the *Aeris* [23] was designed to maximize fuel economy by leveraging high-efficiency engines at high-altitude flight; see FIGURE 3.

The aerodynamics model for each aircraft was generated from the EDET (Empirical Drag Estimation Technique) drag estimation code. This program was developed by NASA to provide estimations on drag in the conceptual phase of aircraft design. [24] However, prior research has found this method to be suitable to develop aerodynamics databases for real-world aircraft. [25] This tool was used to generate the following aerodynamic parameters: lift coefficients (CL) and drag coefficients (CD) at specific angles-of-attack (α) and mach numbers, buffet onset CL at specific mach numbers, and drag corrections at a variety of mach numbers and altitudes.

The propulsion model for each aircraft was generated by the use of the NPSS (Numerical Propulsion System Simulation) program. NPSS was also developed by NASA as a programming framework for modelling the mechanical, fluid, and thermodynamic processes within an engine. [26] This tool generates "five-column"

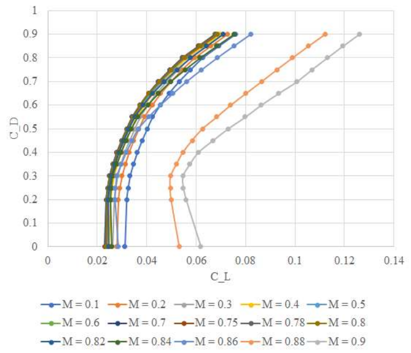


FIGURE 4: Airbus A320 Drag Polars [25]

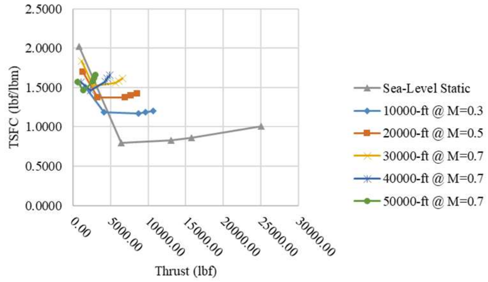


FIGURE 5: Airbus A320 Power Hooks [25]

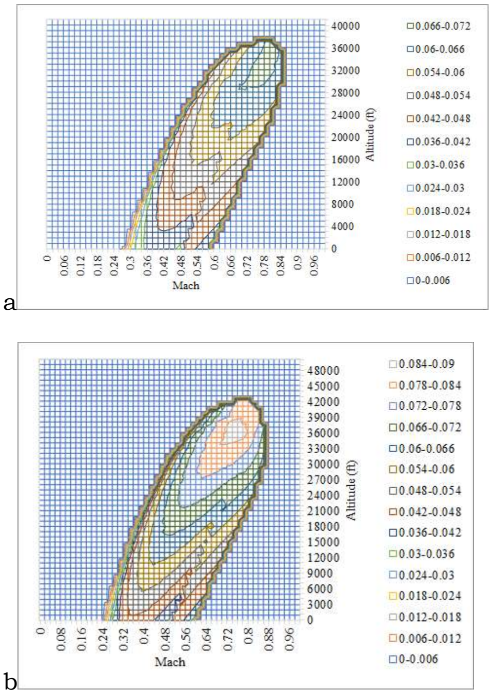


FIGURE 6 – Specific Range "skymap" plot - still air / standard a) Heavy – W=170,000-lbm, b) Light – W=135,000-lbm

thrust data for engines. This dataset includes engine thrust and engine thrust specific fuel consumption (TSFC) at specific altitudes, Mach numbers, and power lever (PLA) settings.

A. Airbus *A320*

A well-calibrated aerodynamic and engine model which closely mimics its published performance has been developed in previous research. This provides an accurate basis on which to test the effects of weather on its mission performance. [27] The aerodynamics model is based on a nominally-sized *A320* aircraft, with basic wing and fuselage dimensions shown in table.

Table 1: Airbus *A320* Dimensions [22]

Item	Value
Wing Reference Area	1319-ft^2
Wing Aspect Ratio	9.17
Wing Quarter-Chord Sweep	25-deg
Wing Taper Ratio	0.24
Fuselage Length	123.25-ft
Fuselage Width	12.95-ft

The physics model of the *A320* is developed from a combination of its aerodynamics model and engines model. The drag polars of the *A320* form the basis of the aerodynamics data used for modelling the aircraft. The drag polars (shown in FIGURE 4) of this model are estimated using an EDET model calibrated to match published performance. [25][27]

The engines are modelled as twin 25,000-lbf static reference static thrust, bypass-ratio (BPR) 5 engines.[22] Power hooks from this engine data are shown in FIGURE 5.

A point-performance "skymap" of specific range as a function of speed and altitude for standard-day conditions in still wind may be found in FIGURE 6 [28]. From the skymaps we can see that the *A320* lacks the ability to fly at its certified ceiling at high weights. Lower weights lead to an optimal specific range altitude of approximately 36,000-ft, and higher weights shows a drop in altitude to 32,000-ft. This means that the *A320* wants to fly below the jet-stream through all weight configurations.

B. The Aeris

The *Aeris* (refer back to FIGURE 3) was chosen to contrast against the *A320*. The *Aeris* is a hypothetical higher-altitude aircraft developed by a senior design team at Arizona State University for the purpose of maximizing fuel economy over a 1,500-nM mission by targeting its optimal aerodynamic efficiency (M*L/D) at its design payload capacity. [23][30] This is in contrast to the *A320*, which cannot attain its maximum aerodynamic efficiency under modern payload configurations. This aircraft was designed as a regional jet replacement with increased fuel efficiency and flight speeds.

Although the *Aeris* is a paper study, [23] it has a robust aerodynamics and engine model and allows mission investigation of flight altitudes up to 50,000-ft (FL500). In comparison, the *A320* has a maximum flight ceiling of only 40,000-ft (FL400). Considering that the jet-streams are often found near 40,000-ft, the *Aeris* provides a unique opportunity to look at scheduled commercial flight above the jet-stream.

The *Aeris* has a much smaller cabin than the *A320*, and only seats 80 passengers. A view of the seating arrangement on the *Aeris* can be seen in FIGURE 7. Due to the smaller cargo capacity requirements of the *Aeris*, it is ultimately a much smaller aircraft than the *A320*. Basic wing and fuselage dimensions are documented in Table 2. A three-view drawing of the *Aeris* can also be seen in FIGURE 8.

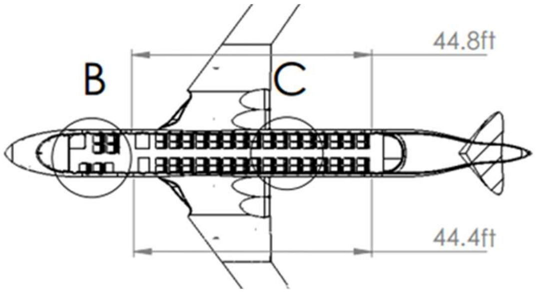


FIGURE 7: *Aeris* Seating Chart with Emergency Exits Labelled [23]

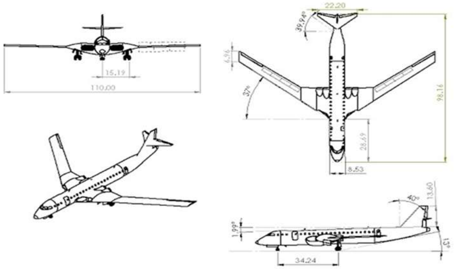


FIGURE 8: *Aeris* 3-View Drawing. Dimensions are in feet [23]

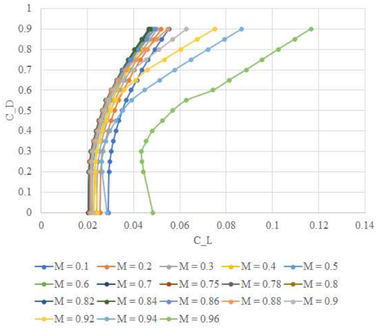


FIGURE 9: *Aeris* Drag Polars [23]

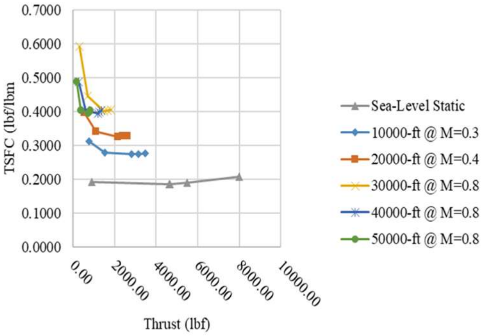


FIGURE 10: *Aeris* Power Hooks [23]

Table 2: *Aeris* Dimensions [23]

Item	**Value**
Wing Reference Area	930-ft^2
Wing Aspect Ratio	13
Wing Quarter-Chord Sweep	37-deg
Wing Taper Ratio	0.7
Fuselage Length	98.12-ft
Fuselage Width	9.09-ft

The drag polars from the aerodynamics model are shown in FIGURE 9. The *Aeris* uses four BPR 12 engines with an 8,000-lbf reference static thrust for each engine. [23] Power hooks for this engine data can be seen in FIGURE 10.

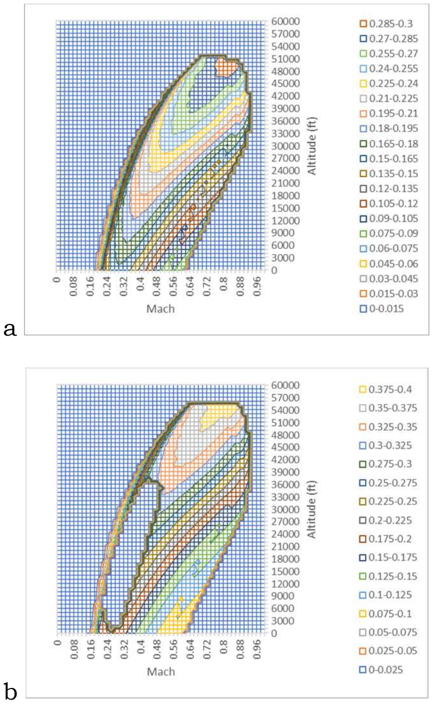


FIGURE 11 – Specific Range skymap for still air / standard day *Aeris* A) Heavy – W=65,000-lbm B) Light – W=47,000-lbm

Point-performance "skymaps" of the specific range of the *Aeris* has also been plotted in FIGURE 11. In contrast to the *A320*, the *Aeris* clearly has much higher altitude potential with the capability of reaching 50,000-ft at its high-weight configuration. Furthermore, the maximum specific range is always located at the highest achievable altitude for the *Aeris*. This presents a very different picture than the *A320* especially when considering winds-aloft, as the jet-stream is often found around 40,000-ft. Thus, the *Aeris*'s design allows it to fly high above the jet-stream.

Although the *A320* and the *Aeris* are very different in terms of their design and mission requirements, this difference can be used to determine the impact of their design philosophies with real-world atmospheric conditions. The *A320* follows a design model where increasing payload capacity upon an existing design yields more favorable mission economies at a lower design cost. The *Aeris* develops an argument for designing new aircraft capable of higher altitudes and greater speeds to increase mission economy. This provides an interesting lens to flight in real-world weather, as the lessons learned from both can impact how current aircraft operators plan missions and how current aircraft designers might develop the aircraft of the future.

III. **Methodology**

We used a trade-study approach to investigate the effects of real-world winds and temperature deviations on en-route performance.

For each study, we vary the cruise altitude and takeoff weight of our particular aircraft to explore change in overall mission fuel and payload economies. Due to the massive variability involved with this field of study, this particular paper focuses on the qualitative and quantitative effects of weather for a single route in still winds, with nominal (seasonal winds) and with actual daily wind patterns.

From an analysis of single route, it is possible to glean how weather impacts domestic flights. This can be used to extrapolate to cover many other routes within reason. Considering that the jet-stream is of primary concern when dealing with winds and that it runs in an easterly fashion, an east-west route was chosen to maximize our analysis of the importance of the jet-stream.

Our chosen route for this thesis simulates flights from the San Francisco bay area to the mid-west. While most operators would actually fly to the Chicagoland area (KORD or KMDR), due to terminal area routing concerns we simplified our mission model to take-off and landing flying a typical route from Oakland, CA (KOAK) to the Quad Cities Airport (KMLI) near Davenport, IA.

The days investigated include a span of five-days in September 2019, as well as a day chosen in each other season (Winter, Spring, and Fall). The five-day series provides an analysis of the effect of day-to-day winds to determine how much an aircraft's optimal flight conditions change based on daily winds. The seasons provide a broader sense of how the weather impacts the performance of an aircraft over the entire year, providing a sense for the bounds of wind-aircraft interaction.

Six major tools were used for this investigation into real-world en-route flight. We describe these in greater detail in our companion paper "*Aircraft Should Not Be Fair Weather Friends – Impact of Winds Aloft on Aircraft Operating Economics*" submitted to this same conference [31]:

1. EDET (Empirical Drag Estimation Technique), mentioned above
2. NPSS (Numerical Propulsion System Simulation), also mentioned previously
3. A *Lateral Flightpath Generator* – this tool provides interpolated weather data along the requested flight path in 25-nM intervals. The weather data provides weather information for vertical slices of pressure altitudes from 10000-ft to 51000-ft at each interval. The data itself includes ISA deviations, corrected density altitudes, and wind speeds/directions at each altitude interval and path interval.
4. *Enhanced Skymaps* is an enhanced aircraft point-performance estimation tool that uses EDET files, NPSS files, and wind/weather files. It includes the impact of winds and density altitude [28][9][31][32] to the specific range computation. We use this tool to pump-prime the mission code by establishing the cruise conditions for an aircraft based upon a weight and altitude by finding the maximum speed corresponding to 99% best specific range.
5. A non-standard day point-mass *Mission Simulator* models aircraft performance from takeoff to touchdown. It uses a specified vertical mission profile file, EDET file, and NPSS file. As the aircraft "flies" its mission downrange from departure, the mission code will adjust its atmosphere model to account for local deviations in density altitude (for engine performance) as well as account for the winds found aloft.
6. *ModelCenter* [33] is a trade-study tool that provides an interface to link excel workbooks, VBA scripts, and a handful of other programs together with simple logic statements to provide simple computational investigation with DOE methods. This tool was used to link the various tools together and perform the overall trade studies this thesis is based on.

FIGURE 12: University of Wyoming weather sounding stations for the continental United States (as seen on http://weather.uwyo.edu/upperair/sounding.html)

We obtain our weather model from the University of Wyoming's (UWYO) atmospheric sounding database. [34] This database provides atmospheric soundings twice a day for sounding stations across the world. A map of the sounding stations for North America can be seen in FIGURE 12. We refer you to our companion paper [31] for more information regarding the mechanics of how we import and pre-process this information for use in our kinematic simulation tools.

Recall, we must account for winds and temperature deviation to estimate real-world performance. In the absence of detailed ISADEV engine decks, we interpolate the standard-day engine data at the density altitude corresponding to flight at a given geometric conditions. We base our correction on an ideal-gas law interpretation of the standard atmosphere, whereby the density of the atmosphere is calculated at a given pressure altitude given a temperature deviation as discussed by Takahashi & Sobester in Reference [9].

IV. **Trade Study Setup**

We coordinated all mission trade studies using the *ModelCenter* environment [33]; refer to FIGURE 13.

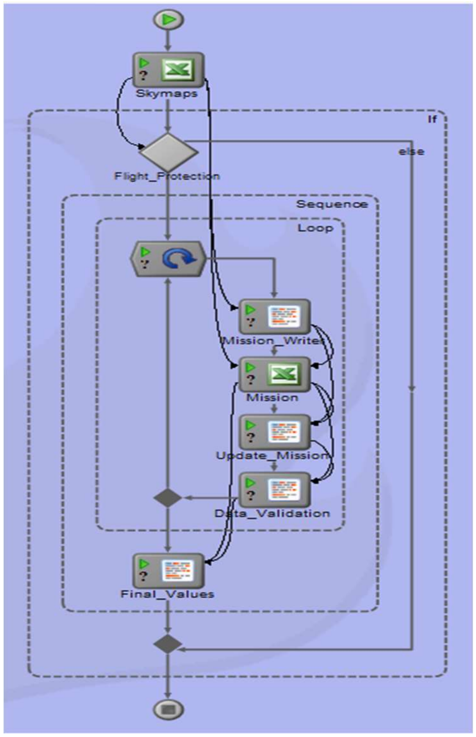


FIGURE 13: ModelCenter Setup

The model uses the point-performance *Enhanced Skymaps* tools to determine the target cruise Mach number for the 99% best specific range high-speed cruise point.

We model the aircraft flight accounting for winds and temperature deviation. We implement a convergence loop to alter the level-flight cruise distance based upon the credit distance error in order to converge the mission to the target credit ground distance.

In order to ensure that each mission is a legal and proper mission, an additional 100nM divert portion and 45-min hold was added to simulate the extra fuel needed for bad weather as required by 14 CFR 91.167 [35] and 14 CFR 121.639 [36].

One of the primary metrics used is the average credit specific range, which provides an indication of the fuel efficiency of the target mission. This is calculated by the equation,

$$SR_{Credit} = \frac{CreditDistance}{CreditFuel} \tag{1}$$

Although the fuel efficiency is an important metric to measure aircraft, aircraft operators are oftentimes highly concerned with a combination of fuel economy and payload capacity. Thus, a flight economy would require a combination of mission excess payload with mission fuel economy. In this paper, this is performed by a measurement designated as payload economy.

The excess payload is calculated from the initial TOW of the aircraft, the credit fuel burn, the reserve fuel, and the operational empty weight (OEW) of the aircraft. The direct calculation is,

$$ExcessPayload = TOW - CreditFuel - OEW - FuelReserve \tag{2}$$

The payload economy or fuel burn per kilopound-mile (lbm/kilopound-nM) can then be calculated from the excess payload,

$$FuelBurnPerKLBMile = \frac{CreditFuel}{CreditDistance \times \frac{ExcessPayload}{1000}} \tag{3}$$

The payload economy determines the cost effectiveness of the mission assuming the total payload can be profit-generating. For the pure payload perspective, a lower number corresponds to a more “efficient” mission (one that generates the best profit). The specific range is inverted in that a higher number corresponds to a more fuel-efficient mission.

A trade-study approach was used in order to investigate the effects of real-world winds and temperature deviations on en-route performance. For each study, the cruise altitude and takeoff weight of a chosen aircraft would be varied which would result in changes in the overall mission fuel, and payload economies. This was done due to the increased interaction between altitude and aircraft performance resulting from changing atmospheric properties with respect to aircraft performance. The interplay between TOW, altitude, and resulting performance become even more nuanced and difficult to predict.

For this paper, we are primarily concerned with the optimal economies of each aircraft for each mission case (day and direction). From each tradespace we search for the optimal economy location for each economy type and use that for further analysis. Analysis is performed upon differences from design conditions (baselines) as well as for each plane against each other.

V. **Results**

A. Baselines

In order to determine the effect of winds and temperature deviations upon the en-route performance of the *A320* and the *Aeris*, baselines that are derived from standard en-route performance simulations must be set. This standard simulation uses standard-day conditions and zero winds.

A baseline trade was performed for both the *A320* and the *Aeris*, where the TOW and the cruise altitude were varied to determine the impact on the fuel economy and payload economy of the aircraft. Since there are no winds, there is no difference in the standard condition trades for flying Oakland to or from Davenport. The baseline trade data for the *A320* is shown below in FIGURE 14 and 15. Please note that the *A320* is incapable of flight at weights above 155,000-lbm at 40,000-ft altitude (FL400); the distortion in the upper left hand corner of the plots reflects this.

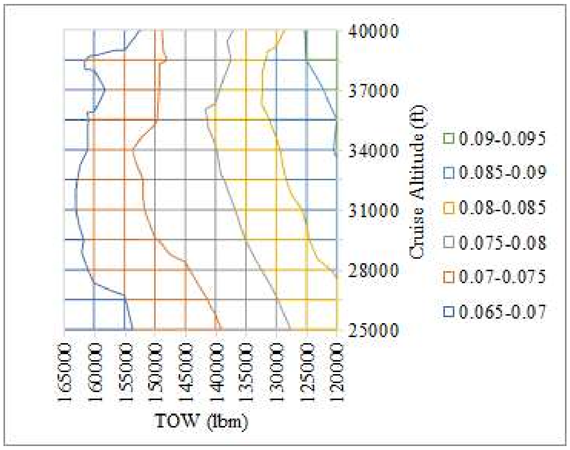


FIGURE 14: Baseline *A320* Credit SR for OAK - DVN

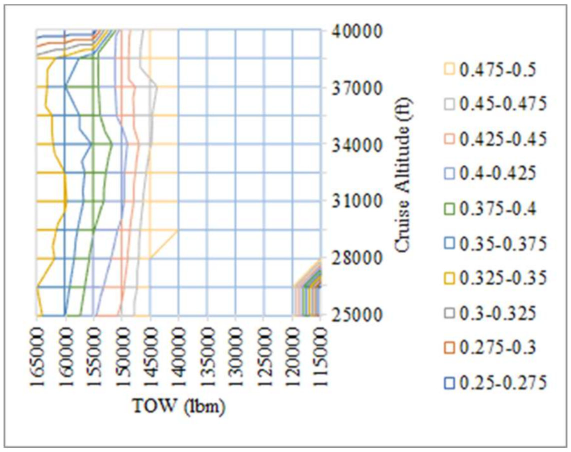


FIGURE 15: Baseline *A320* fuel burn/kilopound-mile for OAK - DVN

For the *A320*, we see that the fuel economy of the aircraft is best light weights and at high altitudes (40,000-ft / FL400). As the take-off-weight increases, the best specific range altitude drops down to ~34,000-ft (FL340). This shows an indication that flying above that altitude for heavier weights “overloads” the aircraft too much and brings about an induced drag rise that negates the drag reductions and thrust efficiencies gained from flying at higher altitudes.

The trend of taking more weight as opposed to flying at greater fuel efficiencies is shown in the overall payload economy of the *A320* in FIGURE 23. In this plot, the optimum payload economy is found when flying at the maximum analyzed weight at ~32,000-ft (FL320).

Since it is obvious that the *A320* has a significant altitude restriction, our hope is that the *Aeris* (which has a flight ceiling of 50,000-ft / FL500) will have a significantly different story with respect to its interaction with winds and density changes. The *Aeris* baselines can be seen in FIGURE 16 and 17, overleaf.

The fuel economy of the *Aeris* shows a very different trend from the *A320*. Although the best specific range is found at the highest altitudes at the lightest TOW, the specific range continues to be most favorable at altitudes above 45,000-ft. When combined with the overall payload economy of the aircraft, a trend appears where the *Aeris* wants to fly at its maximum weight near its flight ceiling of 50,000-ft. Since the *Aeris* was designed for a full loading at this altitude, it does not appear to have the overloading problem of the *A320*, and hence the induced drag rise effect does not appear to play a significant role in the mission economies of the *Aeris*.

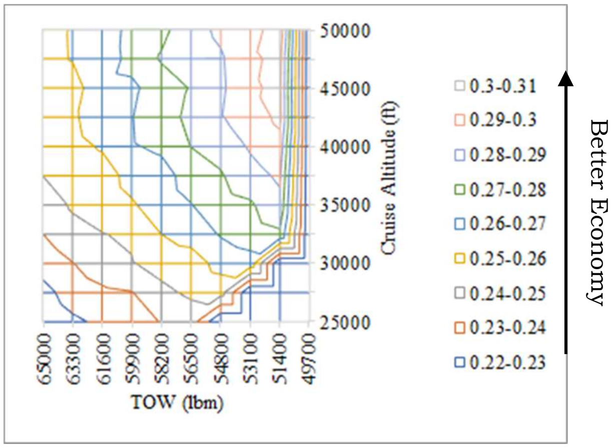


FIGURE 16: Baseline *Aeris* Credit Specific Range (nM/lbm-fuel burn) for OAK → DVN

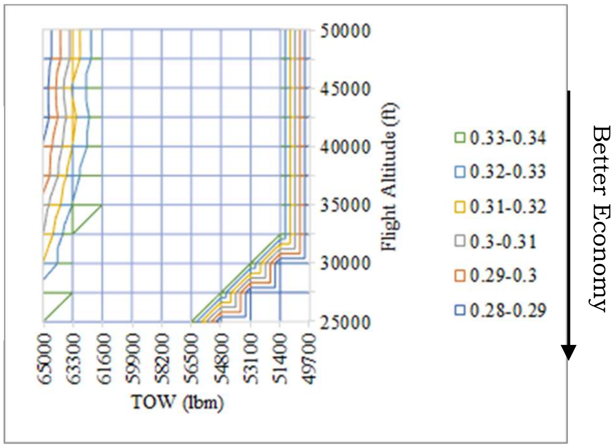


FIGURE 17: Baseline *Aeris* fuel burn/kilopound-mile for OAK → DVN

B. Quantitative Differences

A quantitative analysis on the performance of the *Aeris* and the *A320* provides a deeper understanding of the differences caused by off-standard day conditions. Since both aircraft operators and designers are concerned with getting the best performance out of an aircraft, only the optimal performance of the *Aeris* and *A320* are analyzed in this section. The performance is modelled from the fuel, passenger, and payload economies of these aircraft rather than direct fuel or payload capacity. This is done since those values are implicitly found from the trades as

$$TOW = OEW + PYLD + FuelBurned + FuelReserved \tag{4}$$

Thus, the economies provide a better understanding of the relative impact of the atmosphere upon each aircraft's performance.

To determine the quantitative effect of winds upon the *A320*, the best fuel and payload economies and their percent difference from the standard design mission are tabulated in Table 3, overleaf. The same is done for the *Aeris* and can be seen Table 4. The averaged economies and percent differences are also tabulated, however please note that the average only includes the non-standard (non-design) data points as it is meant to be compared against the design point.

TABLE 3: *A320* OAK to DVN Best Economies

Test Point	Max SR Altitude (ft)	Max SR (nM/lbm)	Max SR Delta from Design	Max Payload Economy Altitude (ft)	Max Payload Economy (lbm/kilopound-nM)	Max Payload Economy Delta from Design
Design	40,000	0.09554	0.00%	31000	0.33231	0.00%
1/20/2019	39,000	0.11196	17.19%	39,000	0.26911	-19.02%
4/20/2019	40,000	0.10042	5.11%	36,000	0.30995	-6.73%
9/8/2019	39,000	0.1043	9.17%	36,000	0.29706	-10.61%
9/9/2019	39,000	0.10491	9.81%	31000	0.29113	-12.39%
9/10/2019	39,000	0.10591	10.86%	33000	0.28749	-13.49%
9/11/2019	40,000	0.1023	7.08%	34,000	0.30199	-9.12%
9/12/2019	39,000	0.10437	9.24%	33000	0.2975	-10.47%
11/20/2018	36,000	0.0985	3.10%	30000	0.31468	-5.30%
AVERAGE	-	0.10408	8.95%	-	0.29611	-10.89%

TABLE 4: *Aeris* OAK to DVN Best Economies

Test Point	Max SR Altitude (ft)	Max SR (nM/lbm)	Max SR Delta from Design	Max Payload Economy Altitude (ft)	Max Payload Economy (lbm/kilopound-nM)	Max Payload Economy Delta from Design
Design	50,000	0.30775	0.00%	50,000	0.28071	0.00%
1/20/2019	40,000	0.36758	19.44%	40,000	0.22721	-19.06%
4/20/2019	50,000	0.32692	6.23%	45,000	0.25838	-7.96%
9/8/2019	43000	0.33941	10.29%	43000	0.252	-10.23%
9/9/2019	45,000	0.33756	9.68%	43000	0.25027	-10.84%
9/10/2019	48000	0.34469	12.00%	43000	0.2496	-11.08%
9/11/2019	48000	0.34283	11.40%	45,000	0.25083	-10.64%
9/12/2019	40,000	0.33579	9.11%	38000	0.25179	-10.30%
11/20/2018	48000	0.33441	8.66%	45,000	0.26426	-5.86%
AVERAGE	-	0.34115	10.85%	-	0.25054	-10.75%

Based upon the values in Table 4, we see that the *Aeris* manages to make a maximum fuel economy of 0.308 nM/lbm under its design conditions. In January, when flying with the high winds of the jet-stream, the *Aeris* is capable of reaching a fuel economy of 0.367 nm/lbm. This results in a fuel savings of 19% as compared to its design mission. The *A320* has a similar story as can be seen in Table 3. Its maximum fuel economy under design conditions is 0.096 nm/lbm, while in January it reaches a maximum fuel economy of 0.12 nm/lbm, which results in a fuel savings of 18% when compared to its design mission.

It appears that both aircraft also obtain similar relative improvements in their payload economy when flying with the winds. For the *Aeris*, an overall optimum payload economy of 0.23 lbm/kilopound-nM is reached in January, as opposed to its design point of 0.28 lbm/kilopound-nM leading to a 19% improvement in payload economy. The Airbus has an overall optimum payload economy of 0.27 lbm/kilopound-nM, which is also a 19% improvement from its design payload economy of 0.33 lbm/kilopound-nM.

If both have similar relative improvements in flight with the winds, what about flight against the winds? The optimal economies of the *A320* and the *Aeris* have also been recorded for flight from Davenport to Oakland in Tables 5 and 6 respectively.

TABLE 5: *A320* DVN to OAK Best Economies

Test Point	Max SR Altitude (ft)	Max SR (nM/lbm)	Max SR Delta from Design	Max Payload Economy Altitude (ft)	Max Payload Economy (lbm/kilopound-nM)	Max Payload Economy Delta from Design
Design	40,000	0.09554	0.00%	31,000	0.33231	0.00%
1/20/2019	40,000	0.07474	-21.77%	31,000	0.4258	28.13%
4/20/2019	39,000	0.09166	-4.06%	28,000	0.34623	4.19%
9/8/2019	39,000	0.08486	-11.18%	31,000	0.3593	8.12%
9/9/2019	40,000	0.08442	-11.64%	31,000	0.36968	11.25%
9/10/2019	36,000	0.08332	-12.79%	33,000	0.37296	12.23%
9/11/2019	40,000	0.08996	-5.84%	33,000	0.34664	4.31%
9/12/2019	39,000	0.08511	-10.91%	30,000	0.36671	10.35%
11/20/2018	40,000	0.08934	-6.49%	33,000	0.35584	7.08%
AVERAGE	-	0.08543	-10.58%	-	0.36790	10.71%

TABLE 6: *Aeris* DVN to OAK Best Economies

Test Point	Max SR Altitude (ft)	Max SR (nM/lbm)	Max SR Delta from Design	Max Payload Economy Altitude (ft)	Max Payload Economy (lbm/kilopound-nM)	Max Payload Economy Delta from Design
Design	50,000	0.30775	0.00%	50,000	0.28071	0.00%
1/20/2019	50,000	0.26909	-12.56%	50,000	0.32873	17.11%
4/20/2019	48,000	0.29344	-4.65%	48,000	0.29882	6.45%
9/8/2019	50,000	0.28326	-7.96%	50,000	0.30334	8.06%
9/9/2019	50,000	0.28292	-8.07%	50,000	0.30254	7.78%
9/10/2019	50,000	0.28098	-8.70%	50,000	0.30433	8.41%
9/11/2019	50,000	0.29101	-5.44%	50,000	0.30244	7.74%
9/12/2019	50,000	0.27953	-9.17%	50,000	0.30596	8.99%
11/20/2018	50,000	0.28526	-7.31%	50,000	0.31023	10.52%
AVERAGE	-	0.28319	-7.98%	-	0.30705	9.38%

From a general perspective, it appears that the *Aeris* nets less negative impact on its mission performance from the fuel economy and payload economy. Looking closely at the fuel economies, it seems that the *Aeris* is less impacted by the winds throughout the studied week in September as well as in January, however the Airbus is less impacted in April and November. The payload economy difference for the *Aeris* is mostly superior in September and heavily superior in January, while the Airbus has less negative impact again in July and November.

It seems that both the magnitude of the winds and the shape of the winds profile along altitude plays a major role in the performance of both the *Aeris* and the *A320*. Although the *Aeris* appears to have the best relative difference in terms of the payload economy, depending on the wind profile the *A320* might be slightly less affected.

From the tables, we can see large differences between the performance of each aircraft and their design point and that these differences are extremely dependent upon the direction of flight. However, from a design perspective an aircraft needs to be designed for both flight with and against the winds. One way to accomplish this is to average the performance deltas from flight with the winds and flight against the winds to see how real-world flight operation as a whole compares to that of the design point. To this end, I have graphed the fuel and payload economy differences for flight with the wind, against the wind, and the resultant average for the *A320* and the *Aeris* in Figures 18 and 19 respectively.

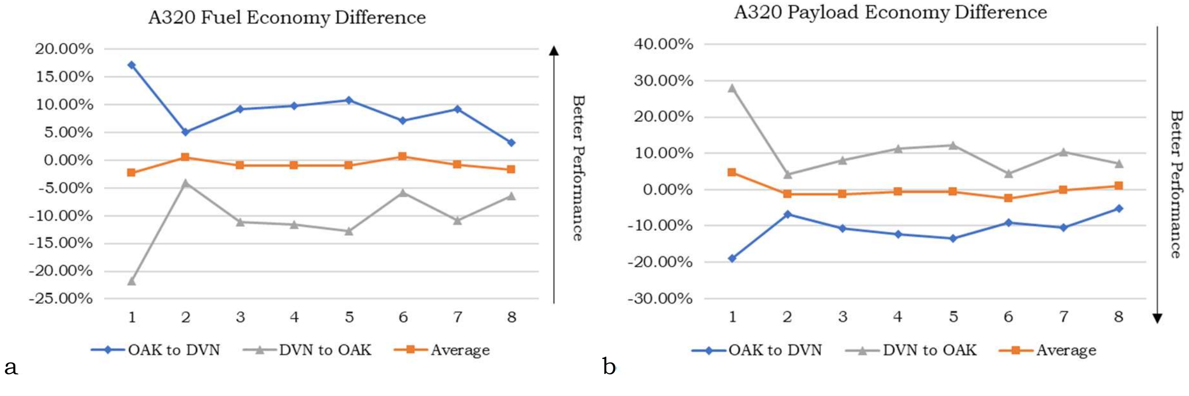
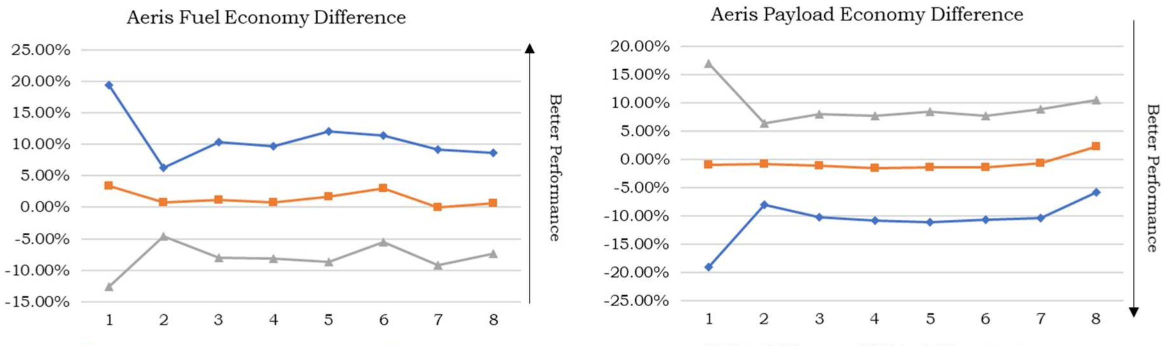


FIGURE 18: *A320* differences against design condition with the winds, against the winds, and averages for a) fuel economy and b) payload economy



a b

FIGURE 19: *Aeris* differences against design condition with the winds, against the winds, and averages for a) fuel economy and b) payload economy

From these figures, we can see that the average trends towards 0%. However, we can also notice that the values tend to stay on one side of the design point (0%) line with a small offset, which indicates that the average real-world performance of both the *A320* and the *Aeris* do not entirely conform to the design point as expected.

The *A320* has a general negative impact in fuel economy and payload economy as that oscillates around the design point line. In contrast, the *Aeris* has a general positive impact in both fuel economy and payload economy. This suggests that real-world conditions cause the *A320* to have slightly worse fuel economy and similar payload economy as targeted by traditional design. However, on average the *Aeris* performs slightly better than its design point in both its fuel economy and payload economy.

Looking back at Tables 3 through 6, we can see that the *Aeris* has major changes in its optimal altitude location compared to its baseline altitude for both the maximum payload economy and fuel economy when flying with the winds. In contrast, there is much less altitude variance found within the *A320* for flight with the winds. However, in flight against the winds nearly all *Aeris* altitudes are found near its design flight altitude, while the *A320* still sees little change in its optimal economy altitudes as compared to its design flight.

It appears that the *Aeris* has a much better ability to maneuver itself around the winds for optimizing its economies. Its wider flight altitude envelope combined with its already high cruise altitude give it a lot more flexibility in how it approaches the winds than the *A320*. This might explain why the *Aeris* has slightly better averages than its design point, because it can better maneuver to capture maximum potential performance in flight with the jet-stream, and its design is far away from the jet-stream that it can better minimize its losses than the *A320*.

Since the averaged values are very close to the design point (only ~1-2% difference normally), it seems that using a standard-day approach can yield very close estimates to the averaged performance of flight in real-world conditions. However, considering the immense pressure on aircraft operators and users to have aircraft that fly as efficiently as possible, that difference in real-world performance can make a significant impact on the overall operating economics.

From interrogating the relative differences of economies within each aircraft, we can see that there are clear differences in how each aircraft actually responds to real-world conditions. What about the direct differences between the aircraft? Although they are designed with very different philosophies and different missions, there is some possibility that we may glean some better understanding of what aspects of each design philosophy should be considered in the design of future aircraft. For that, direct comparisons between the fuel and payload economies of the *Aeris* and the *A320* have been calculated and stored in tables 5 and 6 for flight with the winds.

TABLE 5: *Aeris* vs *A320* Fuel Economy (Credit SR) Comparison for OAK to DVN

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.30775	0.09554	-0.21222	-222.13%	0.00%
1/20/19	0.36758	0.11196	-0.25562	-228.31%	2.78%
4/20/19	0.32692	0.10042	-0.22651	-225.57%	1.55%
9/8/19	0.33941	0.10430	-0.23511	-225.42%	1.48%
9/9/19	0.33756	0.10491	-0.23265	-221.77%	-0.16%
9/10/19	0.34469	0.10591	-0.23878	-225.45%	1.49%
9/11/19	0.34283	0.10230	-0.24052	-235.11%	5.84%
9/12/19	0.33579	0.10437	-0.23142	-221.72%	-0.18%
11/20/18	0.33441	0.09850	-0.23591	-239.51%	7.83%
Average	0.34115	0.10408	-0.23706	-227.22%	2.29%

TABLE 6: *Aeris* vs *A320* Payload Economy (Fuel Burn/Kilopound-Mile) Comparison for OAK to DVN

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.28071	0.33231	0.05160	15.53%	0.00%
1/20/19	0.22721	0.26911	0.04190	15.57%	0.28%
4/20/19	0.25838	0.30995	0.05157	16.64%	7.16%
9/8/19	0.25200	0.29706	0.04506	15.17%	-2.30%
9/9/19	0.25027	0.29113	0.04085	14.03%	-9.62%
9/10/19	0.24960	0.28749	0.03789	13.18%	-15.12%
9/11/19	0.25083	0.30199	0.05117	16.94%	9.12%
9/12/19	0.25179	0.29750	0.04571	15.36%	-1.05%
11/20/18	0.26426	0.31468	0.05042	16.02%	3.20%
Average	0.25054	0.29611	0.04557	15.38%	-0.92%

When comparing actual values, we see that the *Aeris* has a better payload economy than the *A320* under every condition. At the optimal point, the *Aeris* is almost 15% more economic to fly than the *A320*, even though the *A320* can carry more than double the payload of the *Aeris* on a single flight.

This massive improvement on payload economy between the *Aeris* and the *A320* indicates that the current industrial trend of simply adding more payload capacity to existing aircraft does not yield optimum results in either fuel economy or payload economy. Furthermore, the *A320* has been shown to be overloaded in these trades. Adding more payload will drive the *A320* to a lower altitude and further away from the jet-stream core, hurting its mission economy further when weather is involved.

Since the direct difference between the aircraft includes differences due to design and differences in how they interact with the winds, it is also valuable to separate these effects. To determine which aircraft truly had better performance in the presence of winds, the daily differences between the aircrafts to the baseline difference between the aircrafts are compared. This is documented in the "*Aeris* Percent Difference against Design Difference" column in tables 5 and 6. Positive percentages denote that the *Aeris* performs better in winds than the *A320*, and negative percentages denote that the *A320* performs better than the *Aeris*.

In general, the *Aeris* yields better fuel economy when flying with the winds than the *A320*. However, the *A320* seems to get better payload economy performance than the *Aeris* when flying with the winds. Thus, it seems that when the *A320* is heavily loaded, it can potentially benefit more from flight with the winds than the *Aeris*.

A similar perspective can be performed in flight against the winds. Tables 7 and 8 show the direct comparison of the *A320* and *Aeris* mission economies in flight against the winds to determine which design provides superior economic performance.

TABLE 7: *Aeris* vs Airbus *A320* SR Comparison for DVN to OAK

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.30775	0.09554	-0.21222	-222.13%	0.00%
1/20/2019	0.26909	0.07474	-0.19435	-260.03%	17.06%
4/20/2019	0.29344	0.09166	-0.20178	-220.13%	-0.90%
9/8/2019	0.28326	0.08486	-0.19840	-233.78%	5.25%
9/9/2019	0.28292	0.08442	-0.19850	-235.15%	5.86%
9/10/2019	0.28098	0.08332	-0.19766	-237.22%	6.79%
9/11/2019	0.29101	0.08996	-0.20106	-223.51%	0.62%
9/12/2019	0.27953	0.08511	-0.19442	-228.42%	2.83%
11/20/2018	0.28526	0.08934	-0.19592	-219.29%	-1.28%
Average	0.28319	0.08543	-0.19776	-231.49%	4.03%

TABLE 8: *Aeris* vs Airbus *A320* Payload Economy Comparison for DVN to OAK

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.28071	0.33231	0.05160	15.53%	0.00%
1/20/2019	0.32873	0.42580	0.09707	22.80%	46.82%
4/20/2019	0.29882	0.34623	0.04741	13.69%	-11.81%
9/8/2019	0.30334	0.35930	0.05596	15.57%	0.31%
9/9/2019	0.30254	0.36968	0.06714	18.16%	16.97%
9/10/2019	0.30433	0.37296	0.06863	18.40%	18.51%
9/11/2019	0.30244	0.34664	0.04420	12.75%	-17.87%
9/12/2019	0.30596	0.36671	0.06075	16.57%	6.70%
11/20/2018	0.31023	0.35584	0.04561	12.82%	-17.45%
Average	0.30705	0.36790	0.06085	16.54%	4.69%

Despite carrying less than half the payload of the *A320*, the *Aeris* is still more economical to fly on a pound of fuel per pound of payload perspective. Furthermore, the improvements are vastly superior on days with high winds in the jet-stream, where the *Aeris* yields more than 20% better payload economy in January as compared to the *A320*.

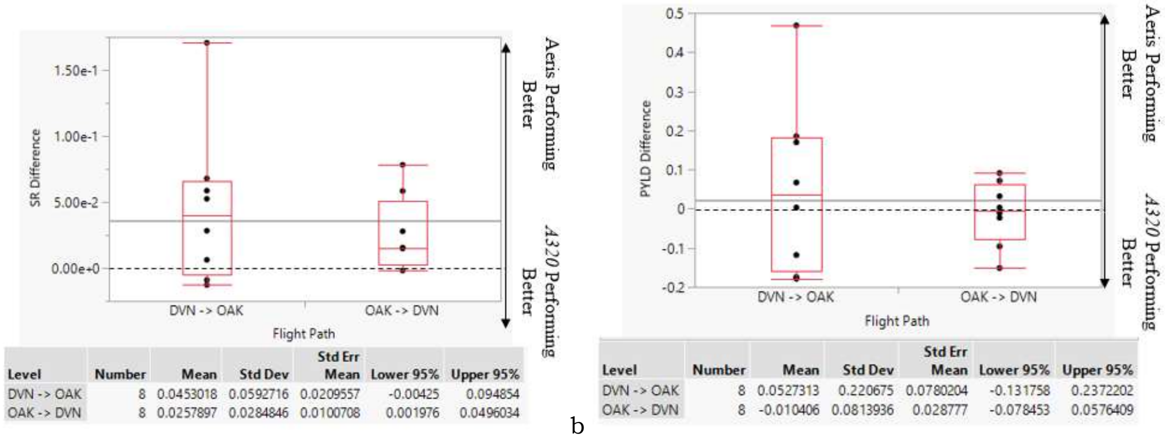
It appears that the strategy of the *A320* in flying below the jet-stream results in less capability against the winds than hoped for. To get away from the jet-stream, the *A320* must descend in altitude, increasing its skin friction drag and reducing the efficiency of its engines. In contrast, the *Aeris* can climb to its design cruise altitude, and does not fall into the induced drag rise region.

Just as in the analysis of flight with the winds, noting the direct differences between the aircraft conflates the combination of inherent design differences and differences due to their interaction with the atmosphere. Using the "*Aeris* Percent Difference against Design Difference" column allows us to determine whether the *Aeris* has better relative performance in the presence of winds as compared to the *A320*.

From this perspective, the effect of winds and temperature deviation once again get more nuanced. There is a spattering of positives and negatives for the fuel economy and payload economy. The real-world atmosphere creates a highly variable effect upon the performance *Aeris* and the *A320*, making it difficult to know exactly which one will benefit more from the winds on any given day. In general however, the *Aeris* appears to obtain better relative performance in its fuel economy and its payload economy.

The variability changes when flying to and from the winds as well as upon the referenced economy. To better visualize the variability of the difference against the design difference, box plots for both flight paths

(OAK to DVN and DVN to OAK) have been generated along with means and standard deviations for the fuel economy differences against the design difference and payload economy differences against the design difference. These can be seen in FIGURE 20. Note that the dashed line represents the 0% mark.



a

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DVN -> OAK	8	0.0453018	0.0592716	0.0209557	-0.00425	0.094854
OAK -> DVN	8	0.0257897	0.0284846	0.0100708	0.001976	0.0496034

b

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DVN -> OAK	8	0.0527313	0.220675	0.0780204	-0.131758	0.2372202
OAK -> DVN	8	-0.010406	0.0813936	0.028777	-0.078453	0.0576409

FIGURE 20: Statistical Analysis on a) fuel economy (nM/lbm), b) payload economy (lbm/kilopound-nM)

From the statistical viewpoint, the variance found in flight against the winds is much larger than in flight with the winds, especially in the fuel economy and payload economies. The location as to where each data is clustered is also different in each plot based upon the direction of travel. For the fuel economy, the mean is more positive flying against the winds than with the winds. The payload economy is more subtle, but the mean is slightly positive when flying against the winds and slightly negative when flying with the winds.

From the maximum fuel economy perspective, the *Aeris* can better handle the winds than the *A320* under all studied conditions. However, from a payload economy perspective, the Airbus has a better mean net improvement when flying with the winds than the *Aeris*, although the *Aeris* has a mean net improvement when flying against the winds as compared to the *A320*.

Since the winds are dependent upon time, true statistical analysis on this data cannot be performed with the assumption that the outputs are randomly selected variables. Thus, the comparison of the means is not quite proper for this data.

The pure payload economy shows the most potential out of each aircraft, however. The variability in flight against the winds is much higher than in flight with the winds. Despite this, both show an average difference between aircraft close to zero, which indicates that in general the effect of the winds upon the payload economy of the *A320* and the *Aeris* is roughly the same whether they fly against the winds or with the winds. While most negative differences are close in magnitude to each other, the positive difference in the against-winds case is massive, which indicates that there is potential for major benefit from the winds with the *Aeris* over the *A320*. It seems that the high-altitude capability of the *Aeris* increases the variance in improvement due to the winds, however it occasionally allows massive improvements so long as the mission is planned for the winds.

VI. **Conclusion**

The different design philosophies inherent to the *A320* and the *Aeris* yield very different results when interpreted through real-world atmospheric conditions. The ever-increasing payload capacity of the *A320* has led to improvements in its payload economy, however it is evident from this paper that the aircraft is on the edge of falling off an induced-drag rise cliff. Because of the already high wing loading, the *A320* struggles to climb towards the jet-stream core even when the core exceeds speeds of 100-kts.

In contrast, the *Aeris*'s high-altitude capability and lower wing loading make it much more dynamic in the presence of winds, where will reduce its cruise altitude as much as 10,000-ft to fly in the jet-stream core when flying with the winds as compared to flight under standard-day conditions and no winds. When flying against the winds, the *Aeris* is able to climb above the jet-stream core and fly at its design cruise altitude.

When averaging performance in flight with and against the winds, the *Aeris* sees a slight net improvement as compared to its baseline, indicating aircraft operators may expect better performance from the *Aeris* on average compared to its design performance. The *A320* does not seem to show this trend, however, and in fact may have a very slight drop in its average real-world performance as compared to its design performance.

When comparing how each aircraft is affected by the winds on a daily basis, there is see a large amount of variance in the differences (especially in flight against the winds as opposed to flight with the winds). This makes it difficult to conclude which design philosophy is objectively superior. The variability does hint at using statistical analysis methods, however.

From the basic statistical analysis performed in this paper, it appears that more data points need to be established to get a better understanding of what aircraft is truly better suited to maximize its performance in the presence of weather. With many days, it might be seen that the data falls under a normal distribution, in which case direct statistical analysis could prove a better design philosophy.

In order to determine a method for designing an aircraft with winds in mind, perhaps a statistical method could be used where weather data for multiple days and routes spread across the desired design range could be analyzed to determine a mean and associated variance. Standard aircraft design methods could continue from there with the mean and variance in mind to provide a predicted fuel economy of flight with or against winds and give lower and upper confidence intervals so customers have a better understanding of what economy they can actually expect from the aircraft depending on the season and route.

No matter the case, it is deafeningly apparent that winds add a large source of variability to the actual performance of aircraft. Although one may want to think of the winds as either static or static with seasons, it is apparent that the variation even on a day-to-day basis develops significant changes in how an aircraft wants to fly. With the rise of interconnected aircraft, increased computation, and an increasing emphasis on big-data approaches to engineering problems, it is clear that the daily analysis of winds should become an industry standard as soon as possible to maximize aircraft performance and mission economy.

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