Aircraft are not Fair-Weather Friends:

An Analysis of Aircraft En-Route Performance and Economy with Real-World Atmospheric Conditions

by

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ABSTRACT

Standard procedures to estimate en-route aircraft performance rely upon the "standard atmosphere". Real-world conditions are then represented as deviations from the standard atmosphere. Both flight manuals and aircraft designers make heavy use of the "deviation method" to account for geographical and temperature differences in atmospheric conditions. This method is often done statically, choosing a single deviation based on temperature and a single wind speed for the duration of an entire mission.

Real-world atmospheric conditions have an incredible amount of variation throughout any given flight route, however. Changes in geographic location can present many changes within the atmosphere; they include differences in air temperature, humidity, wind speeds, wind directions, air densities, and more. Historically, these changes have not been accounted for in standard mission performance models. However, they present major possible impacts on real missions.

This thesis addresses this issue by developing a lateral and vertical mission simulation method that uses real-world and up-to-date atmospheric conditions to determine the effect of changing atmospheric conditions on en-route performance and economy. The custom toolset was used in combination with a series of trades over a series of five days and a representation of each season to show the variation that occurs on a single route over the course of daily and seasonal periods.

Both qualitative and quantitative effects from this perspective were recorded for the Airbus *A320* and a student designed regional jet, the *Aeris*, to determine the effect of atmospheric variation on standard commercial transport and hypothetical high-altitude

capable commercial transport. The variance presented by changing atmospheric conditions is massive and has large implications on future aircraft operations and design.

Due to large geographical and temporal variation in the wind speeds and directions, it is recommended that aircraft operators use daily measurements of atmospheric conditions to determine optimal flight paths and altitudes. Further investigation is recommended in terms of the effect of changing atmosphere for design, however from initial investigations it appears that a statistical method works well for incorporating the large variance added by real-world conditions.

DEDICATION

To my grumpy brother, who has reminded me on multiple occasions that it is not better on the other side of military contracting.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

CHAPTER 1: INTRODUCTION

Aircraft performance analysis is typically performed via a standard-day approach. Under this paradigm, aircraft designers and aircraft operators begin analysis under assumptions that the atmosphere the aircraft flies through can be modelled using a "standard-atmosphere philosophy", where different properties of the atmosphere can be directly calculated based on pressure altitude [1] [2]. This is even codified under federal law, as 14 CFR 1.1 requires FAA certified aircraft to reference performance to the 1962 U.S. standard atmosphere [3]. However, the actual atmosphere may markedly differ from the standard atmosphere. Many flight manuals do not explicitly consider winds, instead they use a method of "equivalent still-air distance" to account for the presence of winds. They also use temperature deviations from the standard atmosphere (ISADEV) to account for all other weather-related atmospheric property changes [4]. These methods are very simplistic; they often make the assumption of a constant ISADEV and seasonal wind averages for calculating fuel consumption and flight fuel economy. This vastly simplifies the real-world conditions, where temperature and winds vary in time through geographical space.

So how should an aircraft best fly when accounting for real-world winds and temperature deviations? Although the manuals and traditional literature may have one think that the current methods are satisfactory, the advancement of the internet and the rising development of big-data analysis lead to the conclusion that there is economic potential to revisit this problem. There is little understanding of prediction with real-world data, and even less so for atmospheric data that varies from location to location.

Thus, this thesis sets out to document how aircraft are impacted by both geographic and temporal changes in atmospheric properties.

The University of Wyoming has an atmospheric soundings database that updates twice a day. It provides atmospheric properties such as temperature, humidity, wind speeds, and wind directions from a variety of sounding stations across the world. The main page of the website is shown in figure 1. From a brief perusal of the website, it becomes immediately clear that there is definite variation of atmospheric properties at different stations and at different times, which further supports a need to perform aircraft performance analysis using these real-world datasets. An example of this variation is shown in figure 2, which provides January 2018 wind averages for a variety of sounding stations across the east coast of the United States.

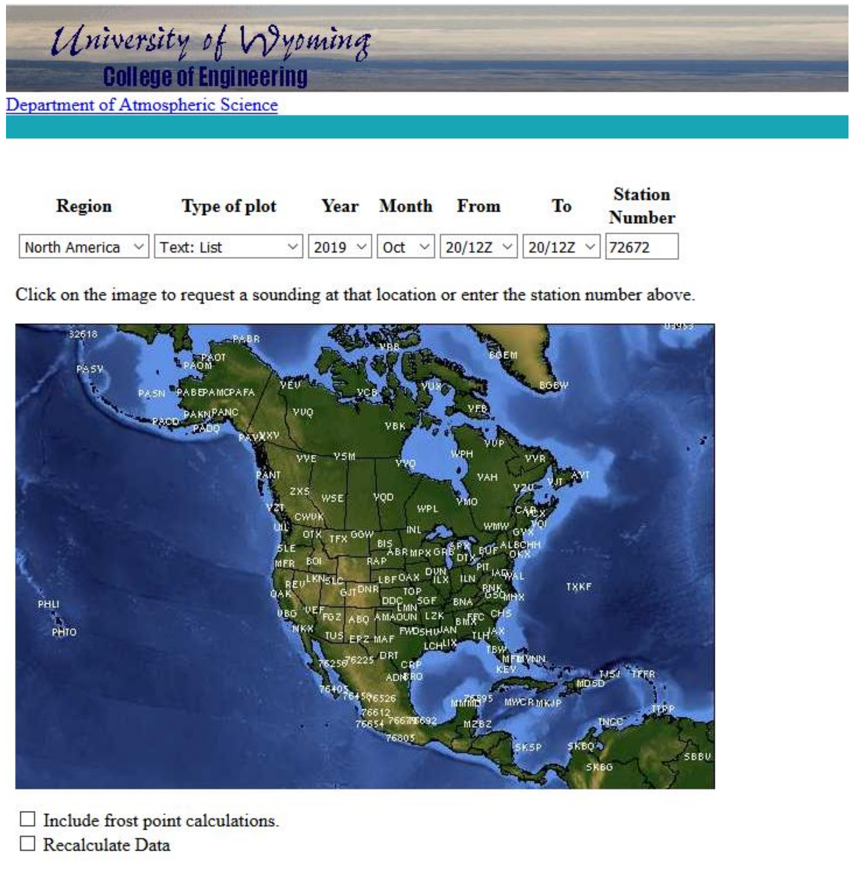


Figure 1: University of Wyoming Atmospheric Sounding Database Website

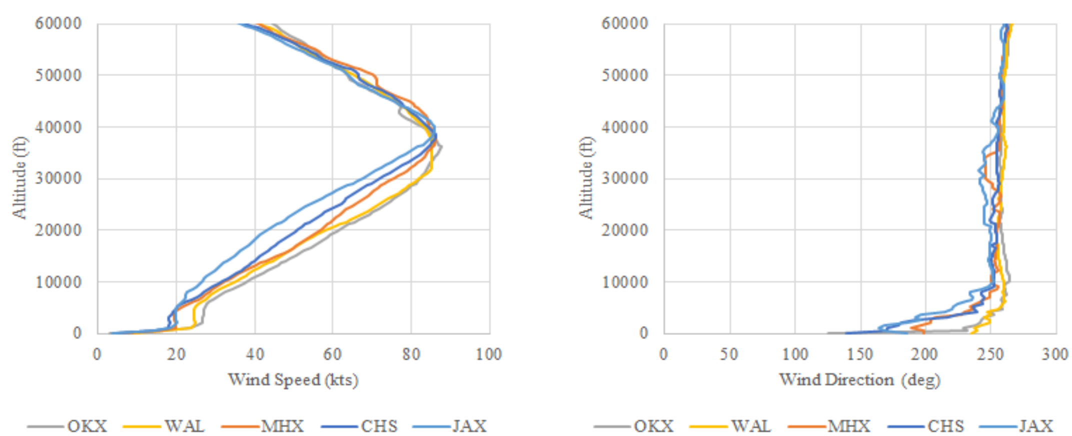


Figure 2: January 2018 Monthly Average Altitude vs Wind Speed and Direction for Sounding Stations along the East Coast

A real-world simulation approach has a large possibility to change how aircraft operators develop their flight plans. Lessons learned from simulating aircraft missions under real-world winds and atmosphere could potentially lead to major changes in recommended cruise altitudes and speeds for aircraft. This can also help determine the optimal payload weight. This is because the economy of aircraft is highly impacted by winds aloft; headwinds artificially lengthen a journey and tailwinds artificially shorten it. Understanding how to maximize an aircraft's performance in the presence of changing winds and atmosphere could provide significant improvements to the overall economy of a mission. Since the maximization of mission economy is a critical goal for all commercial aircraft operators, a large financial incentive exists to develop and perform simulations of aircraft performance with real-world atmosphere models. Even non-commercial operators could benefit significantly from a real-time understanding of aircraft performance, as the winds and atmospheric deviations have a major impact on the true airspeed (TAS), fuel burn and payload capacity, and overall flight dynamics of aircraft.

The design of aircraft may also be influenced by a nuanced understanding of real-world atmospheric impacts upon aircraft performance and flight. Standard atmosphere and variation models are already used to determine the performance qualities and boundaries of nearly all aircraft, however due to real-world conditions these performance estimations may never be properly seen when the aircraft is actually flown [3]. Although a daily approach to real-world atmospheric conditions may not be conducive to design, understanding the variance involved with winds-aloft and temperature deviations can lead to a better understanding of the true dynamics of aircraft, leading to better-resolved confidence intervals for performance measures and aerodynamic loads. This in turn ensures a better understanding of aircraft capabilities between customers and aircraft designers.

CHAPTER 2: STUDIED AIRCRAFT

In this thesis, two aircraft are studied to determine the effects of weather upon mission performance. The first aircraft investigated in this thesis is the Airbus *A320* which can be seen in figure 3. This aircraft is a staple in the United States domestic market and is widely used for standard narrow-body flights by nearly all major airline operators within the continental United States.

Figure 3: Airbus A320 [5]

Different versions of the Airbus *A320* feature a wide range of seating options. However, on average the Airbus *A320* tends to have approximately 150 passengers. This forms the nominal passenger count for the Airbus A320 model used in this thesis. A seating chart of the Delta Airlines A320-200, seating 160 passengers can be seen in figure 4.

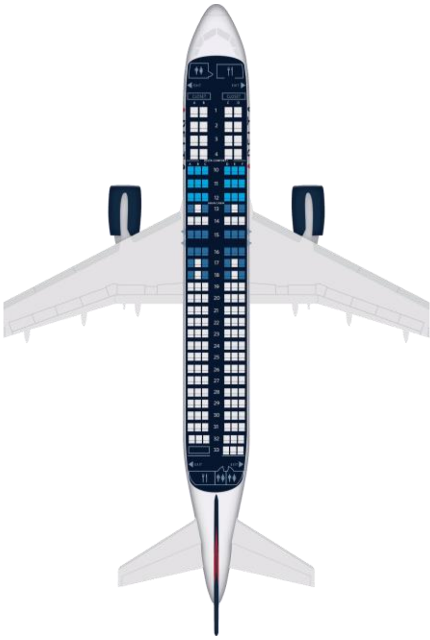


Figure 4: Delta Airlines Airbus *A320* Seating Chart [6]

A well-developed aerodynamic and engine model for this aircraft has been developed in previous research. This provides an accurate basis on which to test the effects of weather on its mission performance [7]. The aerodynamics model is based on a nominally-sized A320 aircraft, with basic wing and fuselage dimensions shown in table 1.

Table 1: Airbus *A320* Dimensions [7]

Item	Value
Wing Reference Area	1320-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 Airbus *A320* is developed from a combination of its aerodynamics model and engines model. The drag polars of the Airbus *A320* form the basis of the aerodynamics data used for modelling the aircraft in this thesis.

The drag polars of this model are shown in figure 5. The engines are modelled as twin 25000-lbf reference static thrust, bypass-ratio (BPR) 5 engines [7]. Power hooks from this engine data are shown in figure 6.

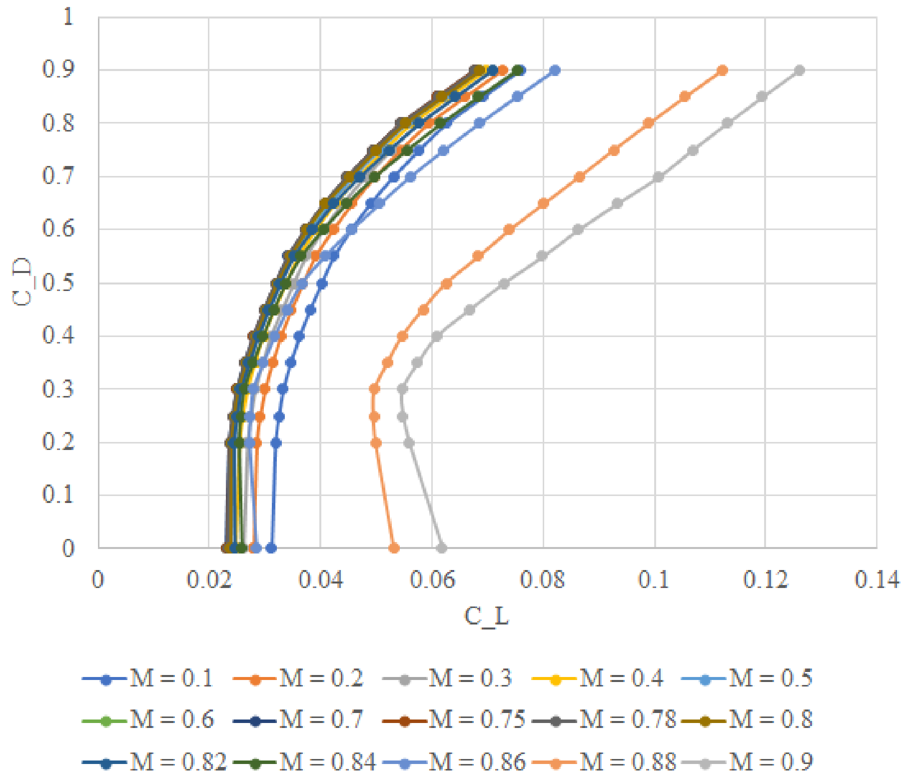


Figure 5: Airbus A320 Drag Polars [7]

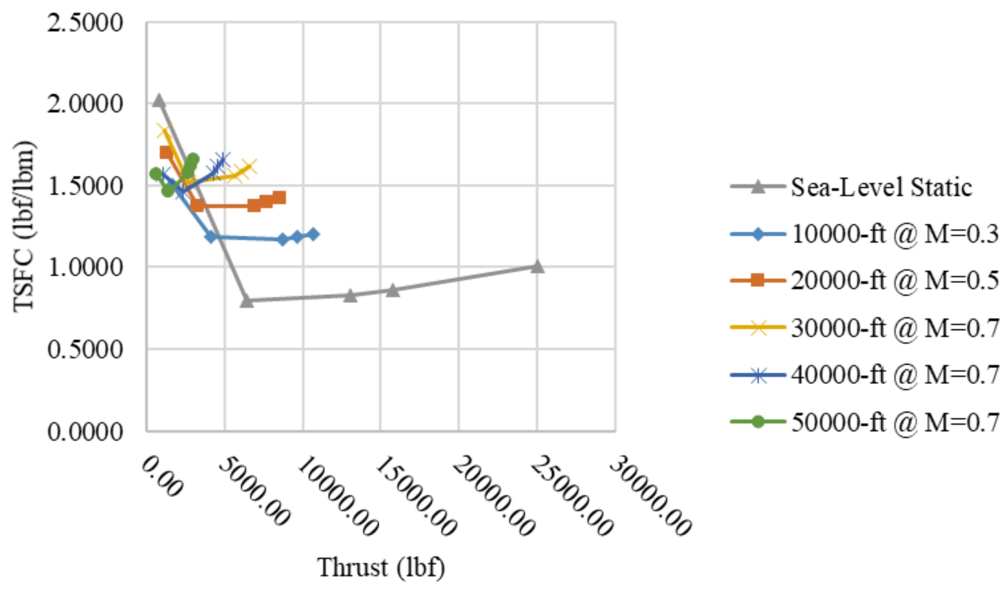


Figure 6: Airbus *A320* Static Condition Power Hook [7]

The *Aeris* is a hypothetical higher-altitude aircraft developed by a senior design team at ASU for the purpose of maximizing fuel economy over a 1500-nM mission by targeting its optimal aerodynamic efficiency (M*L/D) at its design payload capacity [8]. This is in contrast to the Airbus *A320*, which cannot attain its maximum aerodynamic efficiency under current payload configurations (including that studied in this thesis) [7]. This aircraft was designed as a regional jet replacement with increased fuel efficiency and flight speeds and can be seen in figure 7 [8].

Figure 7: *Aeris* Regional Jet [8]

Although this aircraft has never been produced or prototyped, the *Aeris* has a robust aerodynamics and engine model and allows mission investigation of flight altitudes up to 50000-ft (FL500). In comparison, the Airbus *A320* has a maximum flight ceiling of only 40000-ft (FL400). Considering that the jet-streams are often found near 40000-ft (FL400), the *Aeris* provides a unique opportunity to look at flight above the jet-stream.

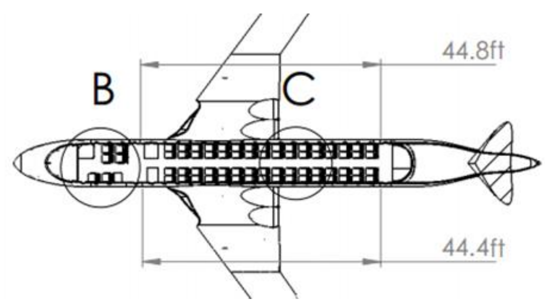


Figure 8: *Aeris* Seating Chart with Emergency Exits Labelled [8]

The *Aeris* has a much smaller cabin than the Airbus *A320*, and only seats 80 passengers [8]. A view of the seating arrangement on the *Aeris* can be seen in figure 8. Due to the smaller cargo capacity requirements of the *Aeris*, it is ultimately a much smaller aircraft than the Airbus

A320. Basic wing and fuselage dimensions are documented in table 2. A three-view drawing of the *Aeris* can also be seen in figure 9.

Table 2: *Aeris* Dimensions [8]

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

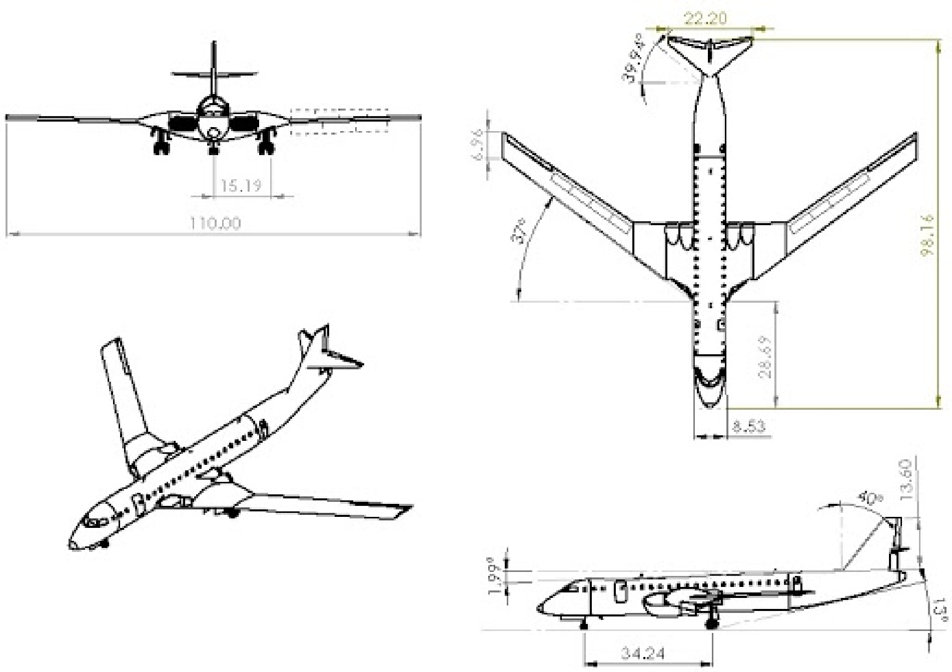


Figure 9: *Aeris* 3-View Drawing. Dimensions are in feet [8]

The drag polars from the aerodynamics model are shown in figure 10. The *Aeris* uses four BPR 12 engines with an 8000-lbf reference static thrust for each engine [8]. Power hooks for this engine data can be seen in figure 11.

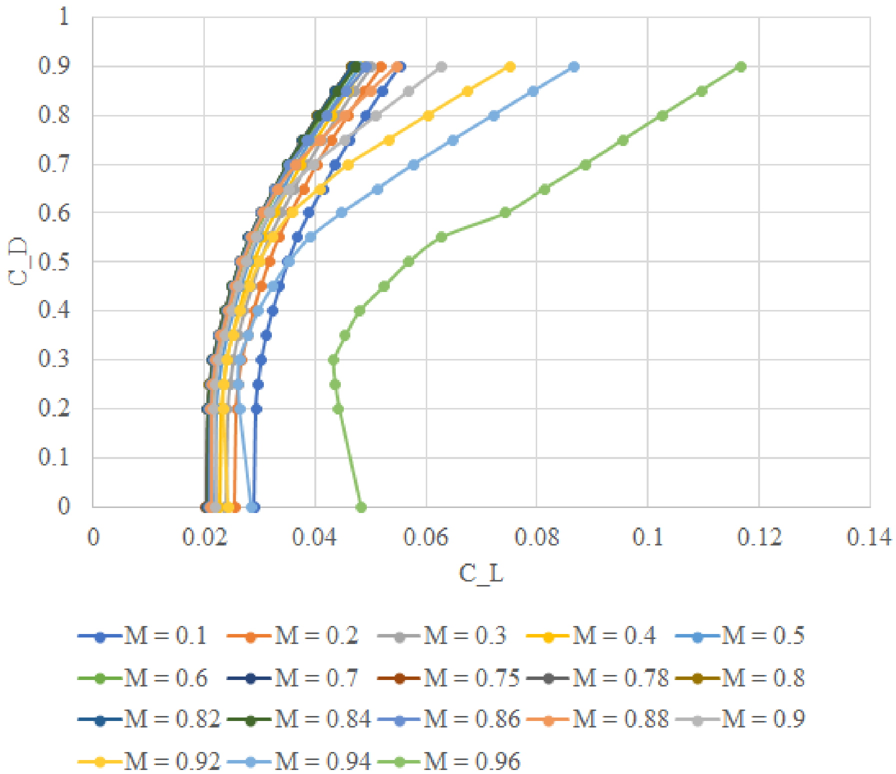


Figure 10: Aeris Drag Polars [8]

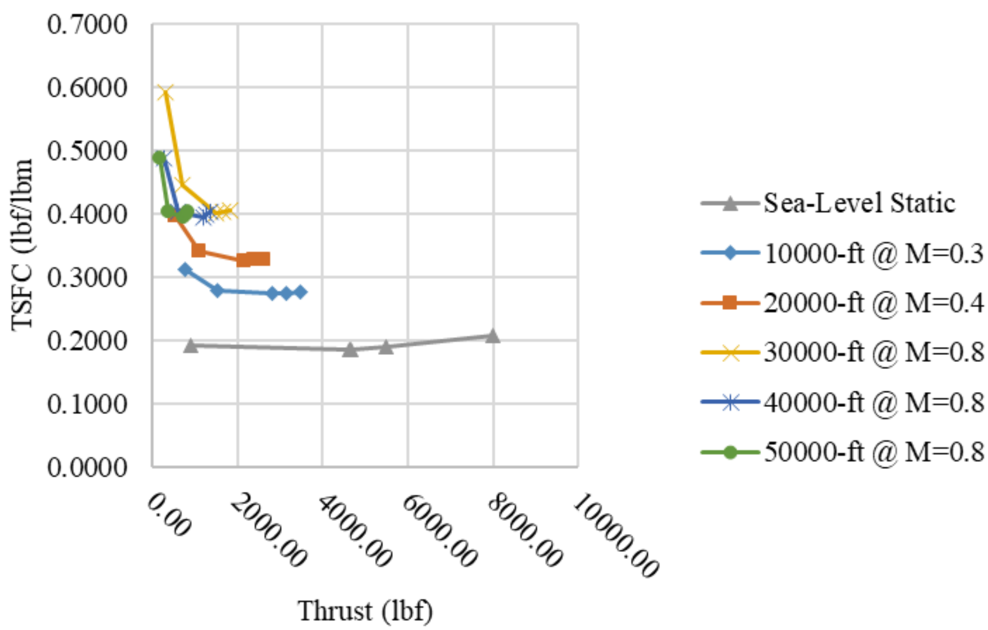


Figure 11: *Aeris* Static Condition Power Hook [8]

Although the Airbus *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 Airbus *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.

CHAPTER 3: METHODOLOGY

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, passenger, and payload economies. Due to the massive variability involved with this study, this thesis focuses on the qualitative and quantitative effects of weather for a single route with two investigated aircraft over different days.

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.

The chosen route for this thesis investigates flights from Oakland, CA to Davenport, IA and back. The initial chosen route was to simulate a flight from Oakland, CA to Chicago, IL. However, numerous extra complications are involved especially regarding the flight vectoring with arrival and departure from Chicago. Limitations on the developed tool also limited options with possible routes. To mitigate these problems, it was decided to cut the route short and fly only to Quad City Airport in Davenport, IA.

The days investigated include a span of five-days in Summer, 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:

1. EDET (Empirical Drag Estimation Technique) is a drag estimation code developed by NASA to provide estimations on drag in the conceptual phase of aircraft design [9]. However, prior research has found this method to be suitable to develop aerodynamics databases for real-world aircraft [7][8]. 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 drag polars for each aircraft in chapter 2 were estimated using EDET.
2. NPSS (Numerical Propulsion System Simulation) was also developed by NASA as a programming framework for modelling the mechanical, fluid, and thermodynamic processes within an engine [10]. This tool generates "five-column" 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. The engine data and power hooks for each aircraft in chapter 2 were estimated using NPSS.
3. The Lateral Flightpath Generator is a custom tool developed in python for this thesis to provide lateral navigation data with real-world weather conditions. The

tool allows a user to input a series of waypoints to generate a lateral flight path. It then parses the waypoints from a navigation-weather SQL database and 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 files to perform a static prediction of aircraft performance over a range of altitude and mach numbers based on an input weight. With a method developed by prior research on point-performance energy-maneuverability, the enhanced version includes the addition of winds and density altitude corrections [11][12]. This tool was used to prime the vertical mission simulator 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. The Vertical Mission Simulator is a tool developed in Microsoft Excel/VBA by Dr. Takahashi [13]. This tool provides a full physics simulation of an aircraft depending on a specified vertical mission profile file, EDET file, and NPSS file. The tool uses a time-step integration method where it solves for the combination of lift/drag/thrust parameters to obtain the requested mission profile over time. It closely follows the vertical flight path of the aircraft and solves for all aircraft

performance parameters during flight. For this investigation, the tool was modified to include the lateral flight path parameters generated by the Lateral Flightpath Generator.

6. ModelCenter 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.

The Lateral Flightpath Generator can be broken down into a series of individual modules that communicate with each other to generate a lateral weather and navigation profile. The modules are: 1) the Weather Scraper, 2) the AeroWinds Database, and 3) the Lateral Navigation Engine.

At the heart of the weather parsing is an online data scraper that integrates to the University of Wyoming's (UWYO) atmospheric sounding database. 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.

Figure 12: University of Wyoming weather sounding stations for North America (as seen on http://weather.uwyo.edu/upperair/sounding.html)

A python script utilizing the Requests library and the BeautifulSoup library fetches the data from the UWYO database over HTTP and then parses and converts the data into a usable format for the Lateral Navigation Engine.

The UWYO sounding database uses a standardized url format with a series of tags that indicate which specific data is to be fetched. An example request with the tags in bold is shown below:

http://www.weather.uwyo.edu/cgi-bin/sounding?region=**[region]**f&TYPE=TEXT%3ALIST&YEAR=**[year]**&MONTH=**[month]**&FROM=**[startday][starttime]**&TO=**[endday][endtime]**&STNM=**[station number]**

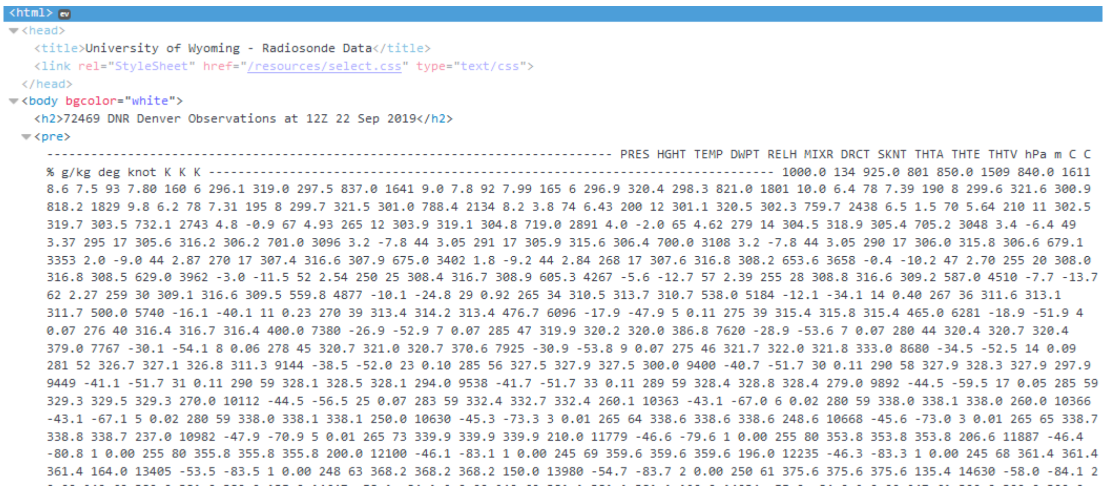
The region tag specifies which region on the world a station is located in. This thesis is limited ourselves to North America, however further investigations could be made in other regions. The year, month, startday, starttime, endday, and endtime flags indicate the timeframe of data to be requested. The sounding database allows a user to request all data up to a month for a given station. Finally, the station number flag indicates from which station the sounding data is to be obtained.

Once this field is provided, the Weather Scraper can obtain the webpage html file via the http request. The BeautifulSoup module is then used to parse the html file to obtain the weather and station data from the html file. An example of the html file can be seen in figure 13. An example of the html file in raw format can be seen in figure 14.

72469 DNR Denver Observations at 12Z 22 Sep 2019

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1000.0	134									
925.0	801									
850.0	1509									
840.0	1611	8.6	7.5	93	7.80	160	6	296.1	319.0	297.5
837.0	1641	9.0	7.8	92	7.99	165	6	296.9	320.4	298.3
821.0	1801	10.0	6.4	78	7.39	190	8	299.6	321.6	300.9
818.2	1829	9.8	6.2	78	7.31	195	8	299.7	321.5	301.0
788.4	2134	8.2	3.8	74	6.43	200	12	301.1	320.5	302.3
759.7	2438	6.5	1.5	70	5.64	210	11	302.5	319.7	303.5
732.1	2743	4.8	-0.9	67	4.93	265	12	303.9	319.1	304.8
719.0	2891	4.0	-2.0	65	4.62	279	14	304.5	318.9	305.4
705.2	3048	3.4	-6.4	49	3.37	295	17	305.6	316.2	306.2
701.0	3096	3.2	-7.8	44	3.05	291	17	305.9	315.6	306.4
700.0	3108	3.2	-7.8	44	3.05	290	17	306.0	315.8	306.6

Figure 13: Sample of the UWYO html sounding file as seen in a web browser



```
<html> ev
▼<head>
  <title>University of Wyoming - Radiosonde Data</title>
  <link rel="StyleSheet" href="/resources/select.css" type="text/css">
 </head>
▼<body bgcolor="white">
  <h2>72469 DNR Denver Observations at 12Z 22 Sep 2019</h2>
 ▼<pre>
   ----------------------------------------------------------------------------- PRES HGHT TEMP DWPT RELH MIXR DRCT SKNT THTA THTE THTV hPa m C C
   % g/kg deg knot K K K ----------------------------------------------------------------------------- 1000.0 134 925.0 801 850.0 1509 840.0 1611
   8.6 7.5 93 7.80 160 6 296.1 319.0 297.5 837.0 1641 9.0 7.8 92 7.99 165 6 296.9 320.4 298.3 821.0 1801 10.0 6.4 78 7.39 190 8 299.6 321.6 300.9
   818.2 1829 9.8 6.2 78 7.31 195 8 299.7 321.5 301.0 788.4 2134 8.2 3.8 74 6.43 200 12 301.1 320.5 302.3 759.7 2438 6.5 1.5 70 5.64 210 11 302.5
   319.7 303.5 732.1 2743 4.8 -0.9 67 4.93 265 12 303.9 319.1 304.8 719.0 2891 4.0 -2.0 65 4.62 279 14 304.5 318.9 305.4 705.2 3048 3.4 -6.4 49
   3.37 295 17 305.6 316.2 306.2 701.0 3096 3.2 -7.8 44 3.05 291 17 305.9 315.6 306.4 700.0 3108 3.2 -7.8 44 3.05 290 17 306.0 315.8 306.6 679.1
   3353 2.0 -9.0 44 2.87 270 17 307.4 316.6 307.9 675.0 3402 1.8 -9.2 44 2.84 268 17 307.6 316.8 308.2 653.6 3658 -0.4 -10.2 47 2.70 255 20 308.0
   316.8 308.5 629.0 3962 -3.0 -11.5 52 2.54 250 25 308.4 316.7 308.9 605.3 4267 -5.6 -12.7 57 2.39 255 28 308.8 316.6 309.2 587.0 4510 -7.7 -13.7
   62 2.27 259 30 309.1 316.6 309.5 559.8 4877 -10.1 -24.8 29 0.92 265 34 310.5 313.7 310.7 538.0 5184 -12.1 -34.1 14 0.40 267 36 311.6 313.1
   311.7 500.0 5740 -16.1 -40.1 11 0.23 270 39 313.4 314.2 313.4 476.7 6096 -17.9 -47.9 5 0.11 275 39 315.4 315.8 315.4 465.0 6281 -18.9 -51.9 4
   0.07 276 40 316.4 316.7 316.4 400.0 7380 -26.9 -52.9 7 0.07 285 47 319.9 320.2 320.0 386.8 7620 -28.9 -53.6 7 0.07 280 44 320.4 320.7 320.4
   379.0 7767 -30.1 -54.1 8 0.06 278 45 320.7 321.0 320.7 370.6 7925 -30.9 -53.8 9 0.07 275 46 321.7 322.0 321.8 333.0 8680 -34.5 -52.5 14 0.09
   281 52 326.7 327.1 326.8 311.3 9144 -38.5 -52.0 23 0.10 285 56 327.5 327.9 327.5 300.0 9400 -40.7 -51.7 30 0.11 290 58 327.9 328.3 327.9 297.9
   9449 -41.1 -51.7 31 0.11 290 59 328.1 328.5 328.1 294.0 9538 -41.7 -51.7 33 0.11 289 59 328.4 328.8 328.4 279.0 9892 -44.5 -59.5 17 0.05 285 59
   329.3 329.5 329.3 270.0 10112 -44.5 -56.5 25 0.07 283 59 332.4 332.7 332.4 260.1 10363 -43.1 -67.0 6 0.02 280 59 338.0 338.1 338.0 260.0 10366
   -43.1 -67.1 5 0.02 280 59 338.0 338.1 338.1 250.0 10630 -45.3 -73.3 3 0.01 265 64 338.6 338.6 338.6 248.6 10668 -45.6 -73.0 3 0.01 265 65 338.7
   338.8 338.7 237.0 10982 -47.9 -70.9 5 0.01 265 73 339.9 339.9 339.9 210.0 11779 -46.6 -79.6 1 0.00 255 80 353.8 353.8 353.8 206.6 11887 -46.4
   -80.8 1 0.00 255 80 355.8 355.8 355.8 200.0 12100 -46.1 -83.1 1 0.00 245 69 359.6 359.6 359.6 196.0 12235 -46.3 -83.3 1 0.00 245 68 361.4 361.4
   361.4 164.0 13405 -53.5 -83.5 1 0.00 248 63 368.2 368.2 368.2 150.0 13980 -54.7 -83.7 2 0.00 250 61 375.6 375.6 375.6 135.4 14630 -58.0 -84.1 2
```

Figure 14: Sample of the weather html file in raw text as seen from a web browser element inspector

The file contains tabulated data with 11 columns. However, for our purposes only 4 columns were used. These are the HGHT, TEMP, DRCT, and SKNT columns, which provide information on the geopotential height for a sounding, atmospheric temperature, wind direction, and wind speed. For the purposes of this thesis, the geopotential height given by the atmospheric sounding data is conflated to pressure altitude.

Once the raw data is obtained, the Weather Scraper then standardizes the atmospheric column via linear interpolation in a series of 500-ft intervals, starting with the lowest 500-ft increment up to the highest 500-ft increment all within the scope of the weather data. During this standardization, the Weather Scraper converts all units to British Nautical units, as is the standard for aircraft performance. The Weather Scraper then finally generates a weather file that has all required data. This can be seen in figure 15.

```
*LOCATION:
72456 TOP Topeka
*DATE:
2019-09-03:12 TO 2019-09-03:12
*N_ALTS:
217

*P_ALTITUDE(FT) RHO_ALTITUDE(FT) ISADEV(DEGC) NORTH_SPD(KTS) EAST_SPD(KTS) WIND_SPD(KTS) WIND_DIR(DEG)
      1000.000       2300.000        11.282        -8.660        -5.000        10.000       210.000
      1500.000       2900.000        12.033       -19.631       -18.147        26.734       222.750
      2000.000       3800.000        15.562       -24.664       -35.224        43.000       235.000
      2500.000       4300.000        16.038       -23.679       -33.817        41.282       235.000
      3000.000       5000.000        17.044       -22.356       -31.944        38.990       235.013
      3500.000       5600.000        18.202       -17.521       -30.393        35.082       240.037
      4000.000       6200.000        19.123       -13.100       -28.093        30.997       245.000
      4500.000       6700.000        19.065       -12.255       -26.282        28.999       245.000
      5000.000       7200.000        19.006       -11.411       -24.470        27.000       245.000
      5500.000       7700.000        19.392       -13.165       -23.290        26.754       240.521
      6000.000       8400.000        21.089       -14.910       -21.300        26.000       235.008
      6500.000       8900.000        21.030       -14.054       -20.072        24.503       235.000
```

Figure 15: Sample weather file generated by the Weather Scraper module

The density altitude conversion is computed from the ISADEV at a corresponding pressure altitude. The particular method used in this thesis is based 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 [14]. The temperature deviation is used to identify the pressure altitude corresponding to a matching air density in the standard atmosphere [14]. This results in a density-corrected "equivalent" pressure altitude, hereon stated as the "density altitude" of the atmosphere.

The AeroWinds Database module consists of an SQL database of weather files and associated python functions for interacting with the database. The database is designed as a rigid structure to provide access to parsed weather files as requested, allowing a user to quickly obtain weather data based upon a specific station and datetime. The database model can be seen in figure 16.

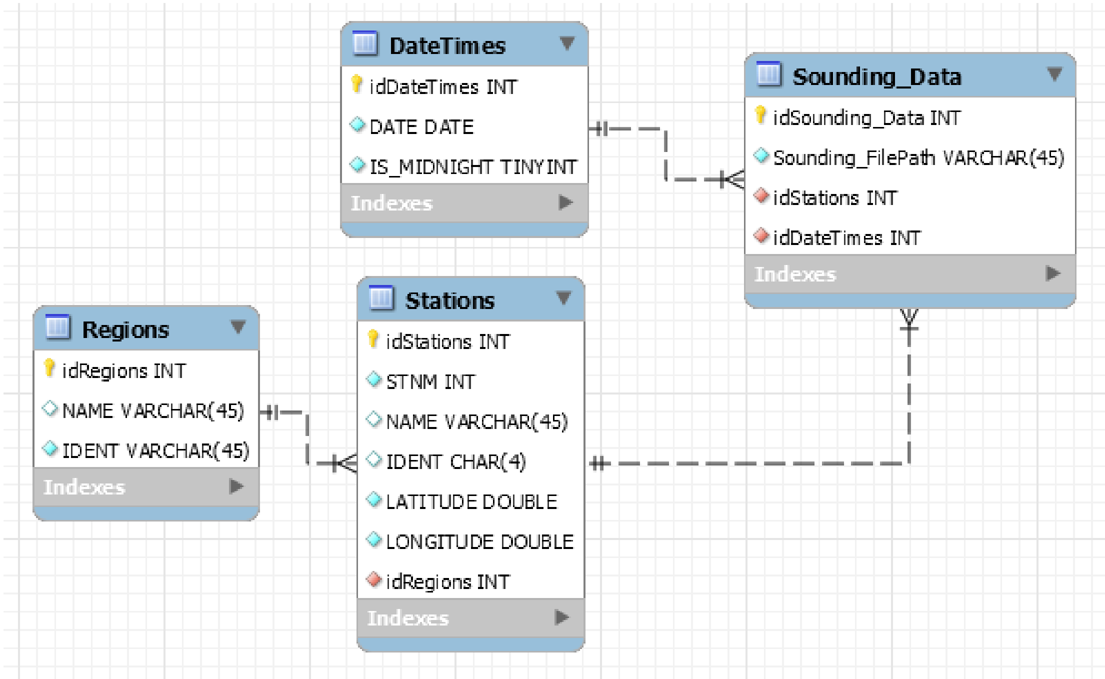


Figure 16: AeroWinds Database SQL Model

When the user requests data from a station at a certain datetime, the API module first determines whether the data exists in the database. If the weather file is not found, it will fetch the file via the Weather Scraper module from the UWYO sounding database. Once the weather file is obtained, the API inserts the file into the database, and provides the user a reference to the file location for further processing. The AeroWinds Database API also includes functions for accessing station latitude and longitude information, which is needed for the Lateral Navigation module.

The database prevents identical requests from being sent to the UWYO website and speeds up the overall lateral path generation. By storing parsed data locally, only one request to the UWYO website is needed for each station and day combination. The local files are much quicker to access as the program does not need to wait for the UWYO website before generating the lateral path. This also reduces the network load to the UWYO website, preventing its servers from being overloaded.

The Lateral Navigation module generates a lateral path from a series of user-specified waypoints corresponding to the sounding stations in the UWYO sounding database. The module will calculate interpolated weather values along the lateral path legs based on the start and end waypoints for each leg. A sample path with waypoints and legs is shown in figure 17.

Figure 17: Sample flightpath from OKX to LQC. Waypoints are shown as circles and legs are shown as arrows. Green is the start waypoint and red is the end.

For each leg, the Lateral Navigation module splits the distance into 25-nM chunks using a WGS84 ellipsoid model of the earth within the geographiclib python library. For each chunk, a vertical profile of winds, temperature deviations, and density altitudes is interpolated from parsed weather data at the start and end waypoints for each leg. The aircraft bearing is also calculated from the latitude & longitude of the start and end waypoints.

Once the Lateral Navigation module has calculated all intermediary points along the flight path, it compiles the data into a single file for use by the vertical mission simulation tool.

The vertical mission simulation tool calculates the simulation of an aircraft for a specified vertical profile. The profile can be defined by altitude constraints, speed constraints, weight constraints, and more. This is the primary tool used to analyze our aircraft performance with winds aloft. A sample of the main sheet of the tool with a winds-aloft profile can be seen in figure 18.

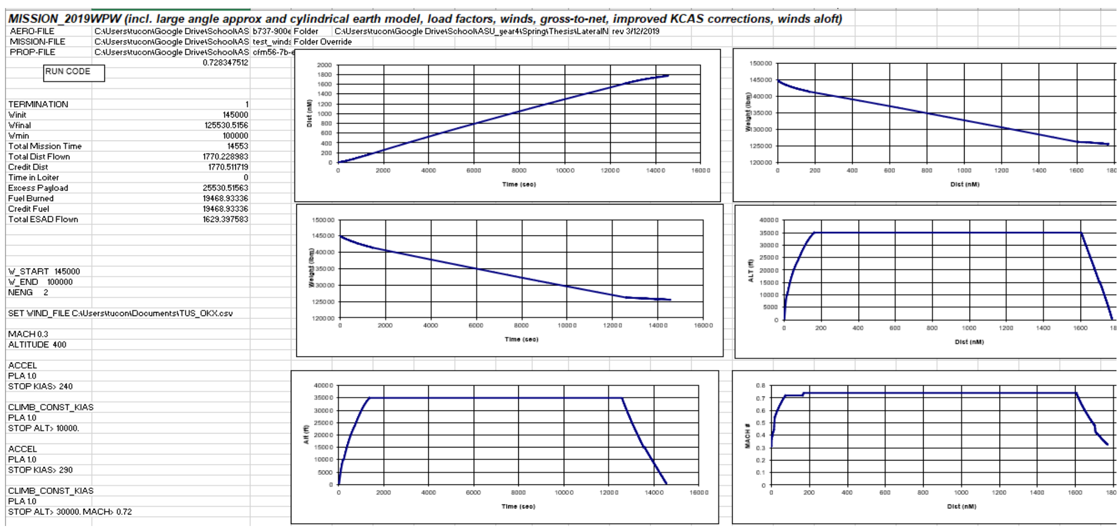


Figure 18: Sample of the main sheet of the vertical simulation tool

The simulation tool runs a full physics-based simulation of an aircraft mission and records the state of the aircraft over time [13]. The vertical mission simulation tool provides the estimated payload, credit distance, total fuel burn, credit fuel burn, total time, and credit time. These are used to derive the fuel, passenger, and payload economies as seen in the Trades Setup section.

CHAPTER 4: TRADES SETUP

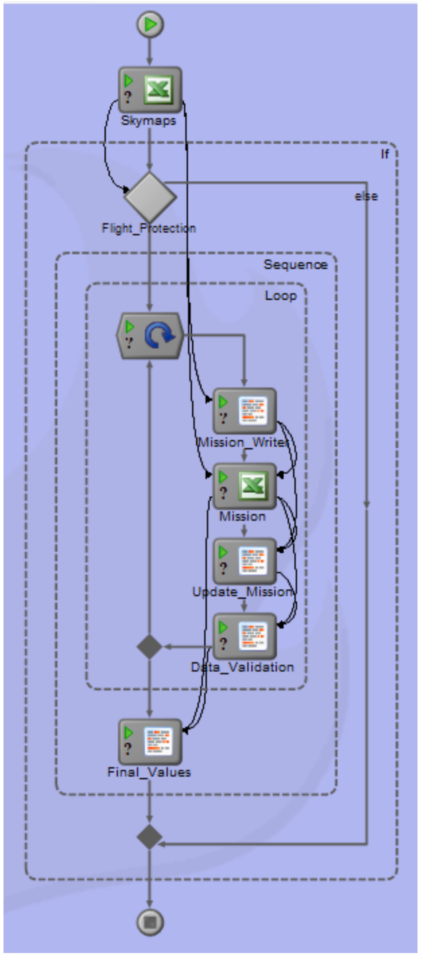


Figure 19: *ModelCenter* Setup

The mission trades were performed using the *ModelCenter* application [15]. A picture of the thesis model setup can be seen in figure 19.

The model begins with the enhanced skymaps excel tool. From the skymaps tool, the target cruise mach number is extracted based upon the input aircraft, weather, and requested cruise altitude [11] [12].

An altitude protection statement in *ModelCenter* prevents the mission simulation from running if the aircraft is incapable of flight at the target altitude and TOW. If this occurs, the run is flagged as invalid in the overall trade study.

Once a run passes the altitude protection statement, it is then passed to a mission distance convergence loop. The vertical mission simulator runs missions where the credit distance is implicitly calculated from an explicit cruise distance.

Thus, a loop is required to alter the cruise distance based upon the credit distance error in order to converge the mission to the target credit distance. The convergence is designed to end when the simulated credit distance is within 10-nM of the target credit distance.

Within the convergence loop, a mission writer script generates the mission file based on the parameters given in the run and those calculated from the skymaps tool. A sample of mission file is shown in figure 20. For the purposes of this thesis, a simple mission without steps was performed for every run.

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 and 14 CFR 121.639 [3]. This prevents illegal flights from being included in the mission and prevents an overestimation of payload capacity.

```
W_START    48000      TOW
W_END      43567
NENG       3.2        OEW

SET DELTA_CD 0.0000
SET APU_BURN 0

GROUND_RUNUP
PLA 1.0
STOP TIME> 90.

SET MACH 0.36
SET ALTITUDE  400

CLIMB_CONST_KIAS
PLA 1.0
STOP ALT> 10000.

ACCEL
PLA 1.0
STOP KIAS> 246.86

SET WIND_FILE C:\Users\tucon\Documents\LatNav\DVN_OAK_01-20-19.csv      Wind File

CLIMB_CONST_KIAS
PLA 1.0
STOP MACH> 0.46      Cruise Mach

CLIMB_CONST_MACH
PLA 1.0
STOP ALT> 25000      Cruise Alt

LEVEL
STOP DIST> 1349      Cruise Distance
```

Figure 20: Sample Mission file with set winds file

Once the mission file is generated, it is simulated via the vertical mission simulator. The credit distance, credit fuel, total distance, total fuel, excess payload, and mission time are obtained from the simulator.

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,

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

To determine the economic efficiency of the mission, it can be viewed from the lenses of passenger economy and pure payload economy. The passenger economy is measured by calculating the fuel burn per seat-mile of the mission. This requires the number of passengers that can be taken by the excess payload.

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 number of passengers is calculated by dividing the excess payload by a nominal weight per passenger. The nominal weight per passenger is based on 115% the FAA standard average passenger weight (185-lbm) with carry-on baggage. 15% extra weight was allotted to better estimate the current average weight per passenger in American flights. One checked bag (nominal weight 25-lbm) per passenger was also added, bringing the total weight per passenger to 237.75-lbm. Therefore, the passengers per flight is calculated as,

$$PAX = MIN\left(Floor\left(\frac{ExcessPayload}{WeightPerPax}\right), MaxPax\right) \quad (3)$$

where MaxPax is the maximum number of passengers that can be carried by the aircraft (150 for the *A320* and 80 for the *Aeris*). The passenger economy or fuel burn per seat-mile (lbm/seat- nM) is then calculated as,

$$FuelBurnPerSeatMile = \frac{CreditFuel}{CreditDistance \times PAX} \quad (4)$$

Since the above places an artificial limit on the maximum payload carried by an aircraft (as an airline would not carry non-economic cargo), a pure payload economy or fuel burn per kilopound-mile (lbm/kilopound-nM) is also calculated,

$$FuelBurnPerKLBMile = \frac{CreditFuel}{CreditDistance \times \frac{ExcessPayload}{1000}} \quad (5)$$

The payload economy determines the cost effectiveness of the mission assuming the total payload can be profit-generating. For both the passenger and pure payload perspectives, 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.

Once *ModelCenter* finishes the vertical mission simulation, the credit distance is compared to the target credit distance in the mission updater script. The mission updater script will update the target cruise distance based on the following formula:

$$NewCruiseDistance = OldCruiseDistance + 0.8 \times DeltaCreditDistance \quad (5)$$

Once the mission has converged, the data validation module will check whether any of the following conditions have occurred: 1) Landing Weight > Max Landing

Weight (MLW), 2) Excess Payload < 0, or 3) New Cruise Distance <= 0. If any are true, then the run is flagged as invalid.

After the loop is finished, the final values script performs a final check of all values. If the run is flagged as invalid, then the final values script sets the output values to -1 to prevent contamination of invalid runs.

CHAPTER 5: BASELINES

In order to determine the effect of winds and temperature deviations upon the en-route performance of the Airbus *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 Airbus *A320* and the *Aeris*, where the TOW and the cruise altitude were varied to determine the impact on the fuel economy, passenger 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 Airbus *A320* is shown below in figure 21 to figure 23. Please note that the Airbus *A320* is incapable of flight at weights above 155000-lbm 40000-ft altitude (FL400), and thus those portions are invalid.

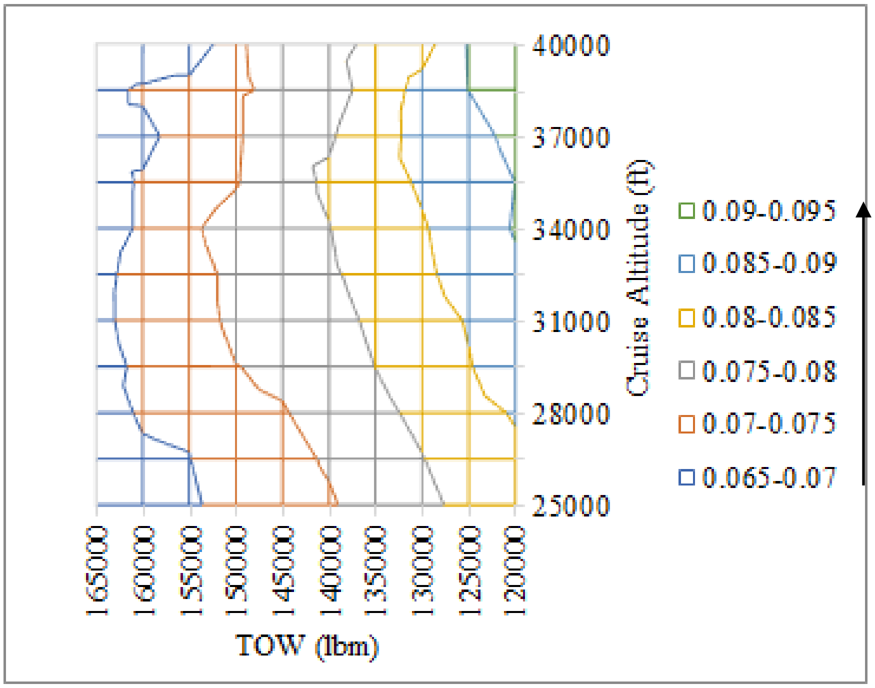


Figure 21: Baseline *A320* Credit SR for OAK - DVN

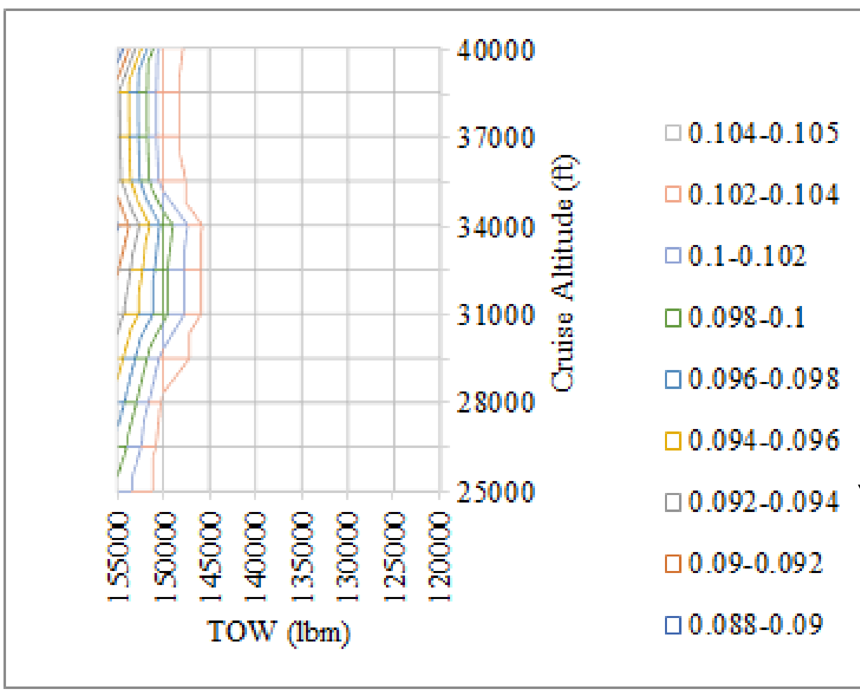


Figure 22: Baseline *A320* fuel burn/seat-mile for OAK - DVN

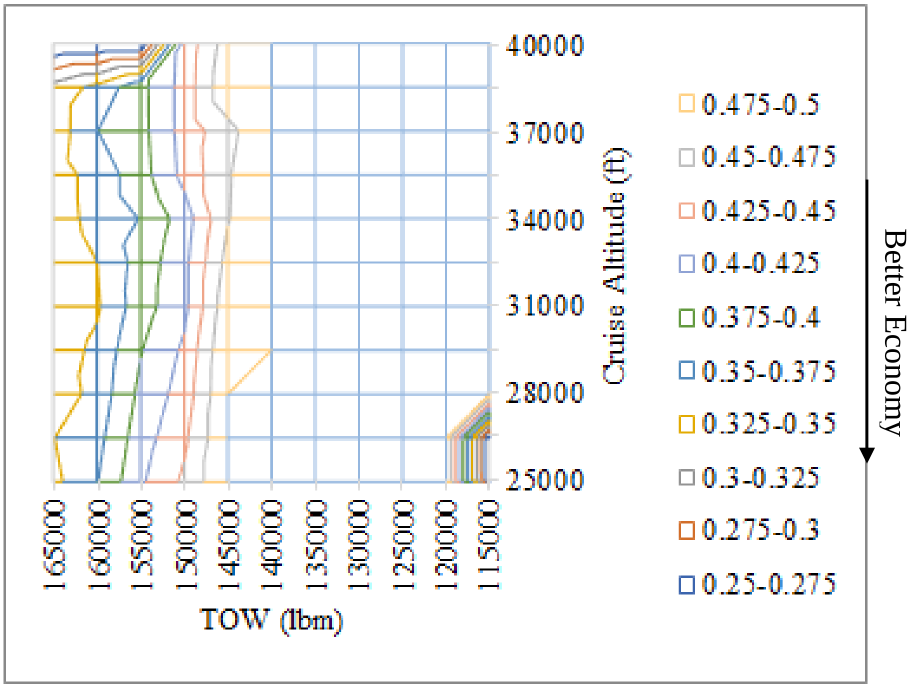


Figure 23: Baseline *A320* fuel burn/kilopound-mile for OAK - DVN

For the *A320*, it appears that the fuel economy of the aircraft is maximized at light TOW and at high altitudes (40000-ft / FL400). As the TOW increases, the best specific range altitude drops down to ~34000-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.

From a passenger economy perspective as seen in figure 22, it appears that the optimal economy for the *A320* is to seat the maximum number of passengers and fly at 34000-ft (FL340). This altitude is significantly lower than the 40000-ft (FL400) flight ceiling of the aircraft, which brings about questions as to the impact of the jet-stream upon the *A320* at its “optimum” passenger economy as the jet-stream winds are typically maximized at 40000-ft (FL400) or higher.

The trend of taking more weight as opposed to flying at greater fuel efficiencies is further shown in the overall payload economy of the Airbus *A320* in figure 23. In this plot, the optimum payload economy is found when flying at the maximum analyzed weight at ~32000-ft (FL320).

Since it is obvious that the Airbus *A320* has a significant altitude restriction, our hope is that the *Aeris* (which has a flight ceiling of 50000-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 24 to figure 26.

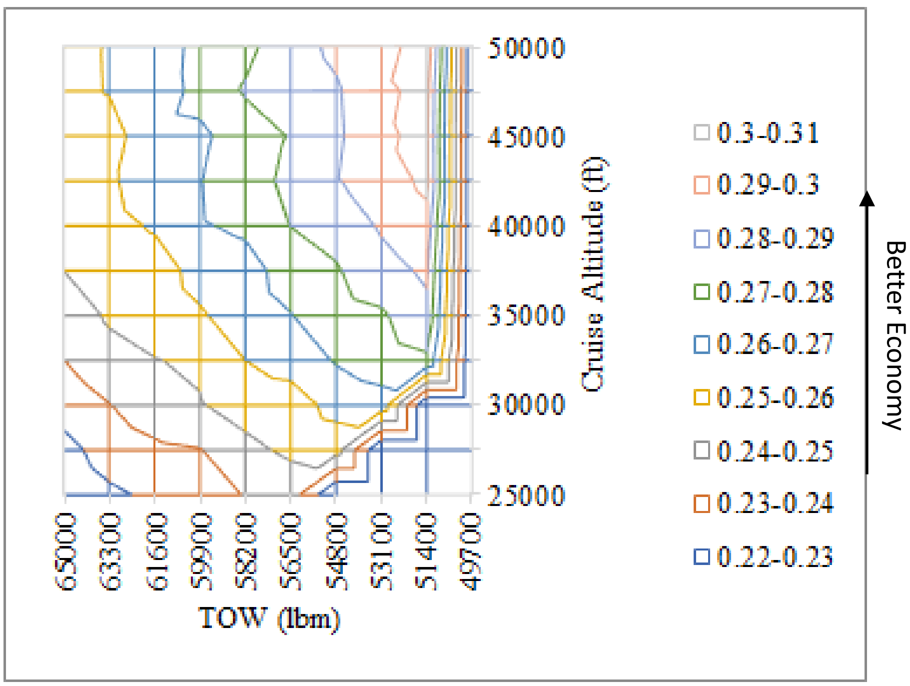


Figure 24: Baseline *Aeris* Credit SR for OAK - DVN

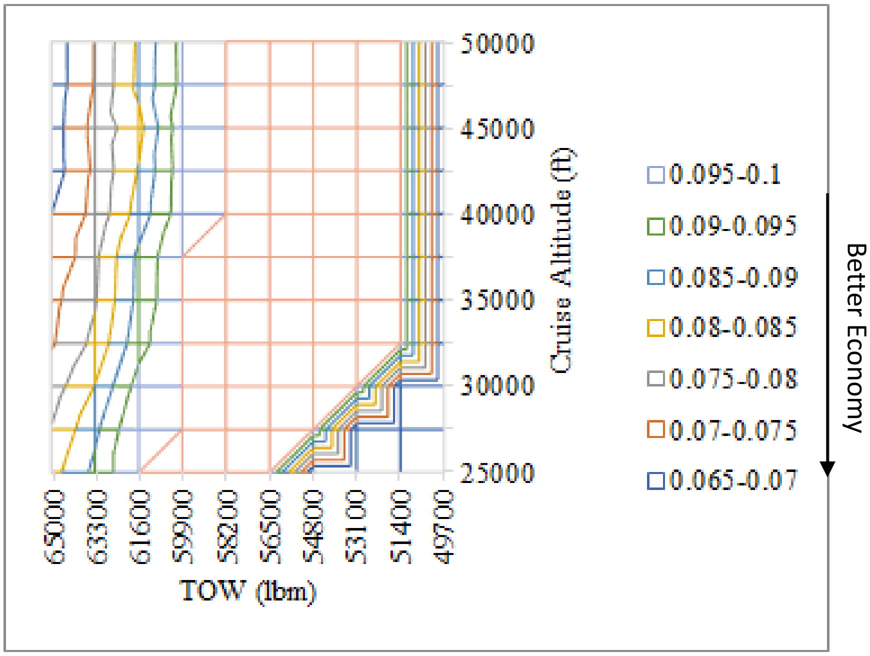


Figure 25: Baseline *Aeris* fuel burn/seat-mile for OAK - DVN

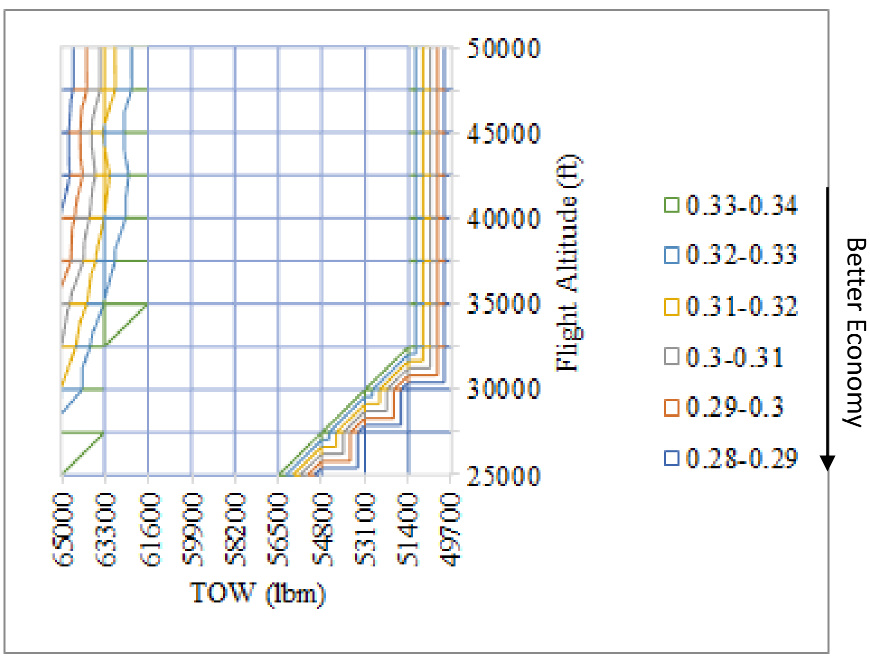


Figure 26: Baseline *Aeris* fuel burn/kilopound-mile for OAK - DVN

The fuel economy of the *Aeris* shows a very different trend from the Airbus *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 45000-ft. When combined with the passenger economy of the aircraft and 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 50000-ft. Since the *Aeris* was designed for a full loading at this altitude, it does not appear to have the overloading problem of the Airbus *A320*, and hence the induced drag rise effect does not appear to play a significant role in the mission economies of the *Aeris*.

CHAPTER 6: TRADES

The day-to-day trades were performed over a period of 5 days running from September 8, 2019 through September 12, 2019. Figure 27 to figure 32 show the variation of the weather across each waypoint for each day.

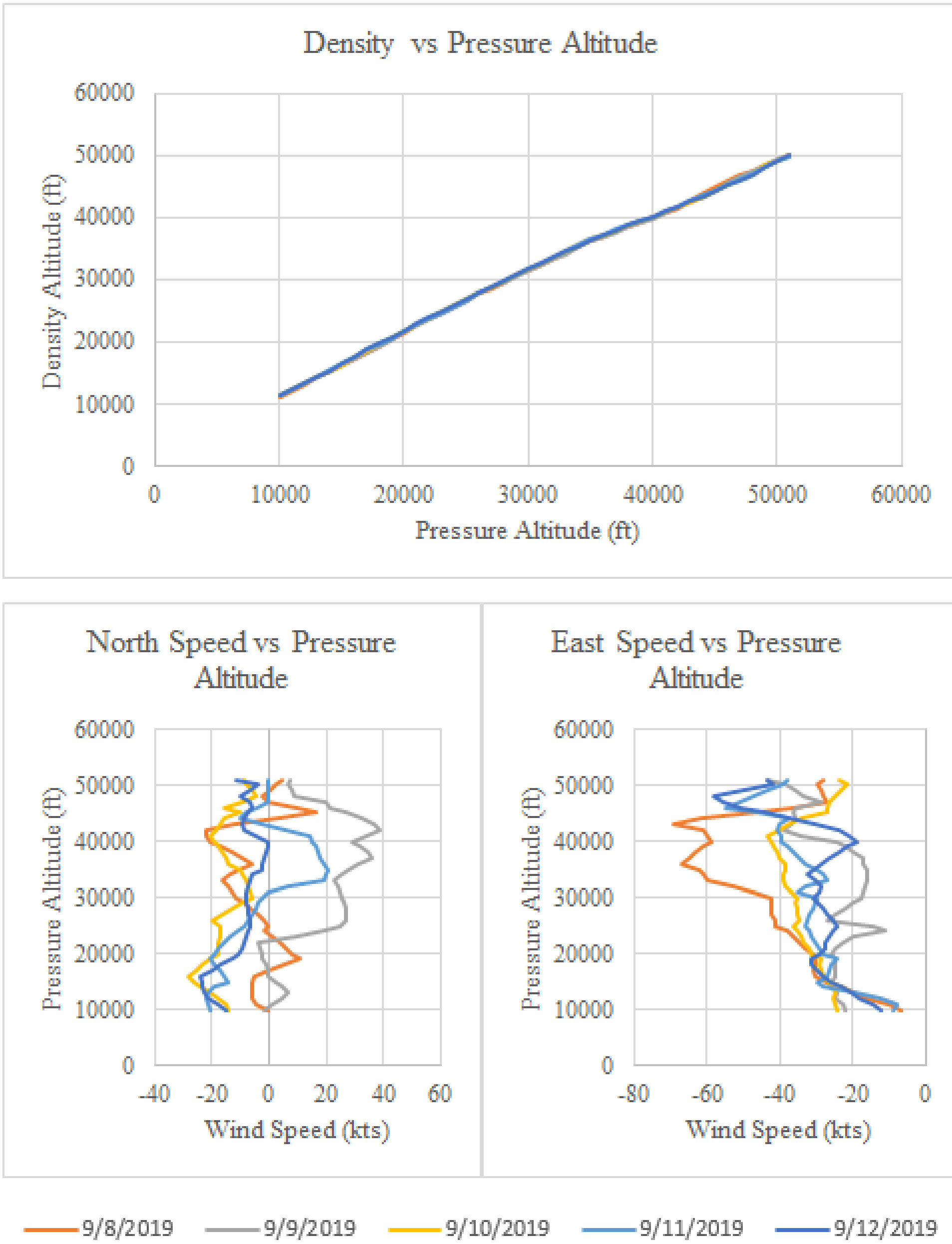


Figure 27: Weather for DVN (Davenport, IA) Station

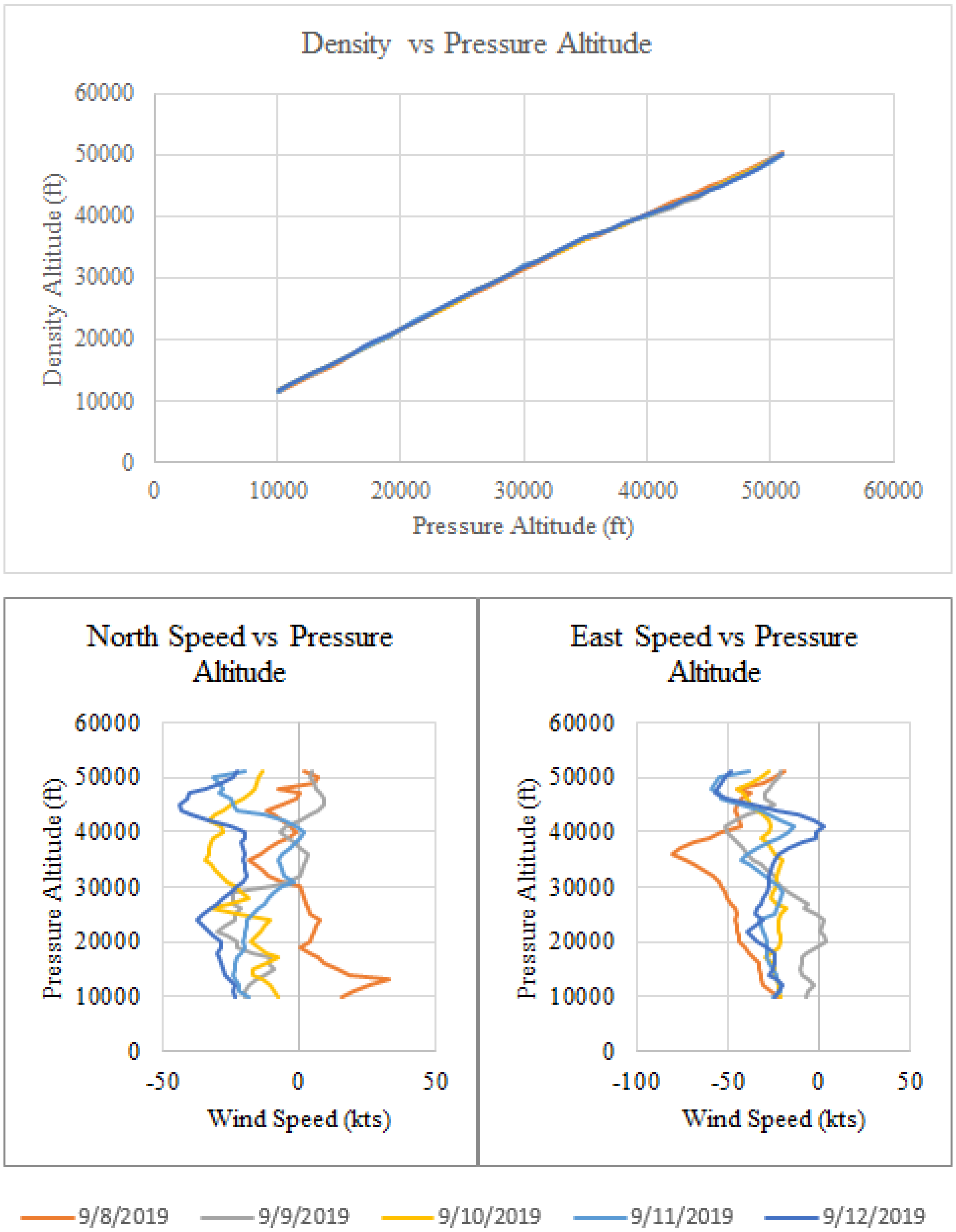


Figure 28: Weather for OAX (Omaha, NE) Station

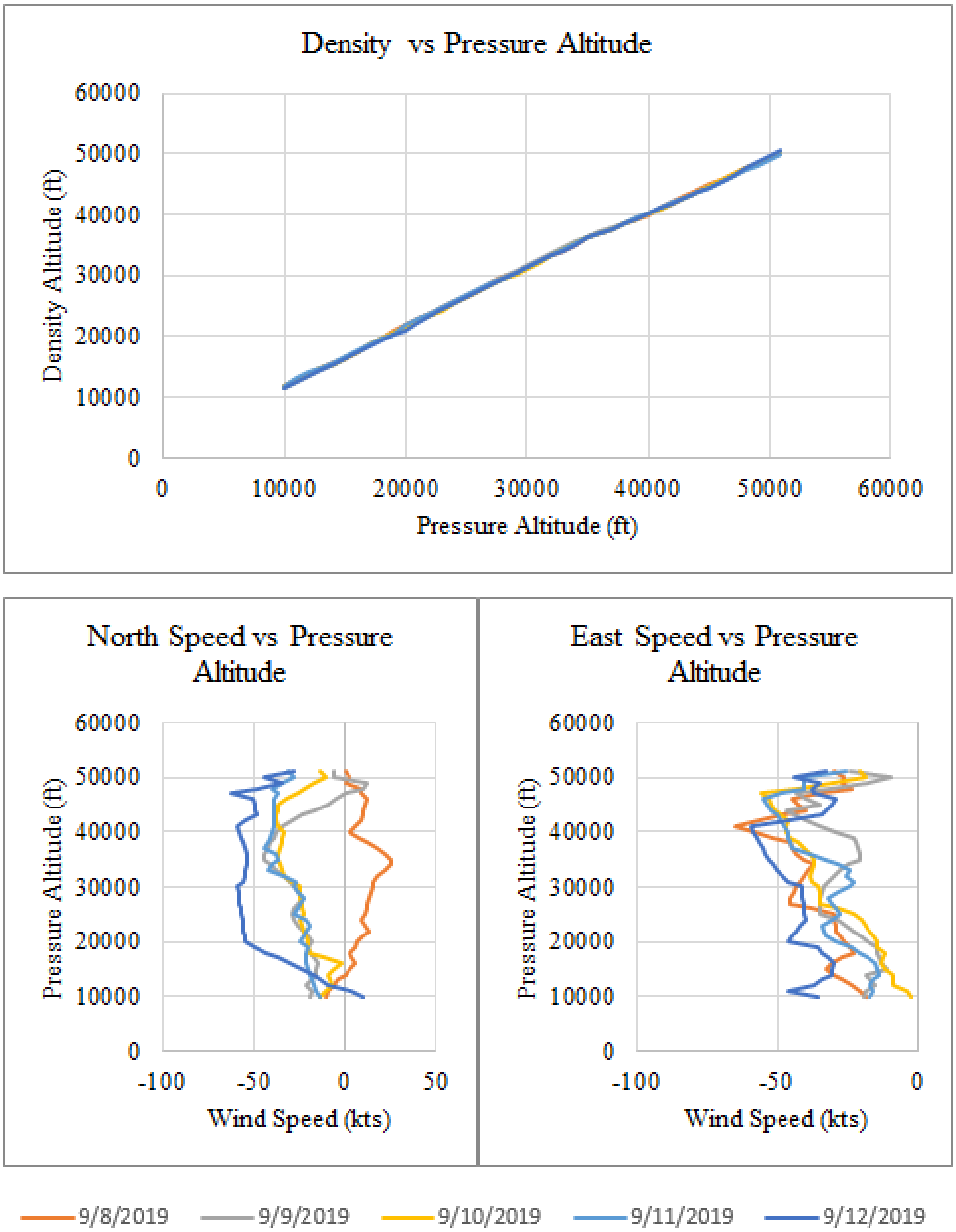


Figure 29: Weather for LBF (North Platte, NE) Station

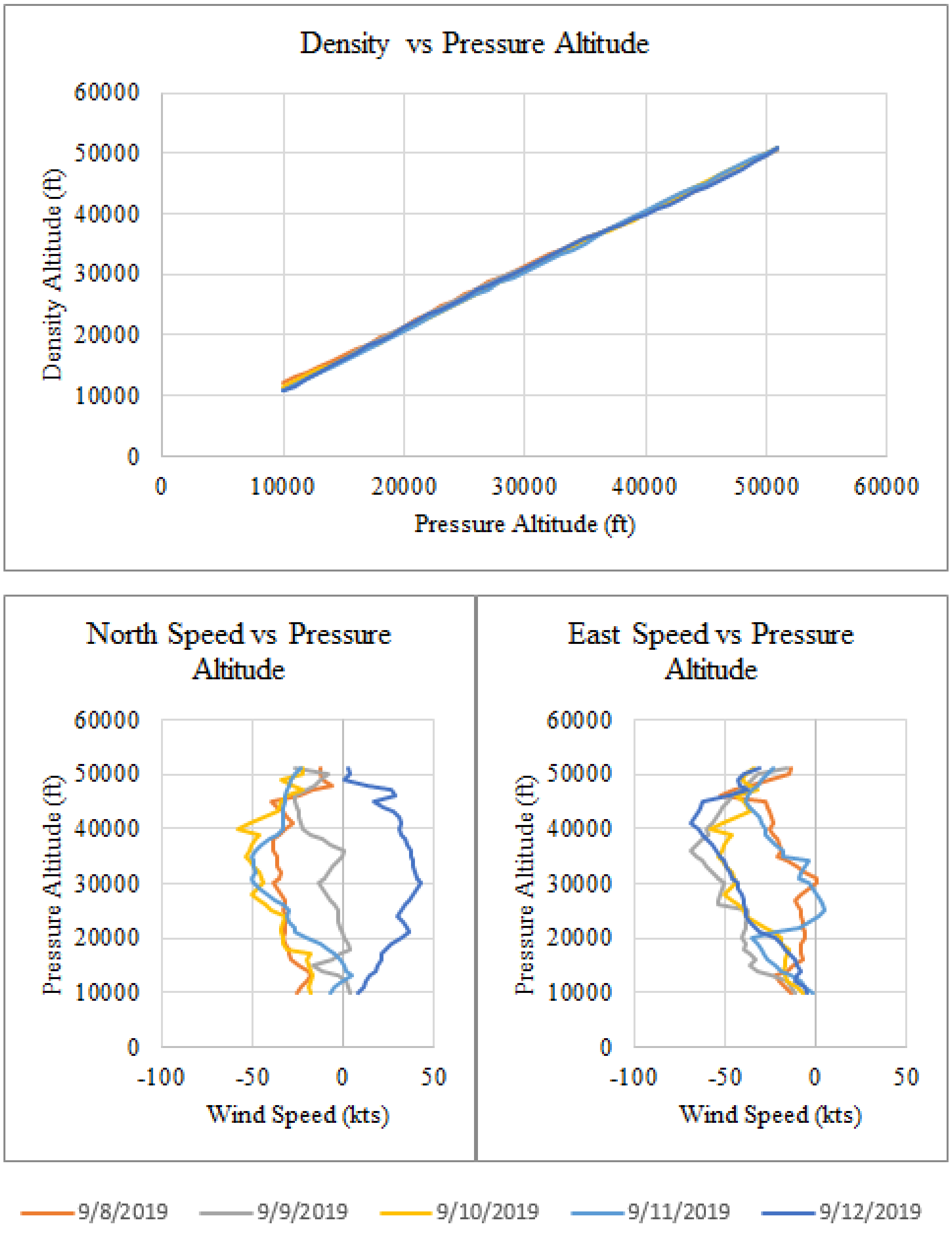


Figure 30: Weather for SLC (Salt Lake City, UT) Station

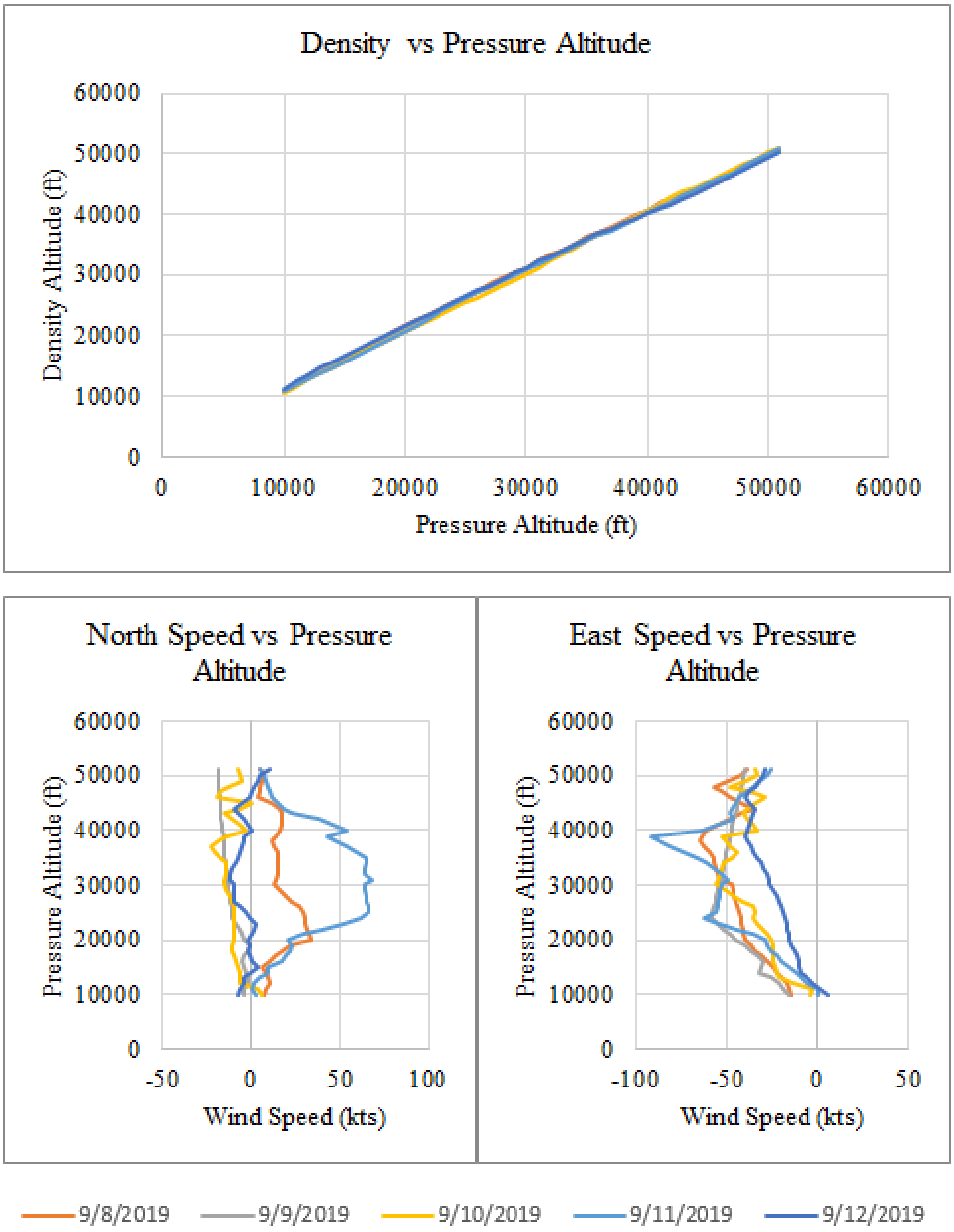


Figure 31: Weather for REV (Reno, NV) Station

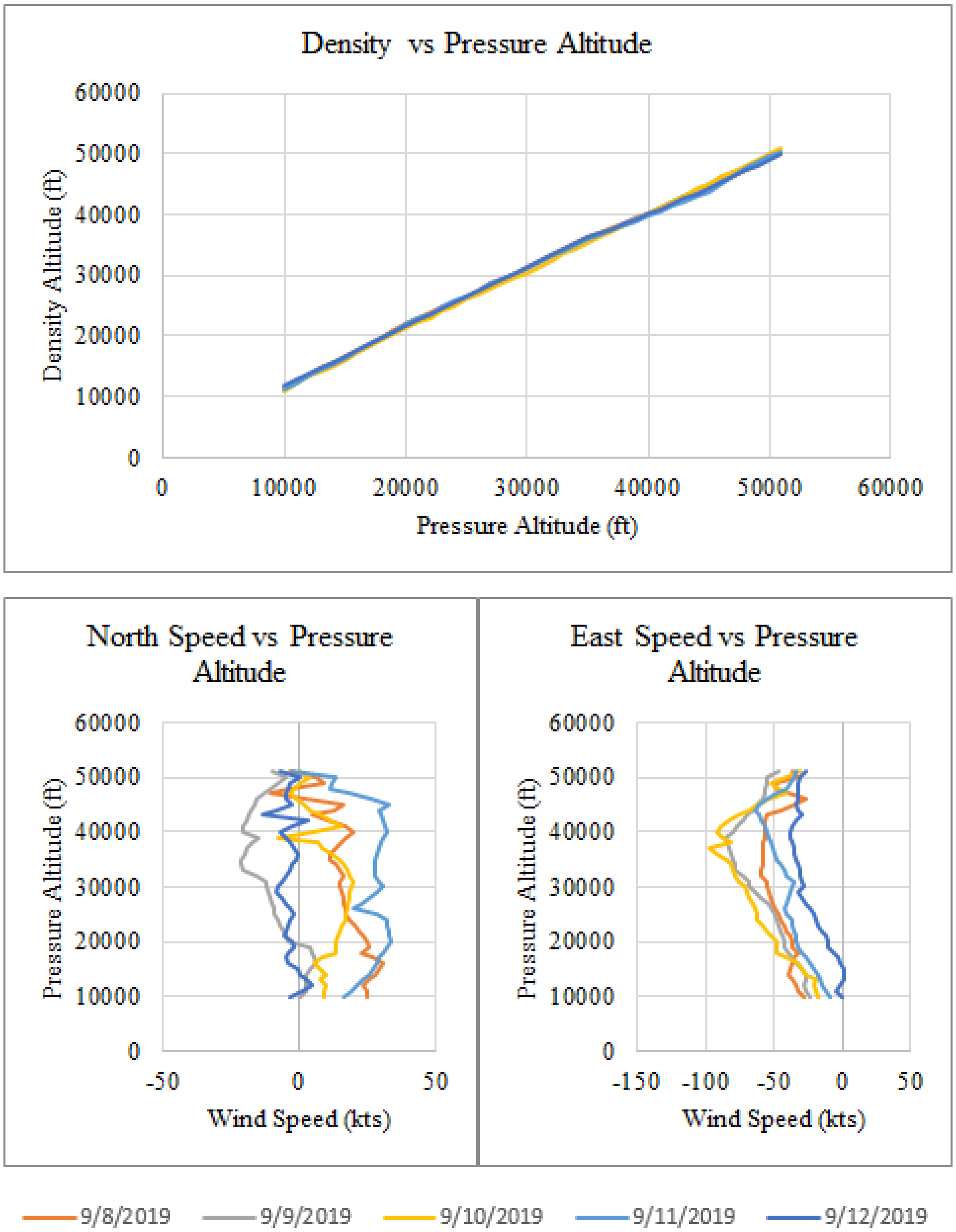


Figure 32: Weather for OAK (Oakland, CA) Station

From the weather graphs, it can be immediately seen that the density altitude effects are far less pronounced than the wind effects. Although there is some variation of the density altitudes based on the temperature deviations from ISA over the waypoints, the temperature deviations are small enough in magnitude from each other that the density altitude lines largely line up with each other.

However, the winds have large variation both between waypoints and between each day. Although the jet-stream can be seen at around 40000-ft (especially when looking at the east-ward wind component), the precise altitude of maximum winds changes between each station and between each day. This shows that the winds are highly unpredictable between stations and days and provides an initial suggestion that one needs to look at the winds from a daily basis if they are to make the most informed decision about where to fly the aircraft.

A320 Trades: OAK to DVN

The Airbus *A320* mission simulations from the above dates for the Eastwards journey have been summarized in the three economies found in the baseline cases. The results for the fuel economy (credit SR) from September 8 to September 12 are shown below in figure 33 to figure 37. Note that the aircraft is unable to fly at 40000-ft (FL400) for TOWs above 155000-lbm and thus the portion of the SR graphs corresponding to those altitudes and weights are invalid. This applies to all *A320* trades.

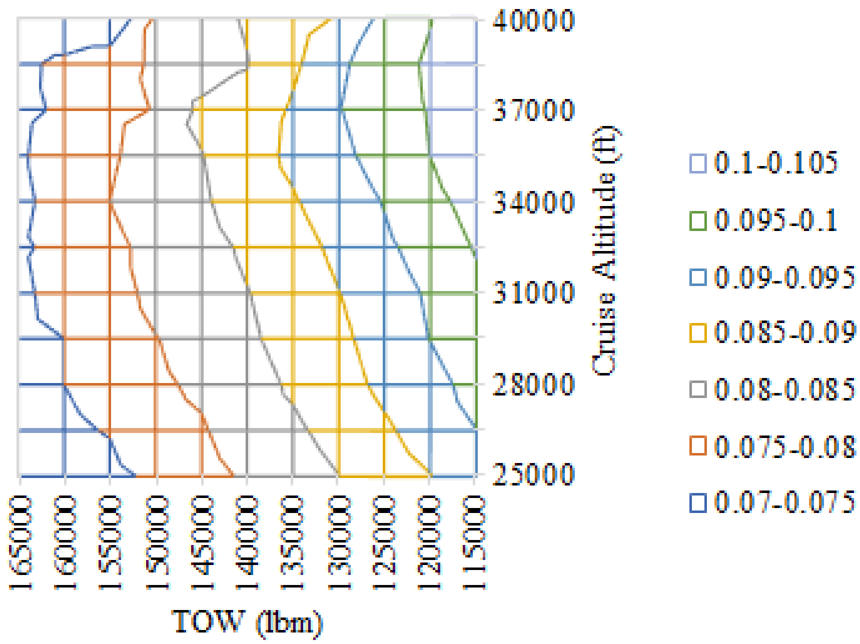


Figure 33: *A320* Credit SR for OAK to DVN on 09/08/19

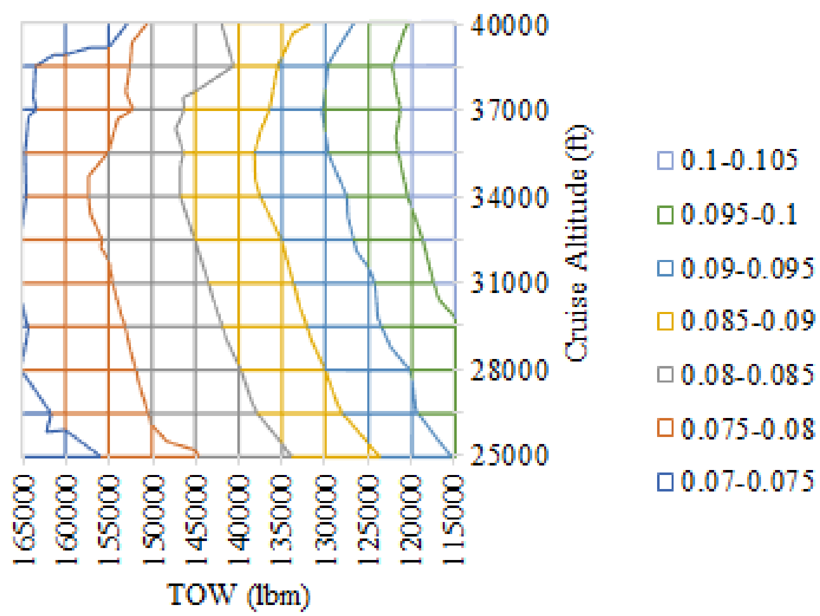


Figure 34: *A320* Credit SR for OAK to DVN on 09/09/19

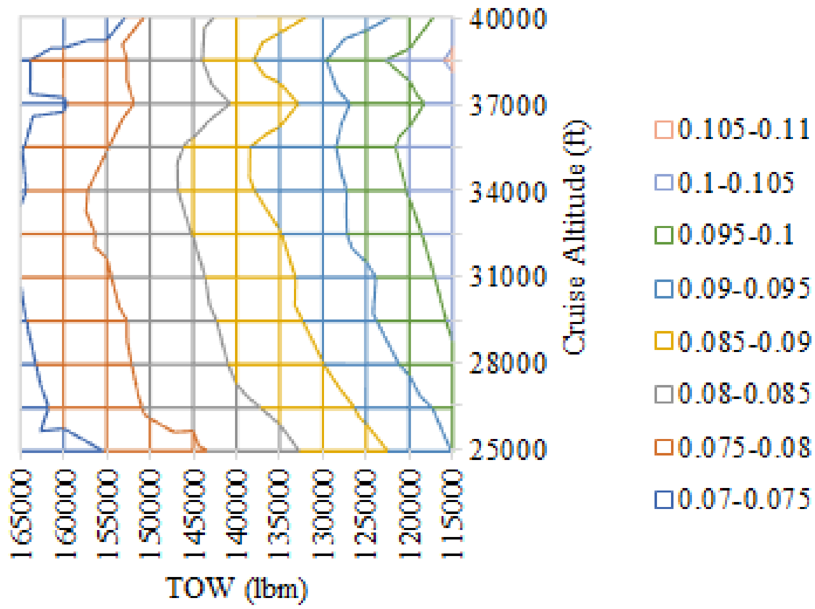


Figure 35: *A320* Credit SR for OAK to DVN on 09/10/19

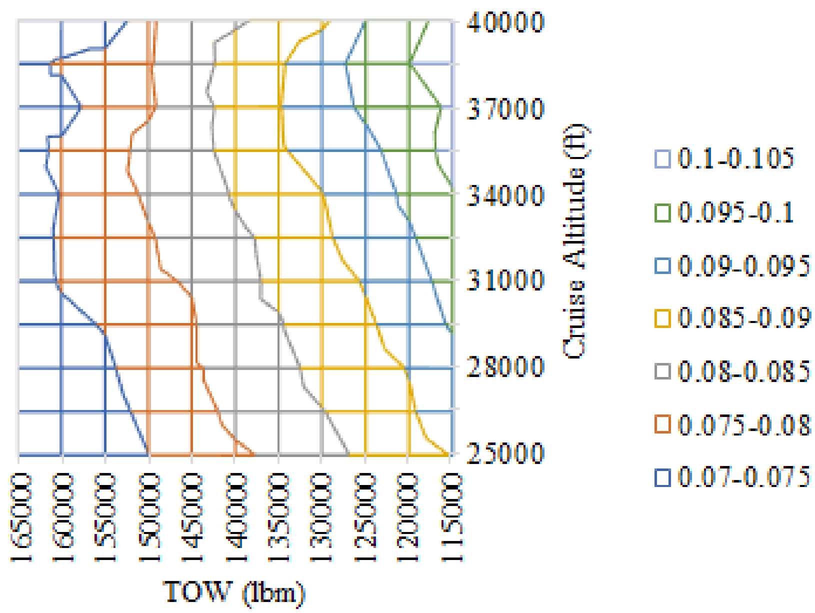


Figure 36: *A320* Credit SR for OAK to DVN on 09/11/19

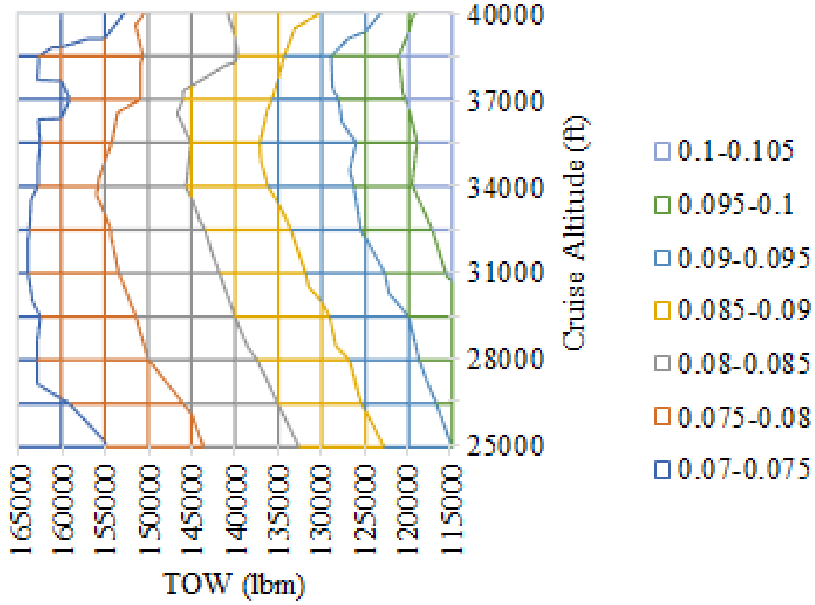


Figure 37: *A320* Credit SR for OAK to DVN on 09/12/19

From the figures, significant interplay between the winds and the credit specific range can be seen. On average, each day the aircraft seems to prefer flying at ~38000-ft (FL380) to maximize the specific range at lower weights. As the weight increases, the best specific range altitude decreases slowly towards ~33000-ft (FL330).

So how do the real-world fuel economies compare to the baseline fuel economy? When compared to the baseline fuel economy in figure 21, the fuel economy magnitudes are significantly increased when flying with the winds as compared to the baseline. This is to be expected, as the aircraft gains additional speed from the winds. However, for the most part the altitudes corresponding to the best specific range at each TOW does not change much from the baseline. The largest change can be seen in figure 33 on September 8, 2019, where the best SR at the highest TOW is found at ~35000-ft (FL350) as compared to the baseline 32000-ft (FL320). It appears that overloading the aircraft wing by flying at higher altitudes still presents too large an induced drag rise for the Airbus *A320* to fly at higher altitudes.

The passenger economy (fuel burn/seat-mile) of the Airbus *A320* can be seen in figure 38 to figure 42. Note that higher weights are not shown as the aircraft reached maximum seating capacity. Since there is almost no incentive for airlines to carry non-profit generating payload, all weights past the maximum seating weight are cut off.

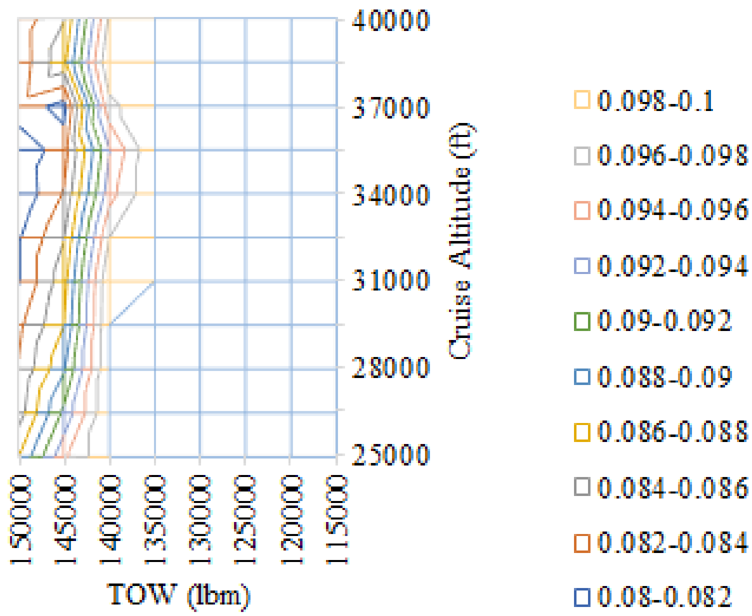


Figure 38: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 09/08/19

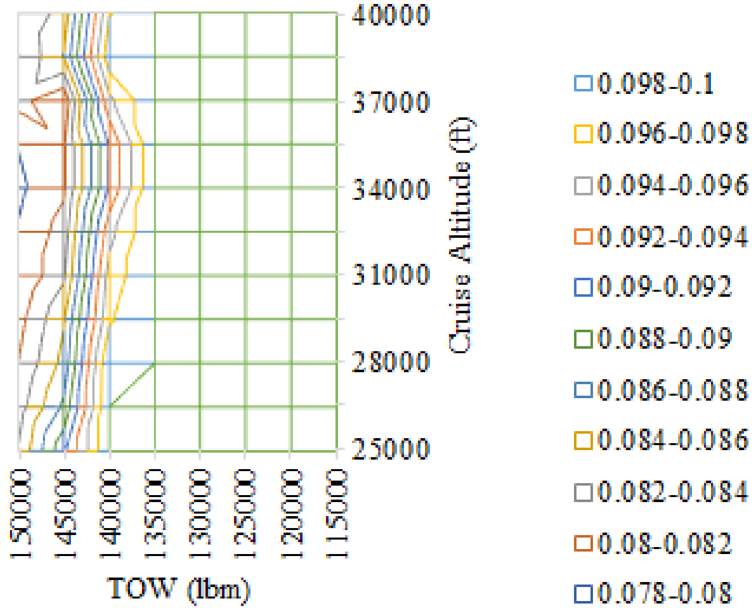


Figure 39: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 09/09/19

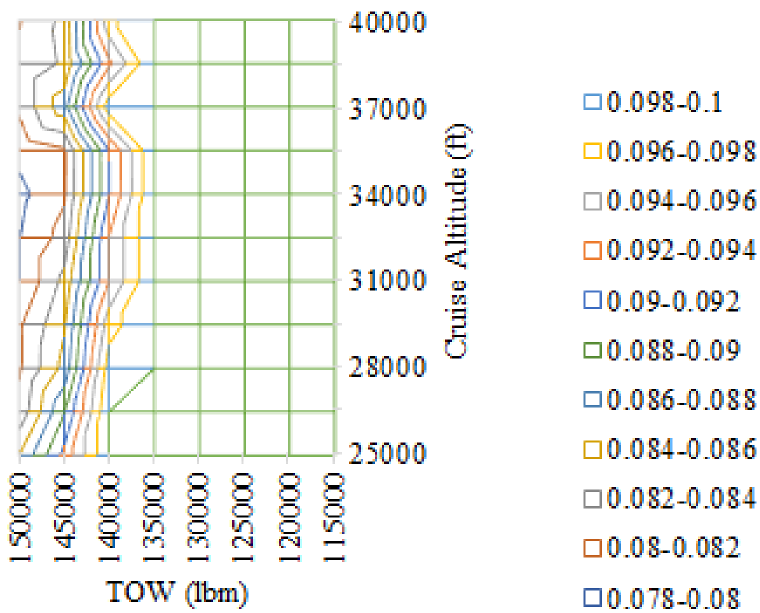


Figure 40: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 09/10/19

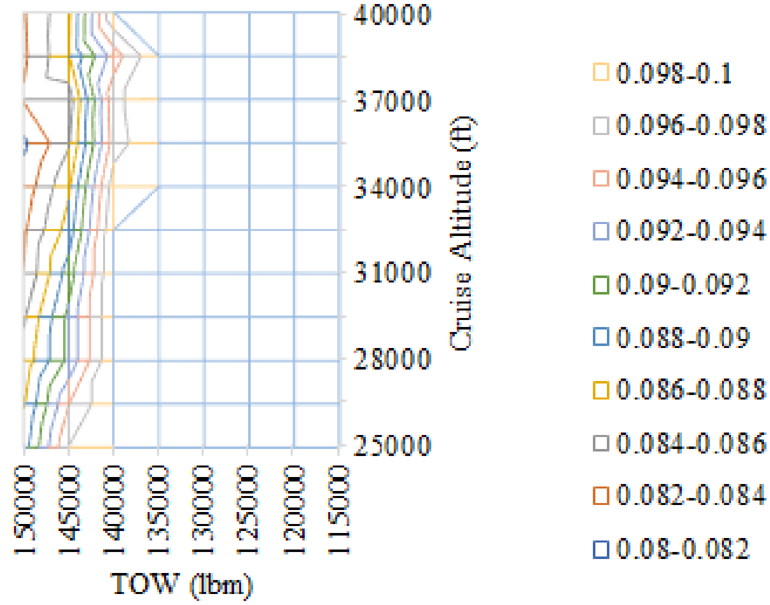


Figure 41: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 09/11/19

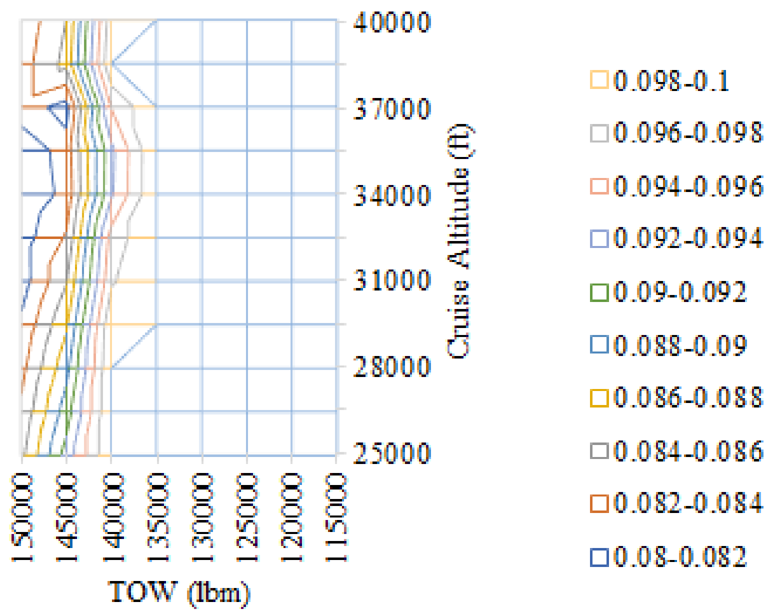


Figure 42: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 09/12/19

From the passenger economy plots in figure 38 to figure 42, it can be seen that there is a very different profile and target altitude than was presented in the fuel economy figures. Instead of flying at ~38000-ft (FL380), the *A320* seems to have a best passenger economy when flying at around 35000-ft (FL350), which corresponds to the best fuel economy altitude at the heaviest profiles.

When compared to the *A320* baseline passenger economy in figure 22, a slight increase on the best passenger economy altitude of the Airbus *A320* appears when flying with the winds. For most of the days tested, the altitude difference is only ~1000-ft, which is not a major difference from the baseline flight altitudes. However, optimizing altitude for flight with winds shows gains of ~2.5% as compared to flying with winds at the baseline altitude.

Considering that the maximum wind magnitudes are found at ~40000-ft (FL400) in figure 27 to figure 32, it seems that the Airbus *A320* is unable to make the most use out of the winds of the jet stream. The induced drag rise overpowers the benefits of flight at the jet stream. This once again begs the question as to the effectiveness of not only the Airbus *A320* but all aircraft that are limited to a 40000-ft (FL400) ceiling, as it would appear that none of those aircraft would likely be able to fly at altitudes where they can both maximize their passenger load and maximize their use of the jet-stream.

The payload economy (fuel burn/kilopound-mile) of the aircraft are plotted in figure 43 to figure 47.

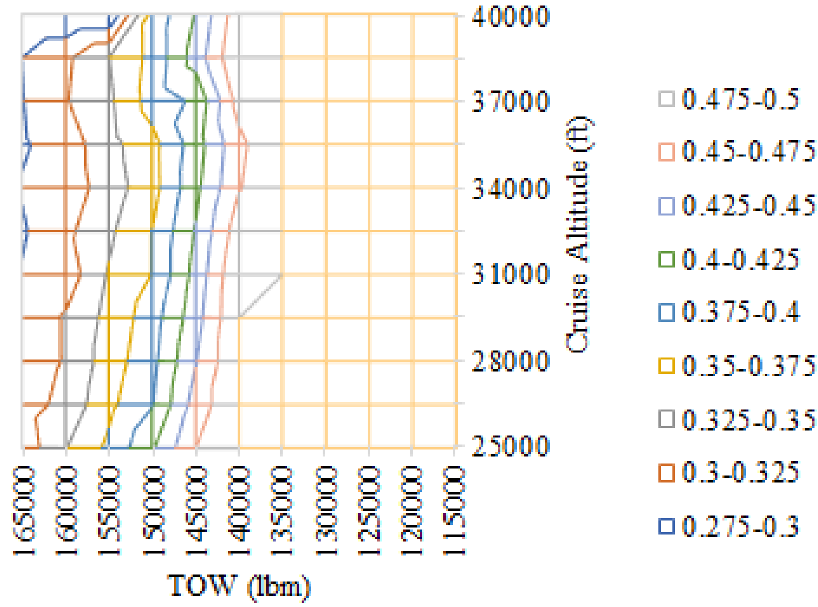


Figure 43: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/08/19

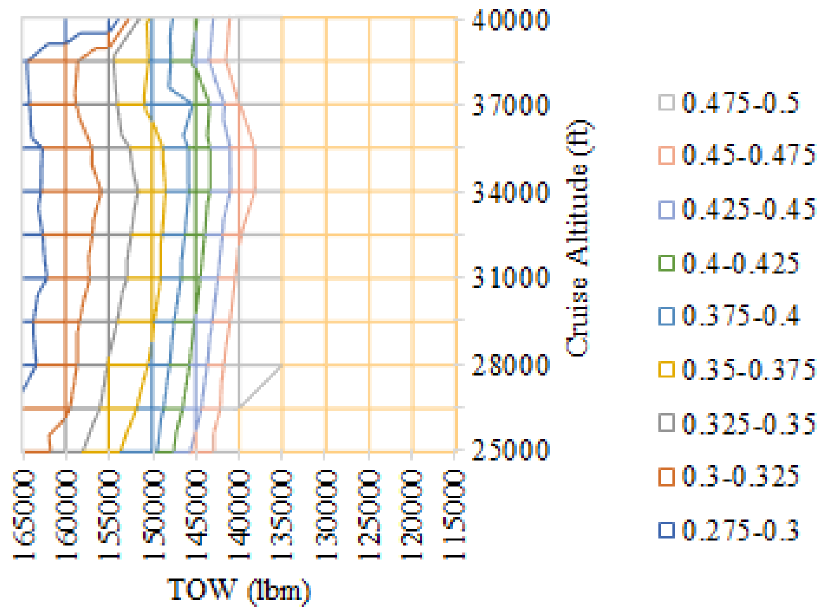


Figure 44: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/09/19

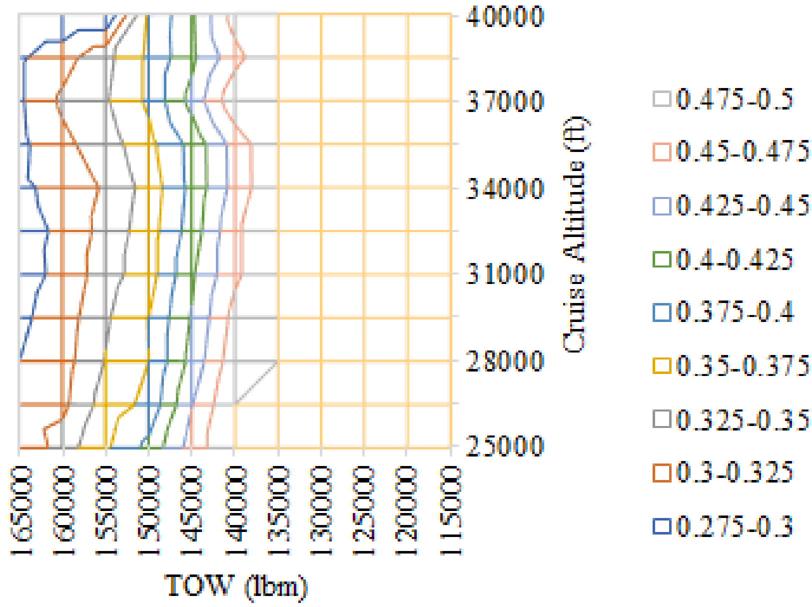


Figure 45: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/10/19

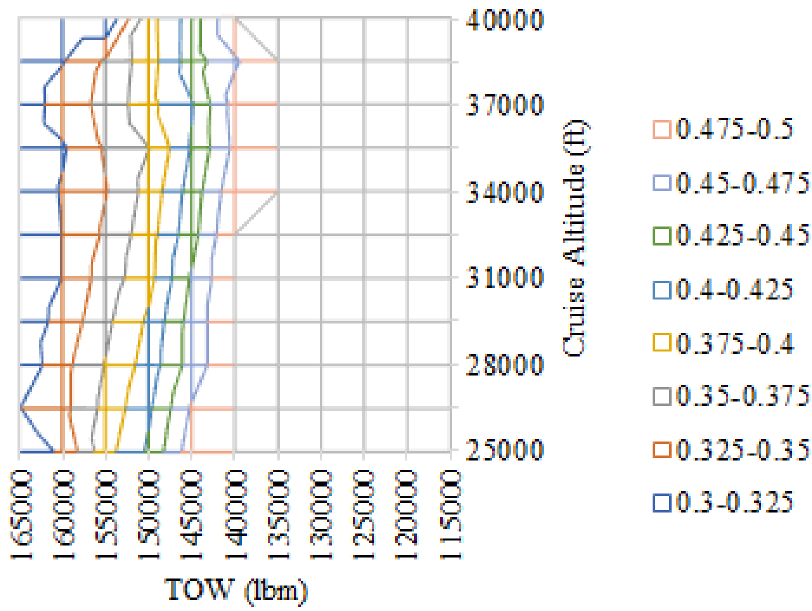


Figure 46: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/11/19

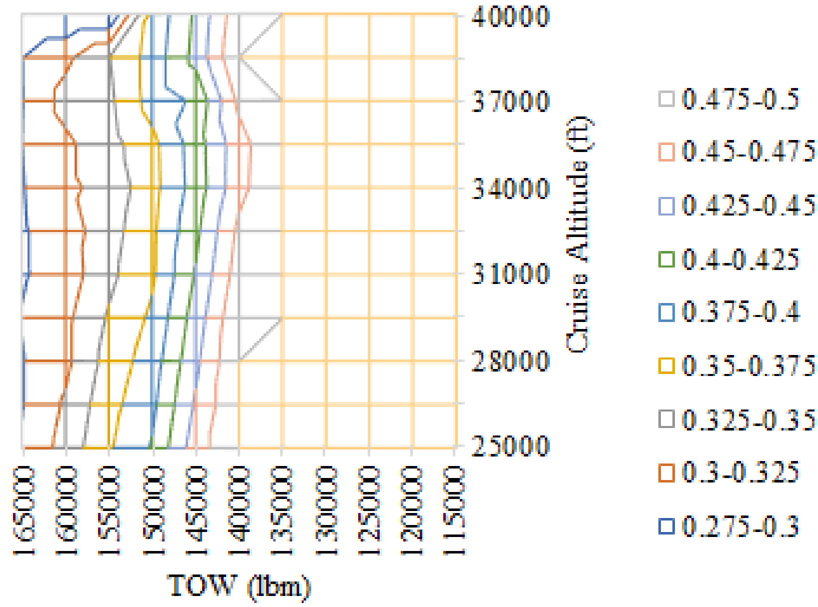


Figure 47: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/12/19

From the pure payload economy perspective, the trend towards taking more payload vs flying higher is still pronounced. From this perspective, the most economic mission is to fly the aircraft at its highest weight at an altitude of 33000-ft (FL330) to 34000-ft (FL340).

When compared to the baseline payload economy in figure 23, there is almost no difference in the maximum payload economy altitudes. Although the maximum payload economy is more favorable in the with-winds case than the baseline, it is obvious that the Airbus *A320* is unable to take full advantage of the jet-stream due to the induced drag penalty of higher-altitude flight.

<u>*Aeris* Trades: OAK to DVN</u>

Since the Airbus *A320*'s induced drag rise overshadows the potential benefits of flying at the jet-stream altitude, the *Aeris* proves to be a unique lens against the Airbus *A320* as its baseline shows that the *Aeris* is most comfortable flying at 50000-ft (FL500) at all TOWs. This means that the *Aeris* has the capacity to take full advantage of the jet-stream winds that occur above 40000-ft (FL400) and thus determine if there is any potential benefit in "underloading" the wings. The fuel economy (credit SR) of the *Aeris* for 09/08/19-09/12/19 has been plotted in figure 48 to figure 52.

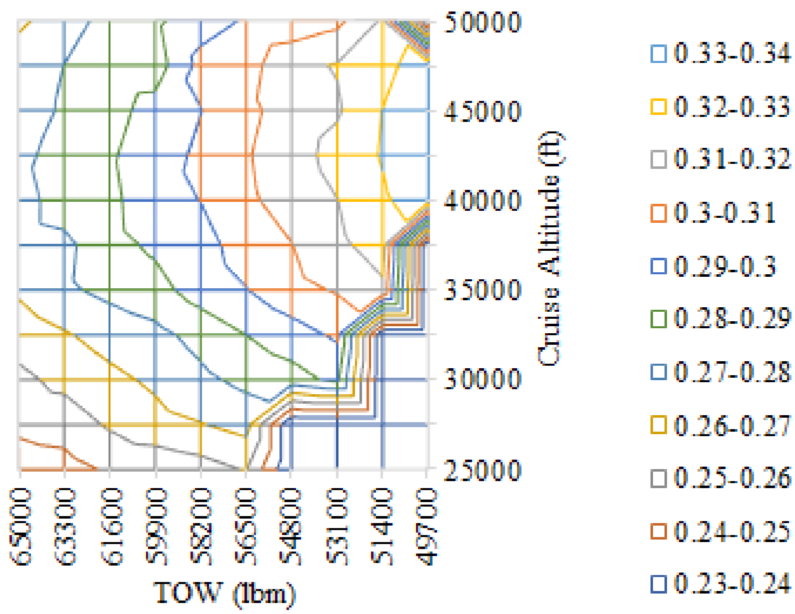


Figure 48: *Aeris* Credit SR for OAK to DVN on 09/08/19

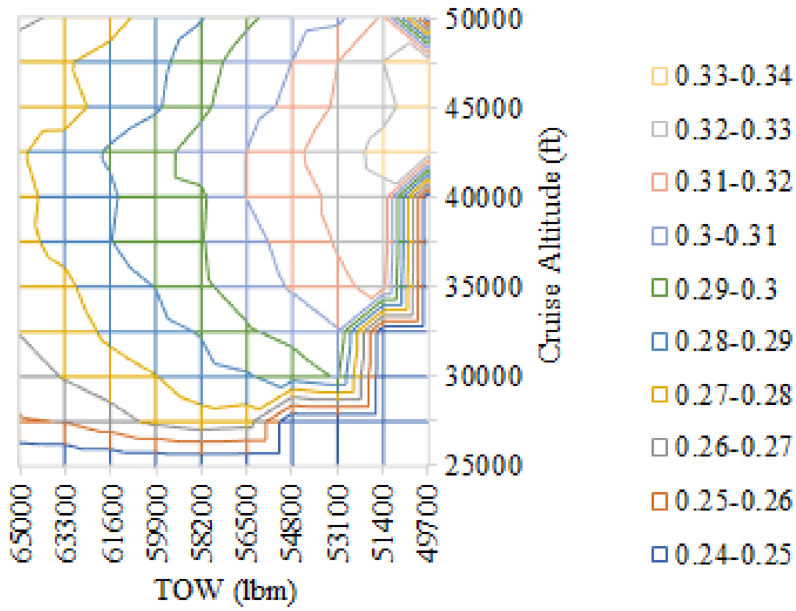


Figure 49: *Aeris* Credit SR for OAK to DVN on 09/09/19

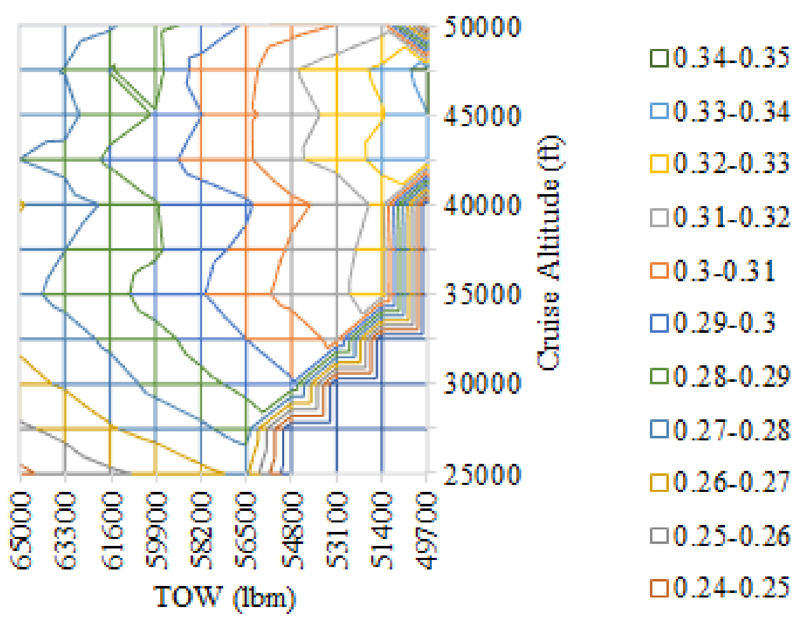


Figure 50: *Aeris* Credit SR for OAK to DVN on 09/10/19

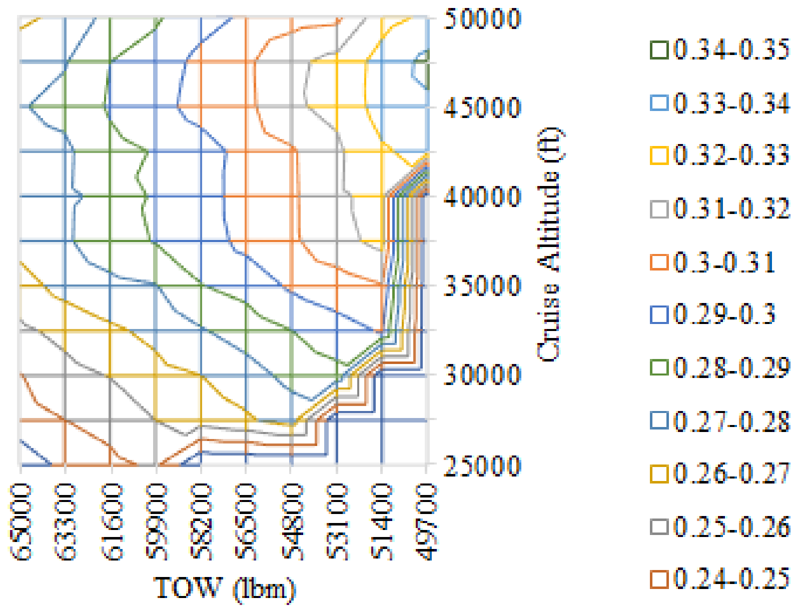


Figure 51: *Aeris* Credit SR for OAK to DVN on 09/11/19

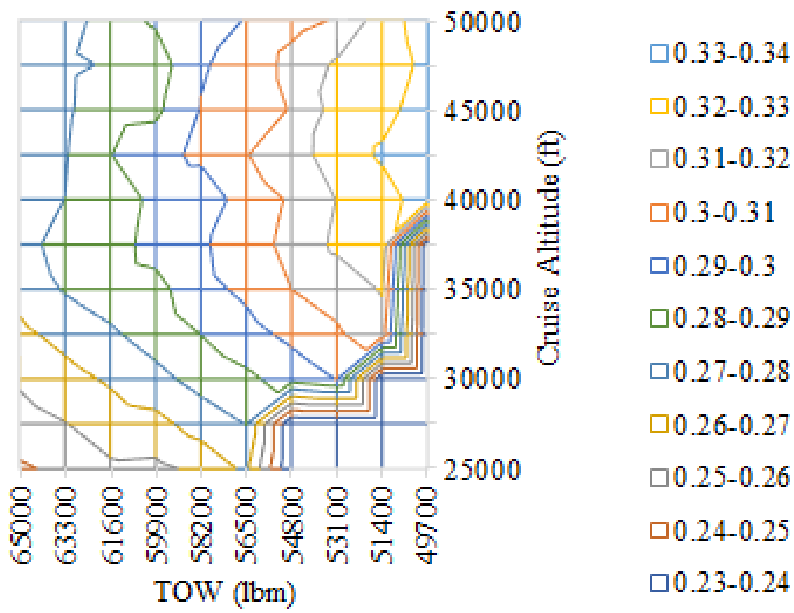


Figure 52: *Aeris* Credit SR for OAK to DVN on 09/12/19

From the fuel economy plots of the *Aeris*, a startling difference can be identified when compared to its baseline credit SR in figure 24. In the baseline, the *Aeris* has maximum fuel economy at 50000-ft (FL500) for each TOW. When flying with the winds, the *Aeris* wants to fly at ~45000-ft (FL450) to ~47000-ft (FL470) depending on the TOW and the day. High winds tend to occur around these altitudes as seen in the wind profiles in figure 27 to figure 32.

Since the *Aeris* is incentivized to fly below the its normal cruise altitude, the *Aeris* actually prefers to underload itself to fly closer to the maximum winds of the jet stream. The fuel efficiency loss from the lower altitudes is overshadowed by the speed gains from the winds at those altitudes.

When simply comparing the shapes and trends of the fuel economy of the *Aeris* to that of the Airbus *A320* when flying with the winds, a major difference appears in that the jet-stream impacts the *Aeris* far more than that of the Airbus *A320*. The net fuel economy gain of the Airbus *A320* is ~0.01 nM/lbm from 0.09 nM/lbm, which corresponds to an 11% increase in its credit SR. The *Aeris* has a net fuel economy gain of ~.05 nM/lbm from 0.3nM/lbm, which corresponds to a nearly 17% increase in its fuel economy.

The passenger economy or fuel burn per seat-mile of the *Aeris* can be seen in figure 53 to figure 57.

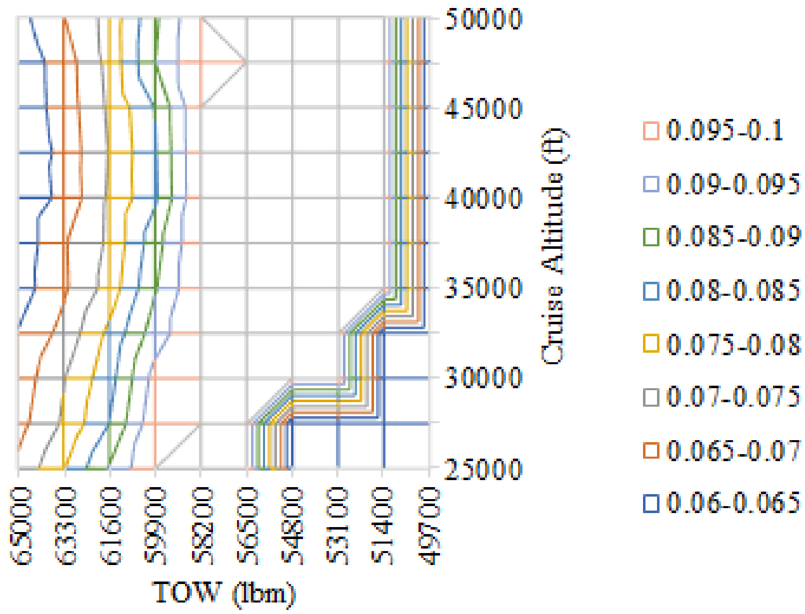


Figure 53: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 09/08/19

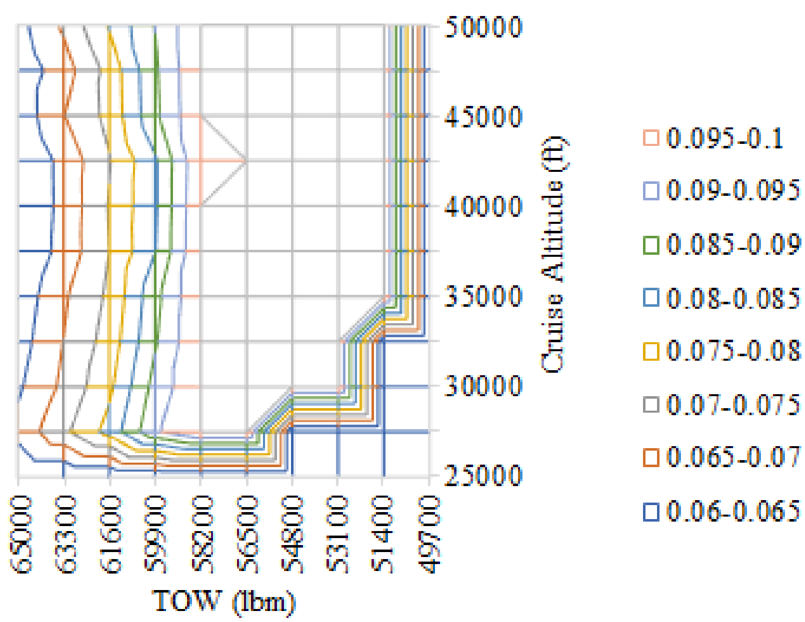


Figure 54: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 09/09/19

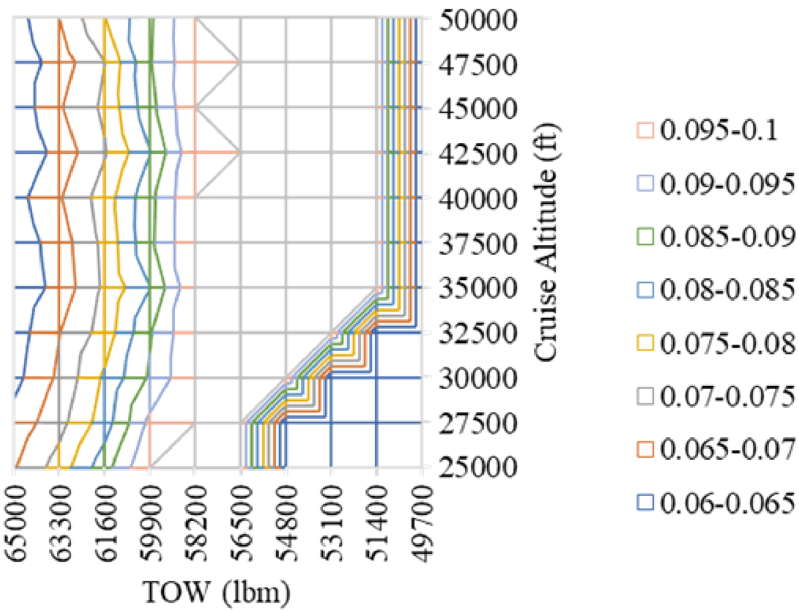


Figure 55: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 09/10/19

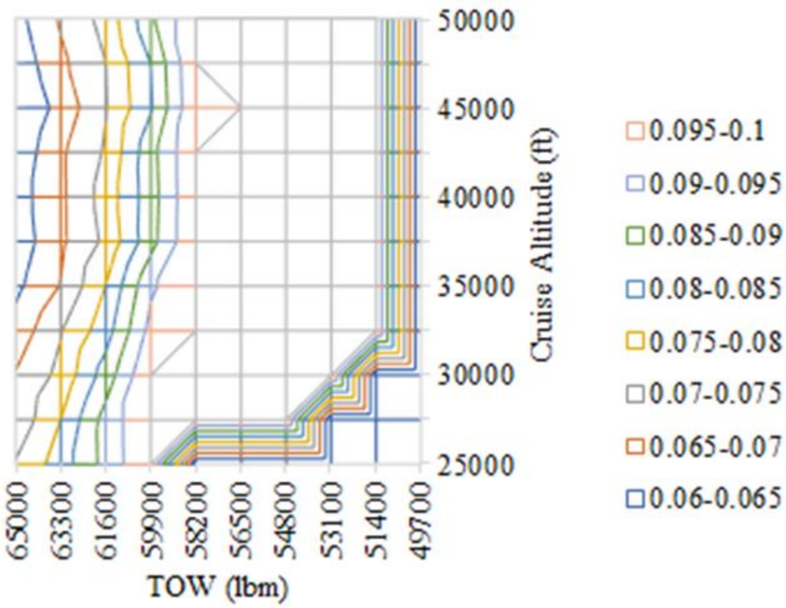


Figure 56: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 09/11/19

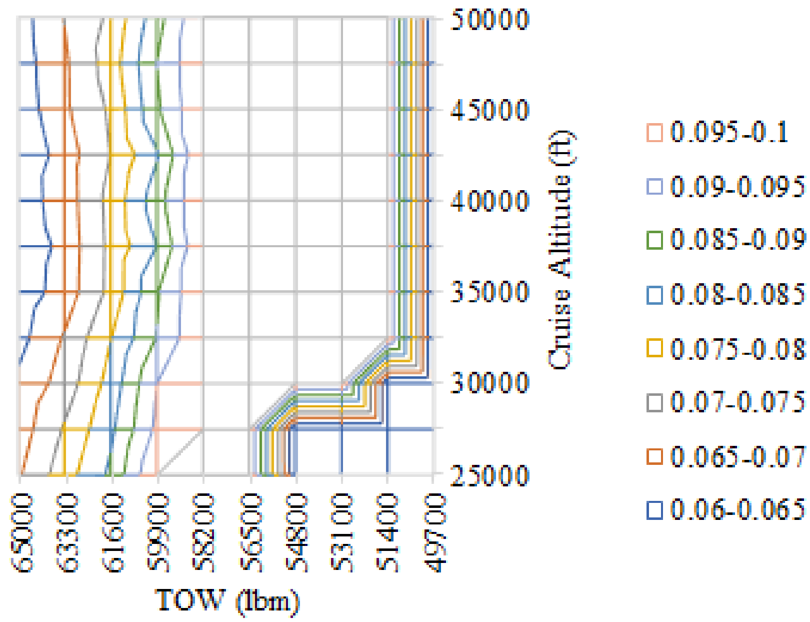


Figure 57: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 09/12/19

The passenger economy plots tell a similar tale in the *Aeris* as the fuel economy plots. The best passenger economy is no longer at 50000-ft (FL500), but rather drops to between 40000-ft (FL400) and 45000-ft (FL 400).

The passenger economy of the *Aeris* is also increased by ~10% from 0.065 lbm/seat-hr-nM to 0.06 lbm/seat-hr-nM when flying with the winds. This seems roughly comparable to the relative change of the Airbus *A320* (0.088 lbm/seat-hr-nM to 0.08 lbm/seat-hr-nM). Thus, despite the major differences in design philosophy between the Airbus *A320* and the *Aeris*, they have similar benefits from the winds.

If the *Aeris* were to simply fly at the cruise altitude given by the baseline, the aircraft would be ~5000-ft from the optimal economic altitude. This indicates that the *Aeris* is particularly sensitive to the presence of winds and makes a strong case that simply flying the baseline mission will not grant maximum economy.

The overall payload economy of the *Aeris* has also been plotted in figure 58 to figure 62.

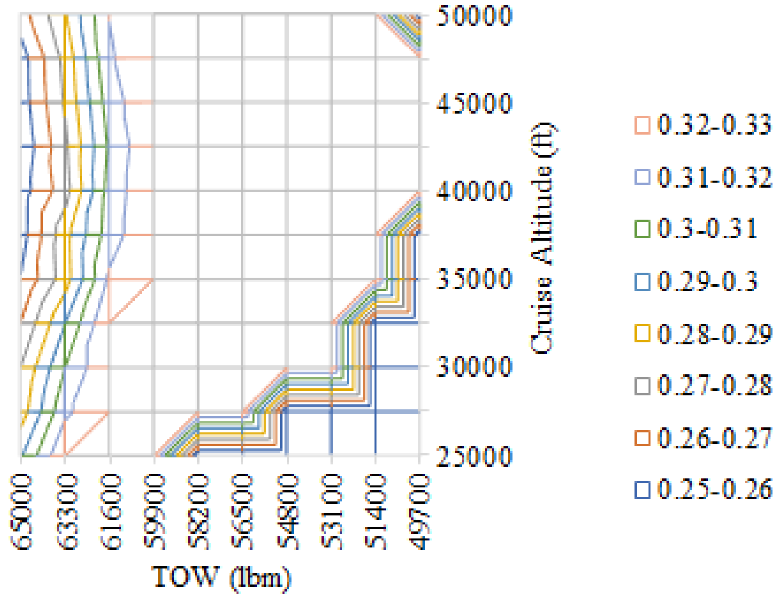


Figure 58: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/08/19

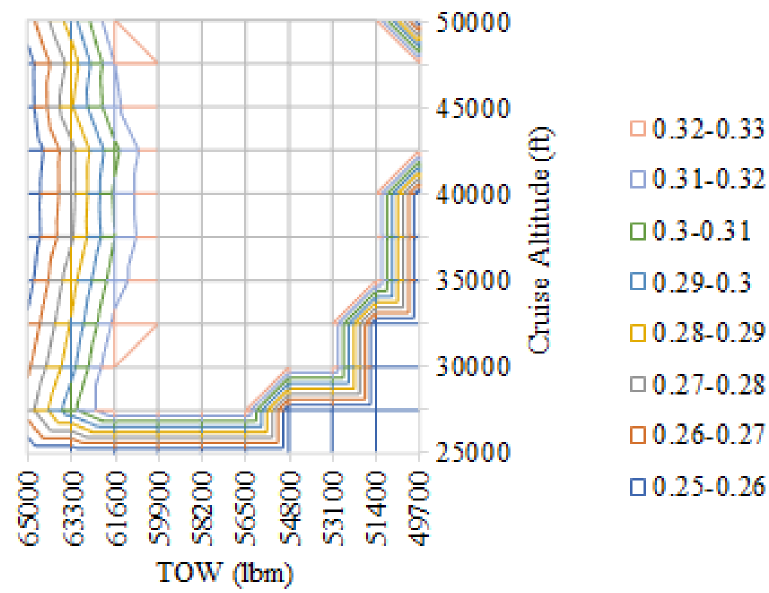


Figure 59: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/09/19

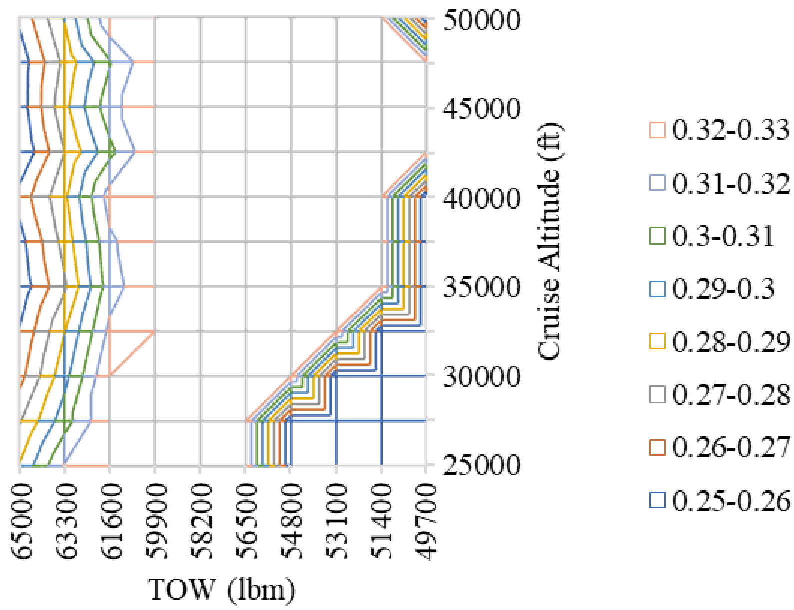


Figure 60: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/10/19

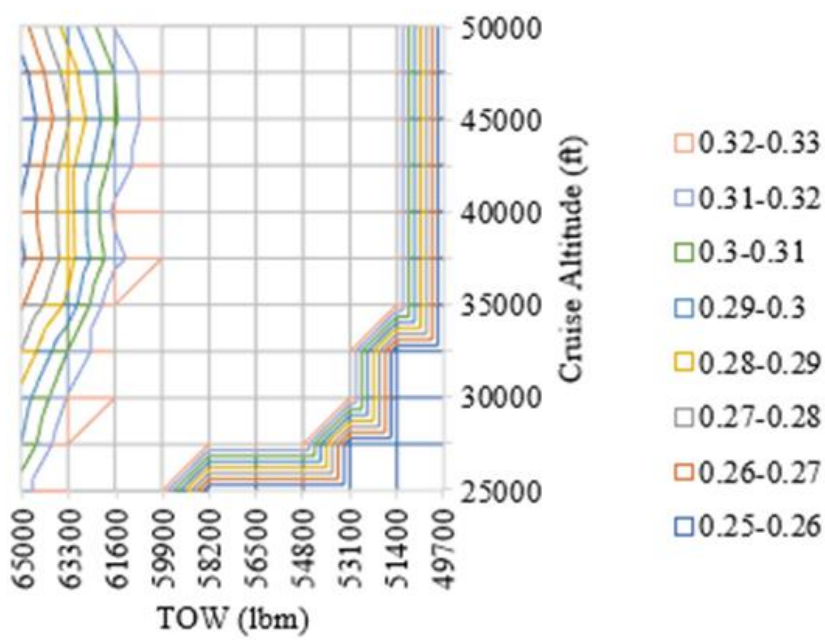


Figure 61: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/11/19

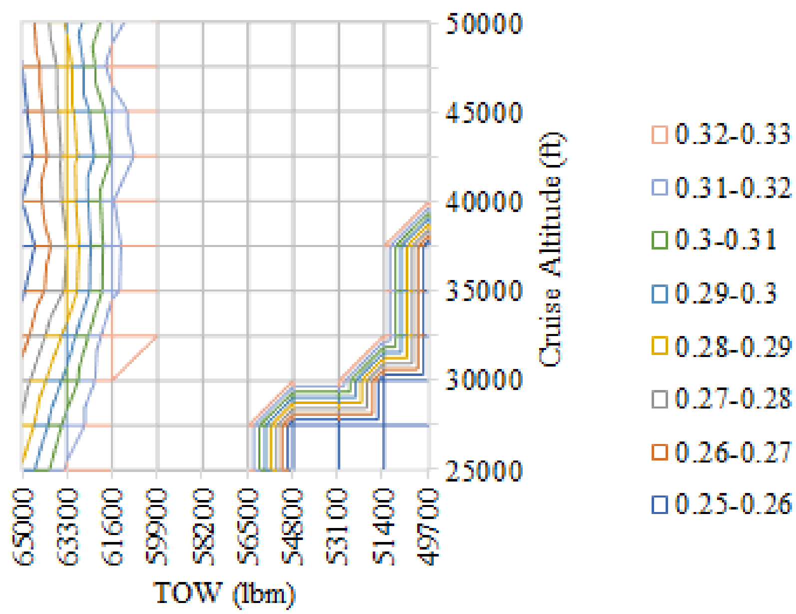


Figure 62: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 09/12/19

For the *Aeris*, the payload economy of the aircraft paints a very similar picture of the overall mission economy as the passenger economy of the aircraft. Flight at higher altitudes is now discouraged in favor of flights at ~45000-ft (FL450). In fact, flight at 50000-ft (FL500) at maximum payload is about 5% less economical than the optimal flight altitude.

The *Aeris* makes a net gain in payload economy of ~0.03 1/kilo-nM from 0.28 1/kilo-nM to 0.25 1/kilo-nM. This corresponds to a relative difference of ~11%. When compared to the net gain of ~.05 1/kilo-nM from 0.325 1/kilo-nM to 0.275 1/kilo-nM of the Airbus *A320* (a relative difference of ~15%), the Airbus appears to have the greater relative gain.

A320 Seasonal Trades: OAK to DVN

The trades above compared the fuel, passenger, and payload economies of the Airbus *A320* and the *Aeris* for a series of five days within September. From looking directly at the wind profiles of the stations over the course of the five days (as seen in figure 27 to figure 32, there is a significant amount of variation within the winds of up to 50 knots depending on the station and day. This results in distortions and variation between the economy plots for each aircraft, where the optimum cruise altitude can drift around ~1000-ft. From an operational standpoint, this suggests that looking at a day-to-day approach for these winds can provide monetary savings over time, however the savings may not be radical.

Overall the basic trends set by the plots appear to be fairly constant. This might suggest that one simply needs to get an initial idea of what the winds look like at altitude, and then use that for all future flights. However, the trades above only study a single week in September, and thus do not capture long-term or seasonal changes. To determine how the aircraft en-route performance is impacted by these seasonal changes, a series of trades were run on days in January, April, and November to capture a sample from the Winter, Spring, and Fall months. The winds for January 20, 2019, April 20, 2019, November 20, 2018, and September 8, 2019 are shown in figure 63 to figure 68 as a comparison of winds between seasons.

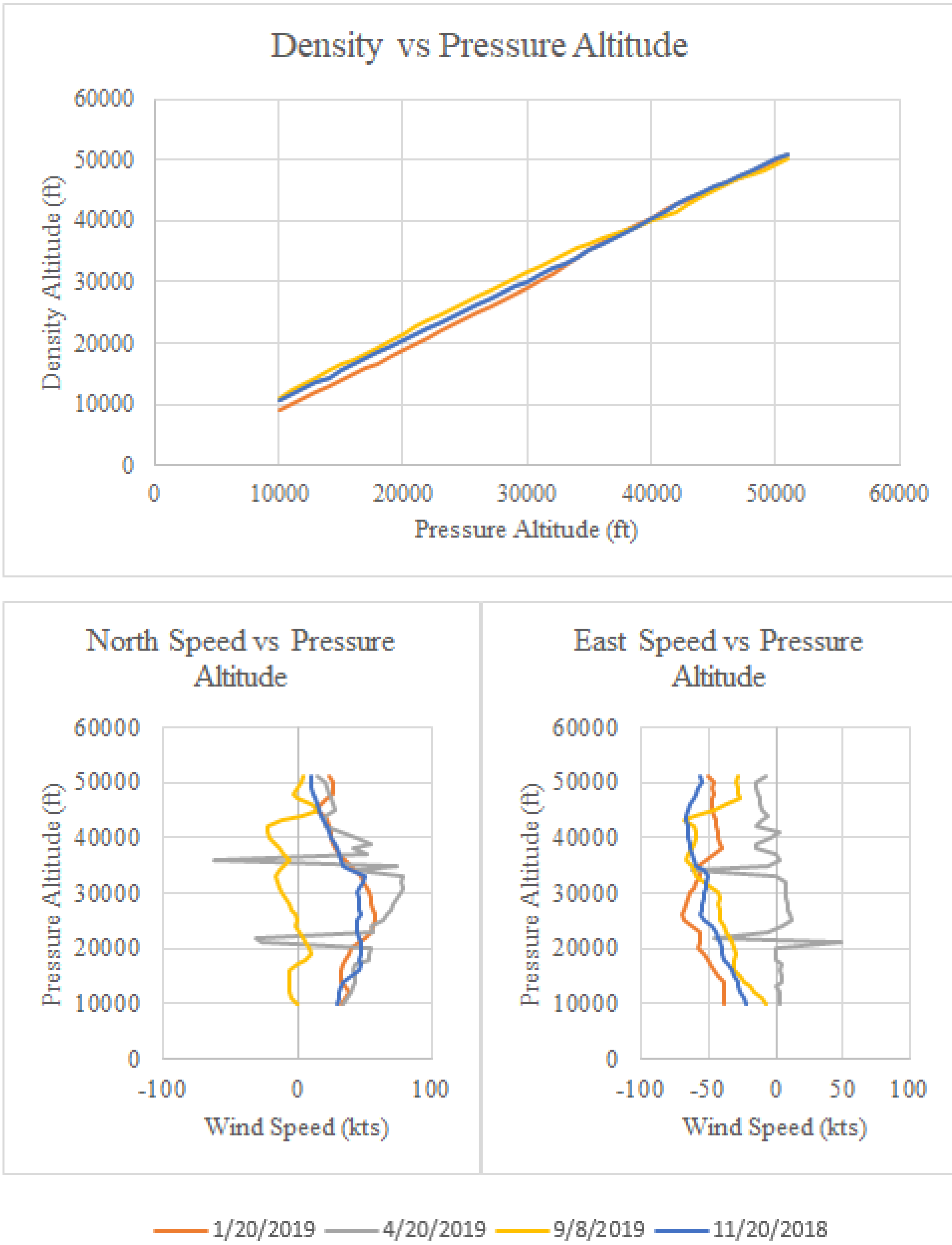


Figure 63: Seasonal Weather for DVN (Davenport, IA) Station

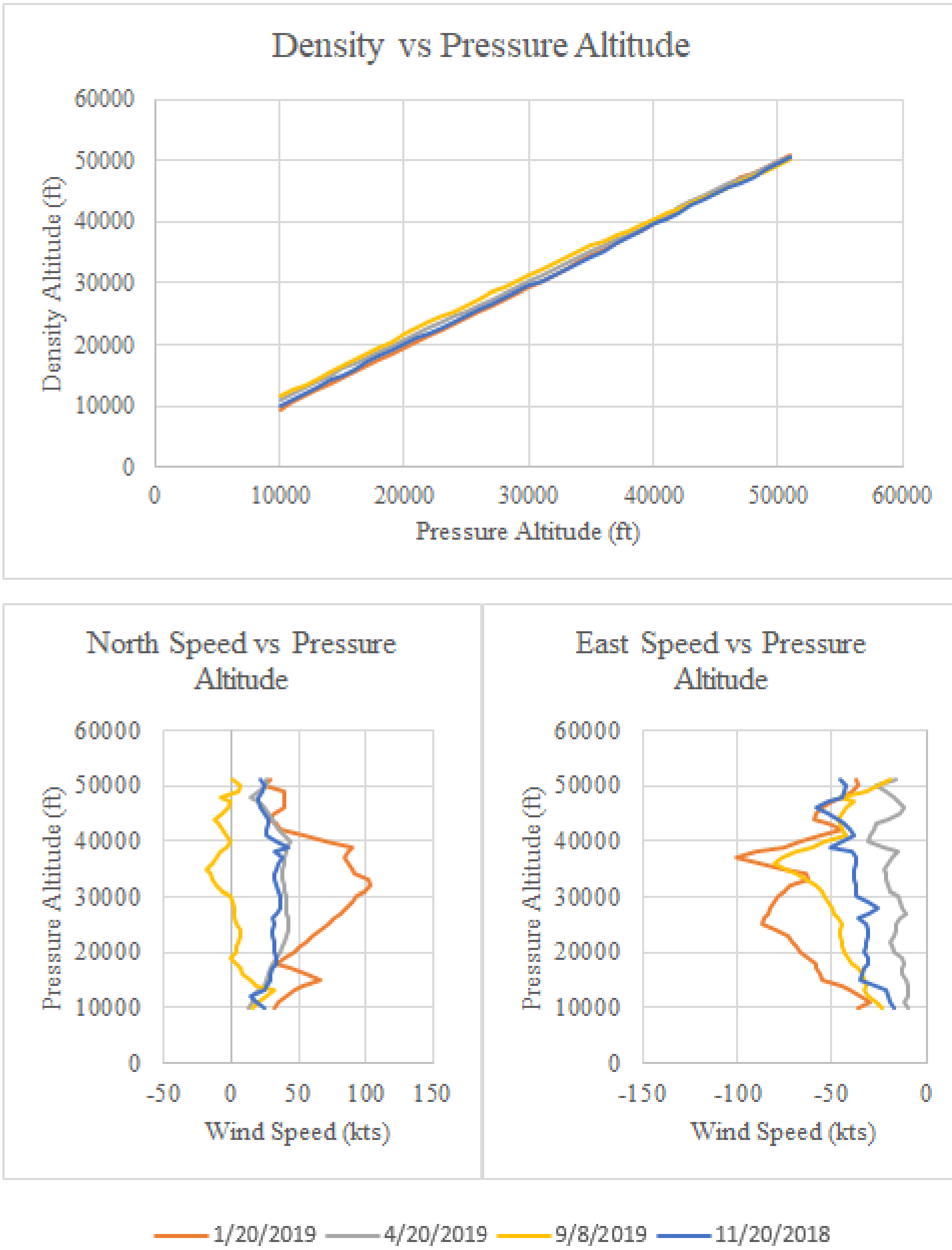


Figure 64: Seasonal Weather for OAX (Omaha, NE) Station

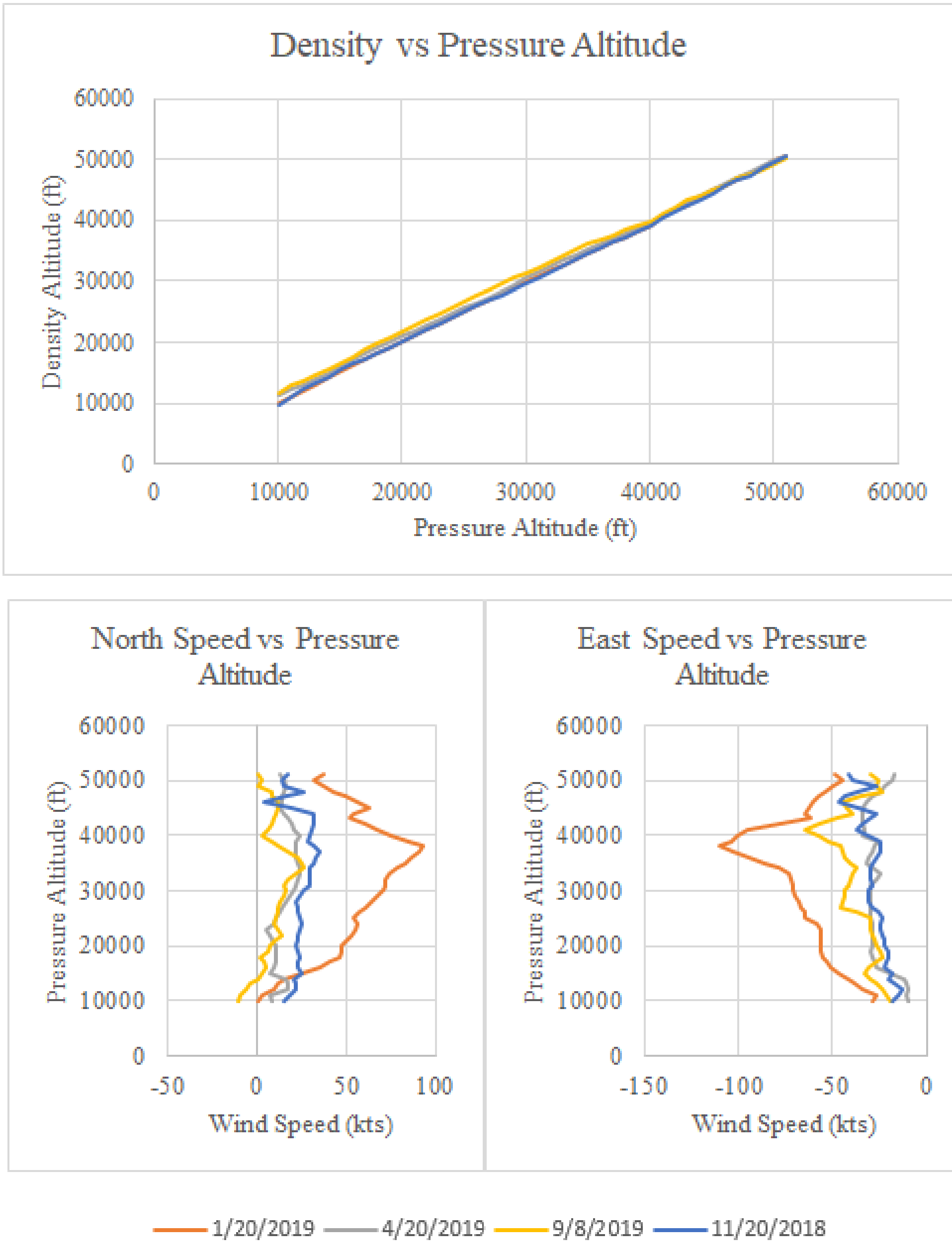


Figure 65: Seasonal Weather for LBF (North Platte, NE) Station

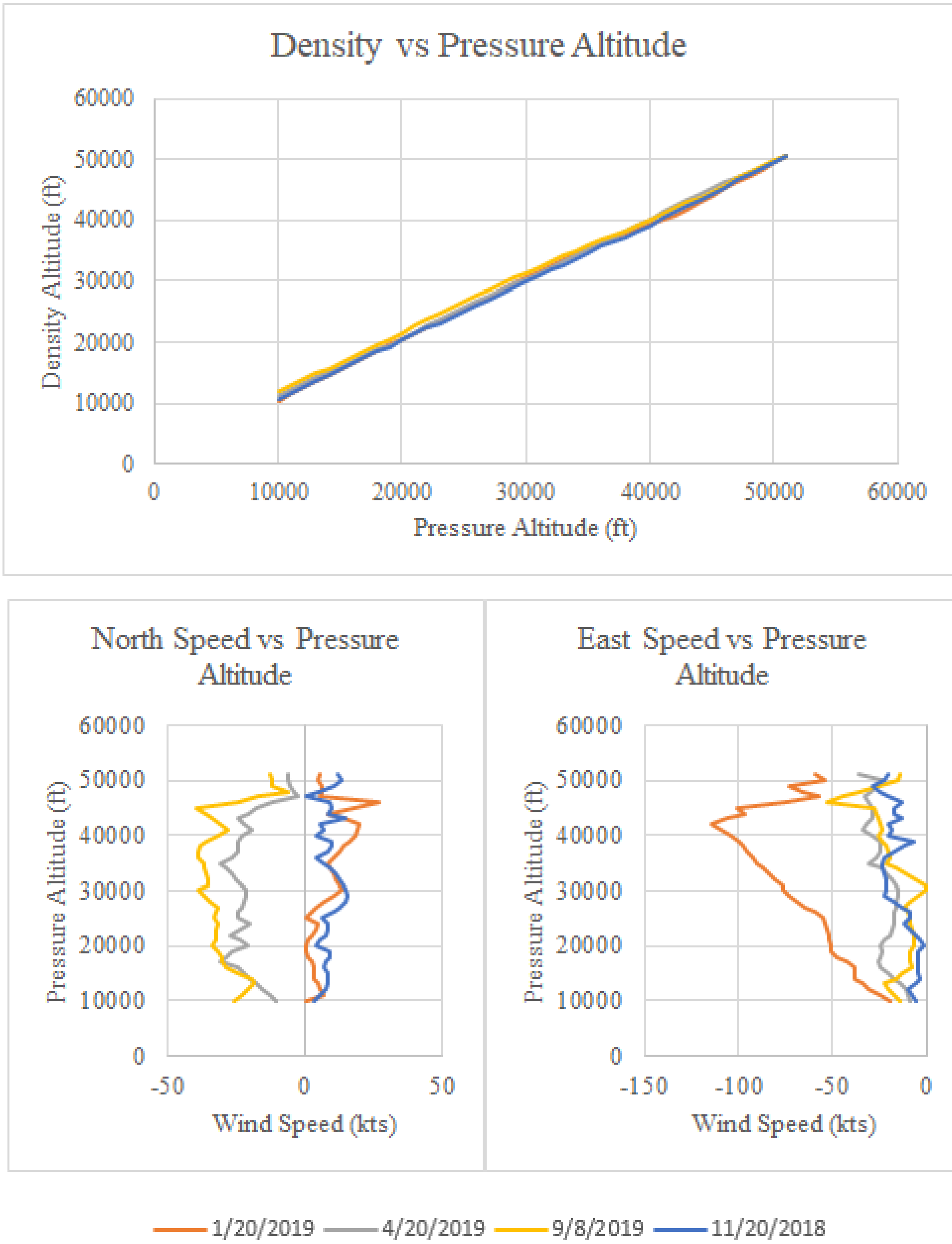


Figure 66: Seasonal Weather for SLC (Salt Lake City, UT) Station

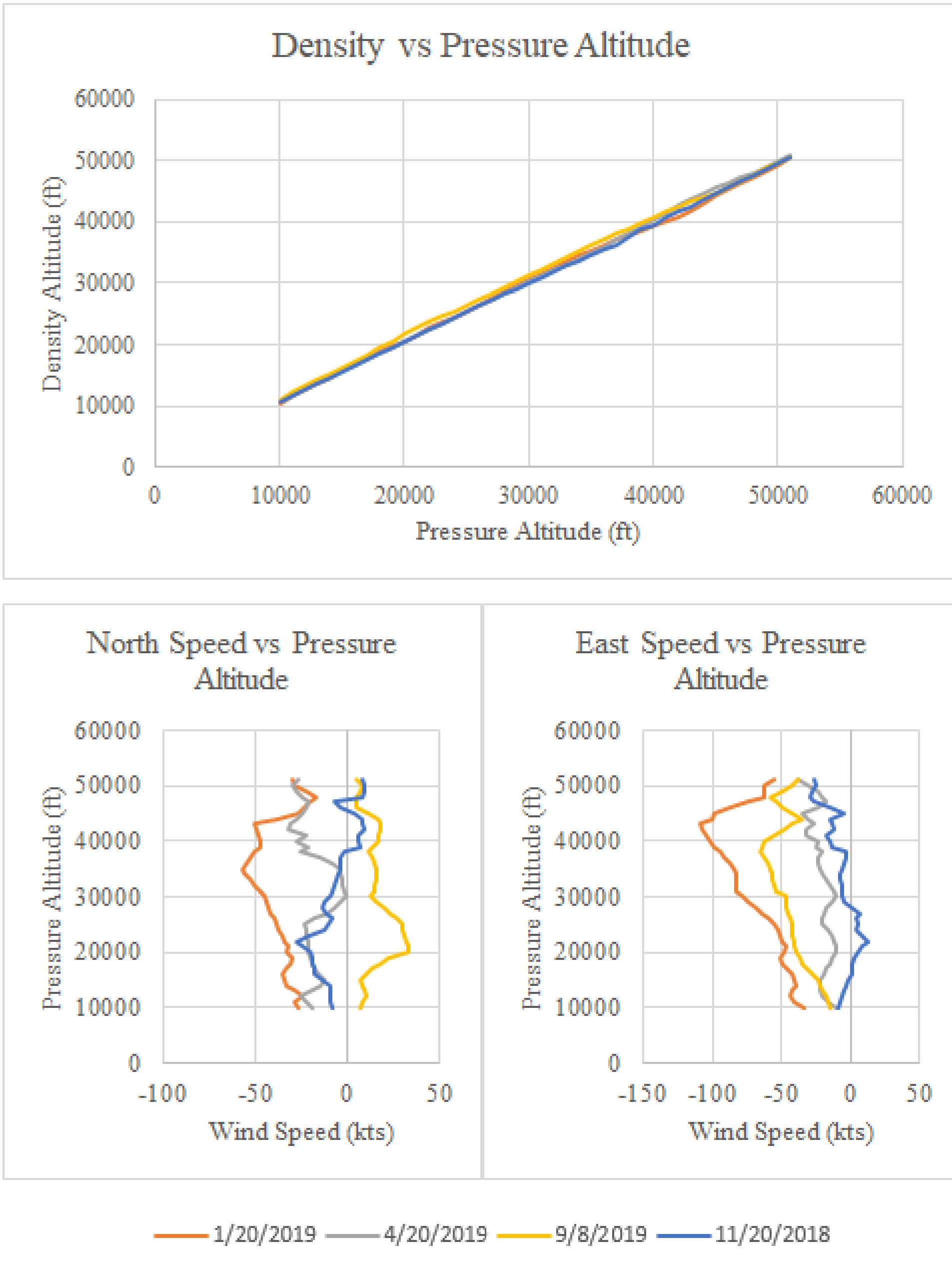


Figure 67: Seasonal Weather for REV (Reno, NV) Station

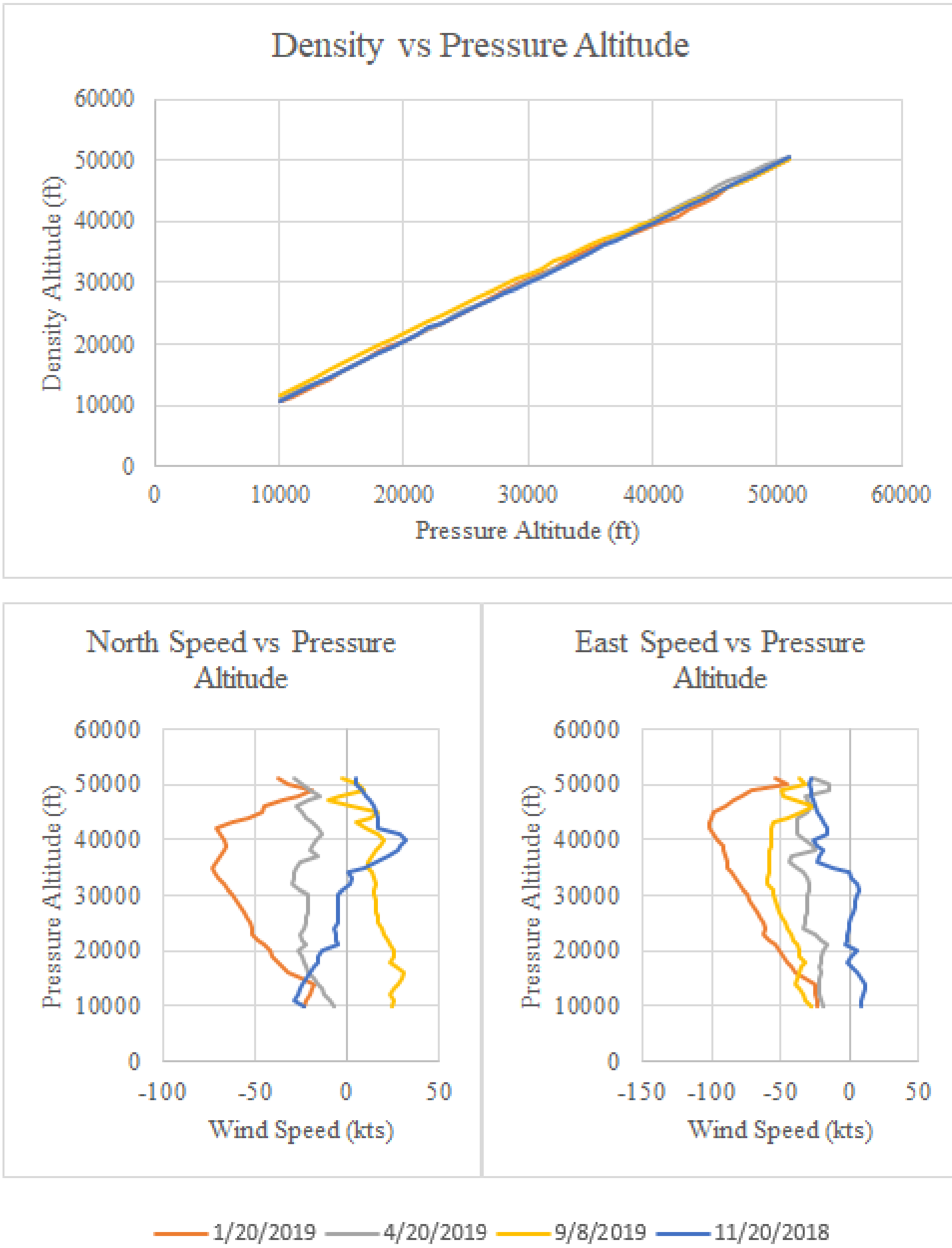


Figure 68: Seasonal Weather for OAK (Oakland, CA) Station

From the winds and density altitude comparisons alone, it can be seen that there is significantly more variation on the seasonal view than on the daily view. Whereas in the daily view the maximum variation was ~50 knots for the wind speeds, a maximum variation of nearly 100 knots appears in the seasonal view.

January has the highest winds, with the Oakland, Reno, and Salt Lake City stations showing wind speeds of over 100 knots in a westward direction and nearly 80 knots in a southerly direction. The jet-stream during the winter months is likely to be very significant to the overall speed of the aircraft and the mission and operational economics. The fall and spring dates however are more tepid on average compared to the summer and winter months. This suggests that there may be a bi-annual pattern that forms with the wind speeds and directions.

More variability also occurs in the density altitudes when looking at a seasonal approach. The warmer months seem to have a higher density altitude than the colder months at lower pressure altitudes, however for some stations (DVN, OAX) the start of a crossover between these months which indicates that the higher altitudes have a higher air density in the fall and winter than in the spring and summer. The variability of the density altitudes also decreases in general with rising pressure altitude, which indicates that higher-altitude flight might result in more stable air densities and thus less air density will yield less variation on en-route performance.

The impact of these winds and altitude densities on the Airbus *A320* has been recorded in contour plots of the fuel economy (credit SR). These contour plots for January 20, 2019, April 20, 2019, and November 20, 2018 can be seen in figure 69 to figure 71.

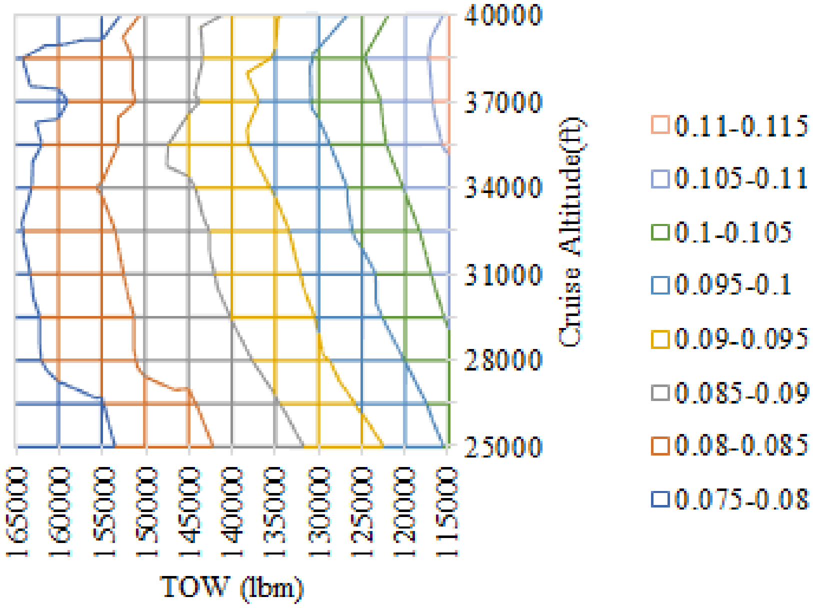


Figure 69: *A320* Credit SR for OAK to DVN on 01/20/19

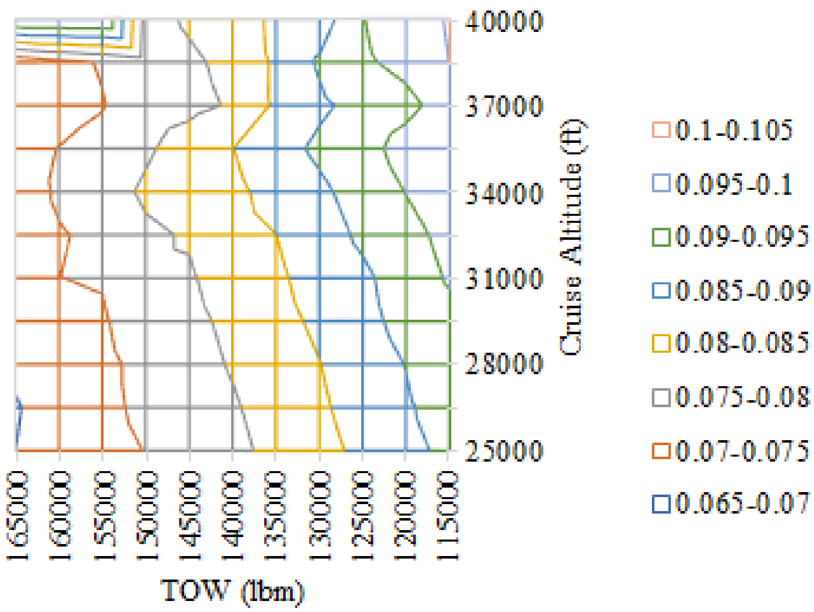


Figure 70: *A320* Credit SR for OAK to DVN on 04/20/19

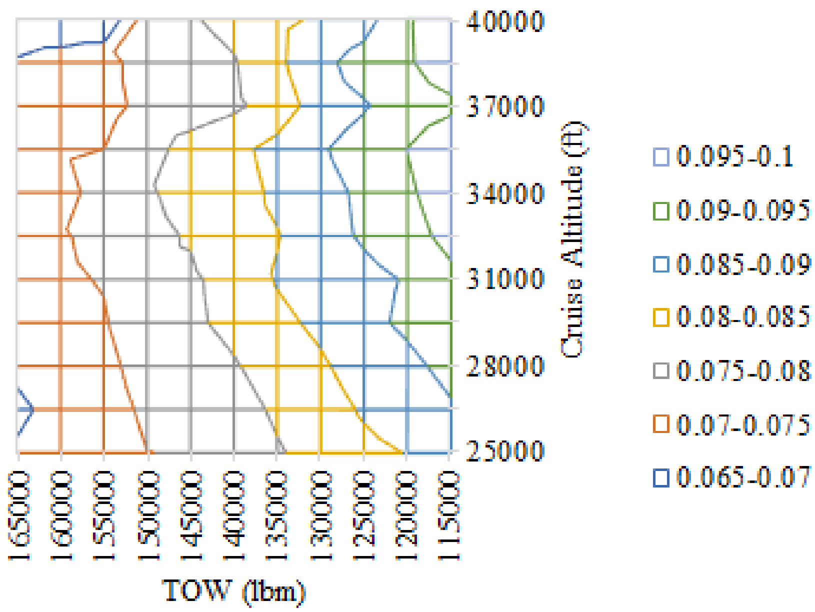


Figure 71: *A320* Credit SR for OAK to DVN on 11/20/18

From the fuel economy plots for the Airbus *A320*, the trend again appears in that from a fuel economy perspective the aircraft favors the lightest weights and the highest altitude. However, the magnitudes of the specific ranges have ~10% variation between the dates. January shows the best specific ranges reaching between 0.11-0.115 nM/lbm, while November shows the worst specific ranges with a maximum of only 0.9-0.95 nM/lbm. The September plots in figure 33 to figure 37 showed an expected maximum specific range of 0.105-0.11 nM/lbm. Considering the wind profiles shown in figure 63 through figure 68, it appears that the bi-annual nature shows up in the specific ranges, where the best fuel economy can be expected to occur in the winter and summer months, while the spring and fall months have less fuel economy benefit.

More variation appears in the shapes of the specific range plots as compared to the five-day trade series. The April plot has a small switchback occurring at ~37000-ft (FL370). Looking at the wind plots, it appears that this may be due to the northerly wind speeds. Since this flight has the Airbus *A320* fly in a southwestern direction, northerly winds will have a negative effect on the fuel efficiency of the flight. The northerly winds of the Midwest region have maximum magnitudes around 37000-ft (FL370), hence the switchback.

There is also a much steeper gradient in terms of the fuel economy in January and September as compared to April and November. Again, this appears to be because of the greater winds in the winter and summer. For the winter and summer months, the winds have a greater magnitude and steeper gradients than in the spring and fall months, hence there is a greater variation of the specific ranges.

To get a better feel for the overall mission economy, the contour plots for the passenger economy (fuel burn/seat-mile) can be seen in figure 72 to figure 74.

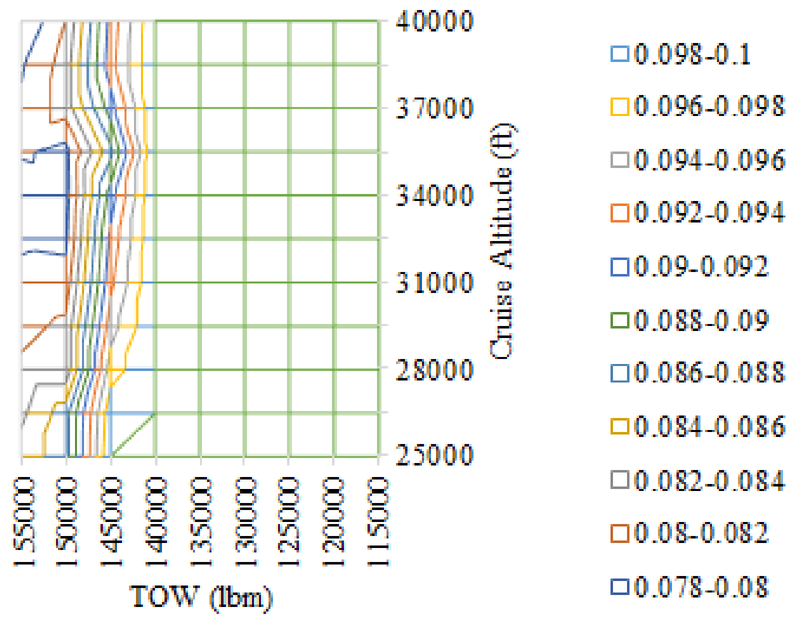


Figure 72: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 01/20/19

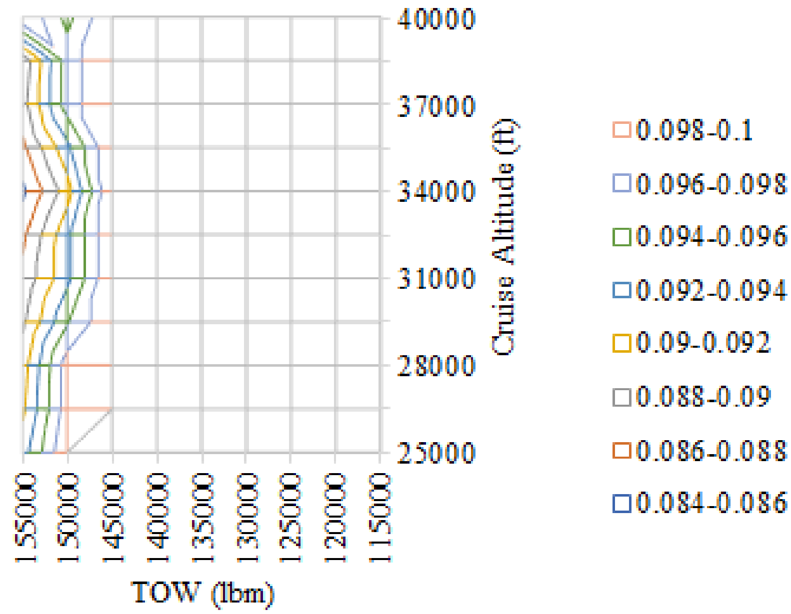


Figure 73: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 04/20/19

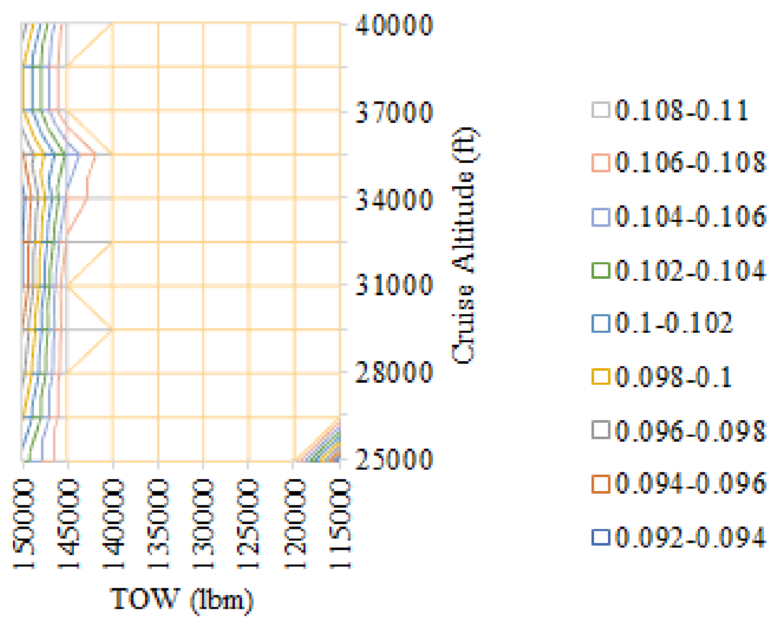


Figure 74: *A320* Fuel Burn/Seat-Mile for OAK to DVN on 11/20/18

From the passenger economy perspective, the optimal flight altitude and weight for the Airbus *A320* is found around 34000-ft (FL340) at maximum passenger loading. However, a significant difference in terms of the magnitude of the passenger economy also appears between the seasons. January again has the best passenger economy, reaching economies of 0.078 lbm/seat-nM. April has a much worse passenger economy score of 0.084 lbm/seat-nM at its best, and November is even worse with an optimal score of 0.092 lbm/seat-nM. For comparison, the passenger economy of the Airbus *A320* reaches 0.08 lbm/seat-nM on September 08, 2019 and has a baseline best passenger economy of 0.09 lbm/seat-nM.

Surprisingly, it appears that the November date has a slightly worse passenger economy than the baseline case. Looking at the winds in figure 63 to figure 68, it can be seen that the winds have very little westward components for November, however there is a significant component coming from the North in the Midwest. This component appears to be creating a net negative in terms of the performance of the aircraft, and thus shows that the west-east route is not guaranteed to come with fuel savings if the aircraft is passenger-constrained.

Finally, the pure payload economy (fuel burn/kilopound-mile)contours have also been plotted in figure 75 to figure 77.

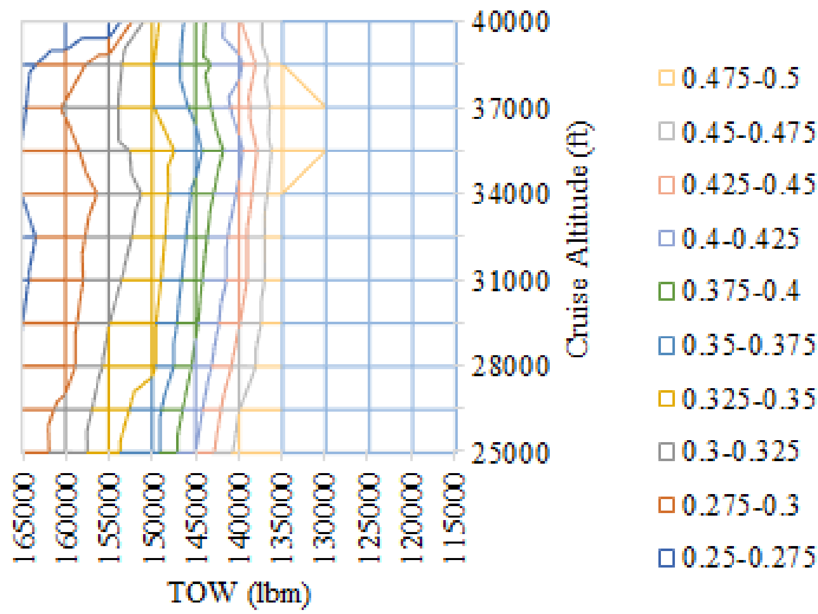


Figure 75: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 01/20/19

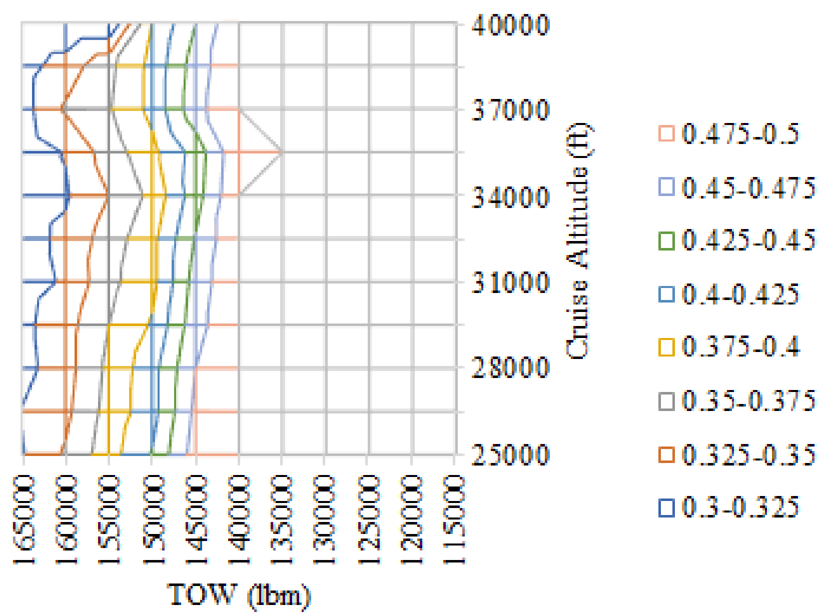


Figure 76: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 04/20/19

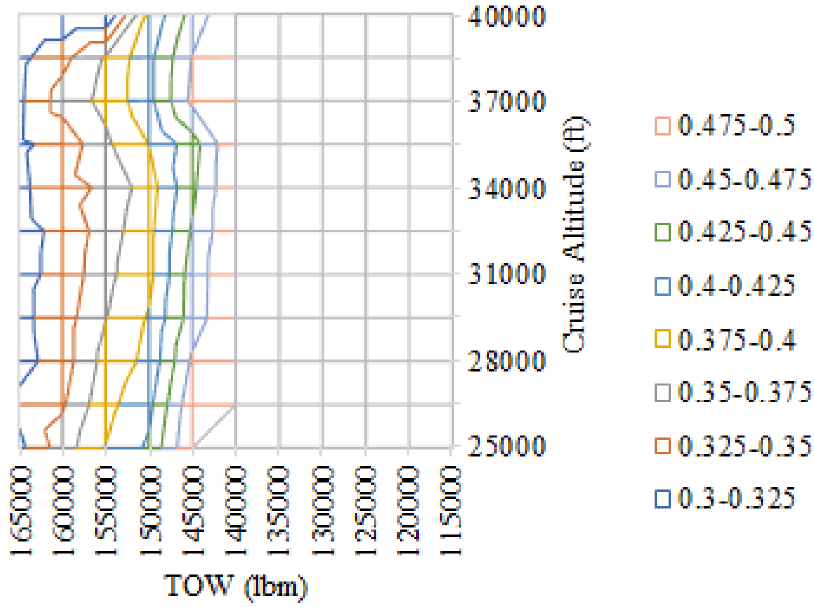


Figure 77: *A320* Fuel Burn/Kilopound-Mile for OAK to DVN on 11/20/18

Although it is already expected that the Airbus *A320*'s best payload economy will occur in January, there appears to be some significant differences in the cruise altitude upon which the best payload economy can be gained. In January, the Airbus *A320* favors 32000-ft (FL320) or 37000-ft (FL370) at maximum payload capacity. However, in April the best payload economy can be found at 34000-ft (FL340). In November, the aircraft's best payload economy is found at an altitude of 32000-ft (FL320). For comparison, the best payload economy for the September 08, 2019 trade can be found at 33000-ft (FL330).

Considering the maximum and minimum altitudes (37000-ft / FL370 and 32000-ft / FL320 respectively), an overall variation of 5000-ft is obtained. This is a significant difference in flight altitudes and suggests that even aircraft such as the Airbus *A320* can gain performance and economic benefits from developing flight plans based on the known winds of the route.

<u>*Aeris* Seasonal Trades: OAK to DVN</u>

There is a significant amount of variability in the optimum cruise conditions for the *A320* when weather is viewed throughout the year. However, this brings about the question as to whether the *Aeris* will have a similar level of variability. Furthermore, there is a question as to how well the *Aeris* performs throughout the year as compared to the Airbus *A320*. Depending on which aircraft appears to have the best mission economy, there may be significant impacts upon not only mission planning of flights, but on the design of future aircraft to take maximum advantage of these weather conditions.

Similar to the previous trades, the fuel economy of the *Aeris* in the presence of winds has been calculated during January 20, 2019, April 20, 2019, and November 20, 2018. These plots have been generated and can be seen in figure 78 to figure 80.

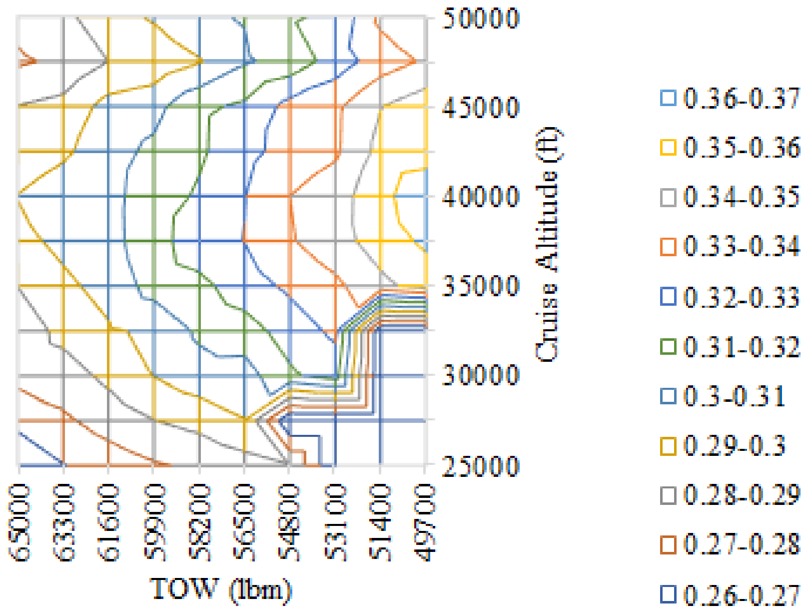


Figure 78: *Aeris* Credit SR for OAK to DVN on 01/20/19

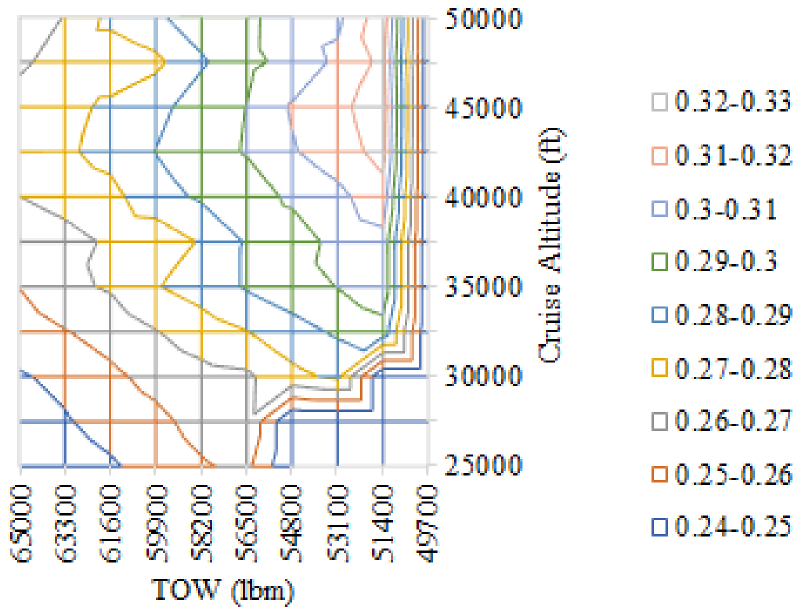


Figure 79: *Aeris* Credit SR for OAK to DVN on 04/20/19

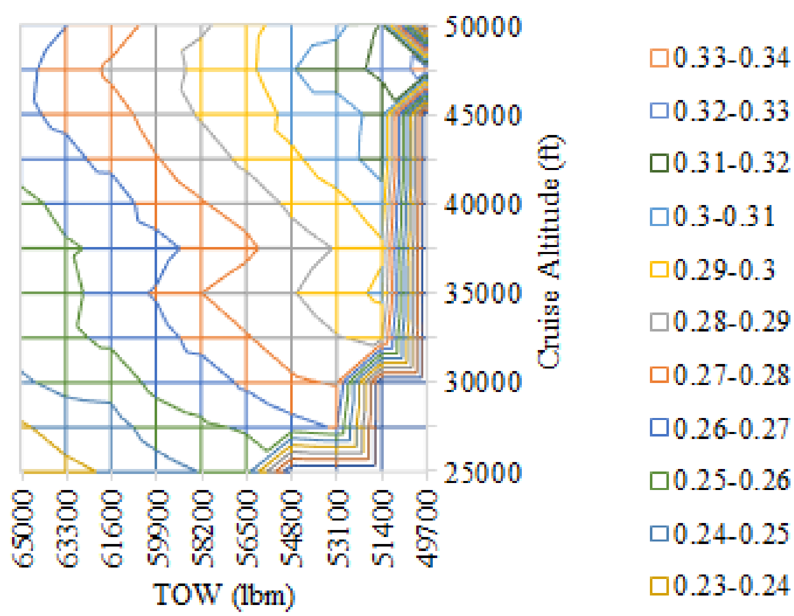


Figure 80: *Aeris* Credit SR for OAK to DVN on 11/20/18

From the SR plots alone, major variability can be seen in the cruise altitudes of the *Aeris* between the different days. In January, it appears that the *Aeris* obtains a maximum fuel economy at 40000-ft (FL400) for all TOWs. In April, the best fuel economy altitude rises to 43000-ft, while in November the best fuel economy altitude is at 48000-ft (FL480). Looking back at figure 48 (September 8), the best fuel economy is obtained at around 44000-ft (FL440).

This range of altitudes is even larger for the *Aeris* than for the Airbus *A320*. Depending on the day, the *Aeris* may fly as much as 10000-ft lower than its design condition! This signifies that when flying with the winds, the *Aeris* significantly underloads itself by flying at a much lower altitude than it was designed for.

However, for both the *Aeris* and the Airbus *A320* it is important to note that the fuel savings are maximum fuel savings based upon maximum SR, which correlates to a minimal payload. Since there is almost no reason for these aircraft to be flown without payload, it is important to determine the effect of the winds upon the passenger and payload economies as well. To this effect, the passenger economy (fuel burn/seat-mile) of the *Aeris* has been plotted for January 20, 2019, April 20, 2019, and November 20, 2018 in figure 81 to figure 83.

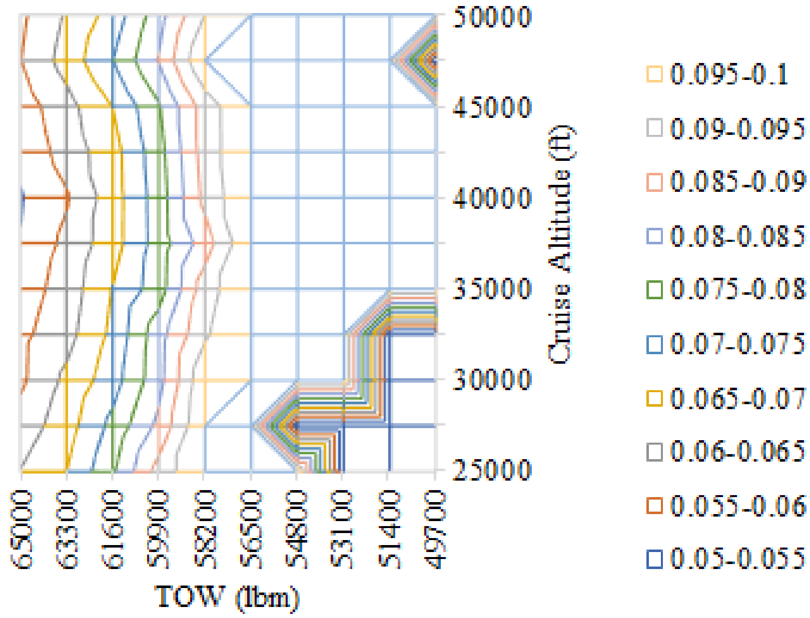


Figure 81: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 01/20/19

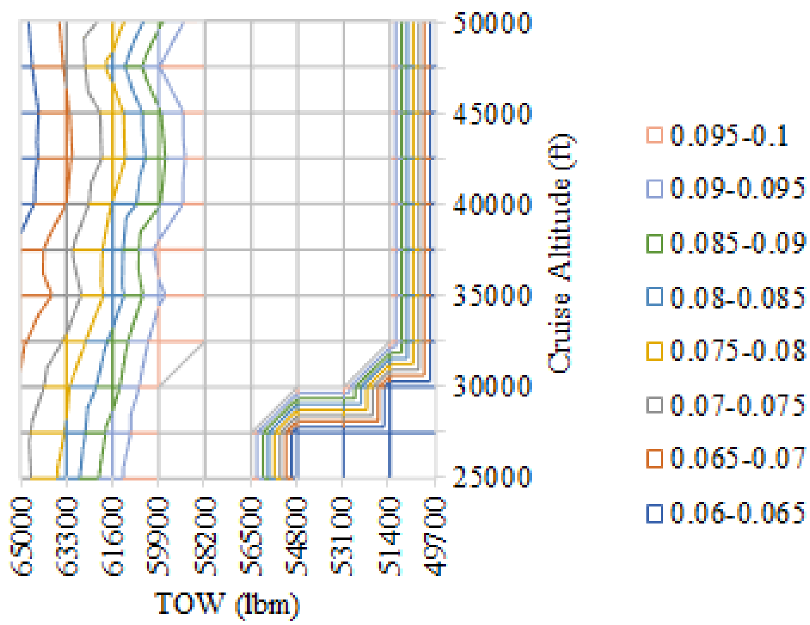


Figure 82: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 04/20/19

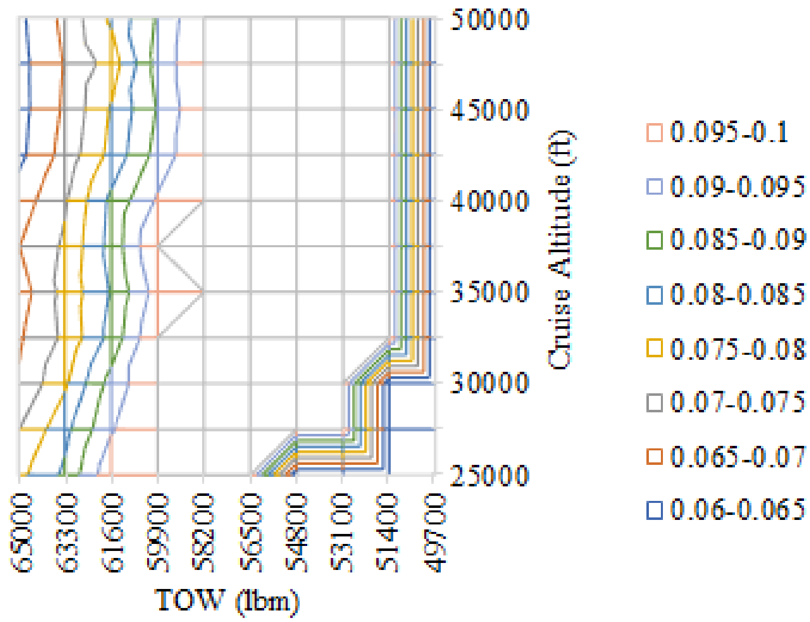


Figure 83: *Aeris* Fuel Burn/Seat-Mile for OAK to DVN on 11/20/18

From the passenger economy (fuel burn per seat-mile) plots, the *Aeris* strongly favors flight at 40000-ft (FL400) with maximum passengers in January. The passenger economy curves are heavily centered around the 40000-ft (FL400) region, only curling back towards better economy at 50000-ft (FL500).

This trend is not seen in April or November, where although it appears that the *Aeris* wants to fly at 43000-ft (FL430) and 48000-ft (FL480) respectively, the payload economy curves are much straighter at high altitudes, showing that the *Aeris* can achieve very similar passenger economies during flight above 45000-ft (FL450). Looking at the September 8 passenger economy in figure 53, the curve looks more similar to that of the January passenger economy in figure 81.

Since the winds are stronger in September and January as compared to April and November, their jet-streams have a greater effect upon the passenger economy of the *Aeris*. Stronger winds lead to a stronger "attraction" towards the jet-stream core to the *Aeris*, which pulls it down further from its design altitude.

However, while the passenger economy perspective provides a view into how economic it is to carry people and their luggage, it is clear that some of the TOWs in the trade result in a larger payload capacity than is needed for a maximum passenger setting (this is clearly the case with the Airbus *A320*). Therefore, the overall payload economy of the *Aeris* has also been calculated to best determine the effect of winds upon aircraft performance on a pound-for-pound basis. The payload economy (fuel burn/kilopound-mile) of the *Aeris* for January 20, 2019, April 20, 2019, and November 20, 2018 are plotted in figure 84 to figure 86.

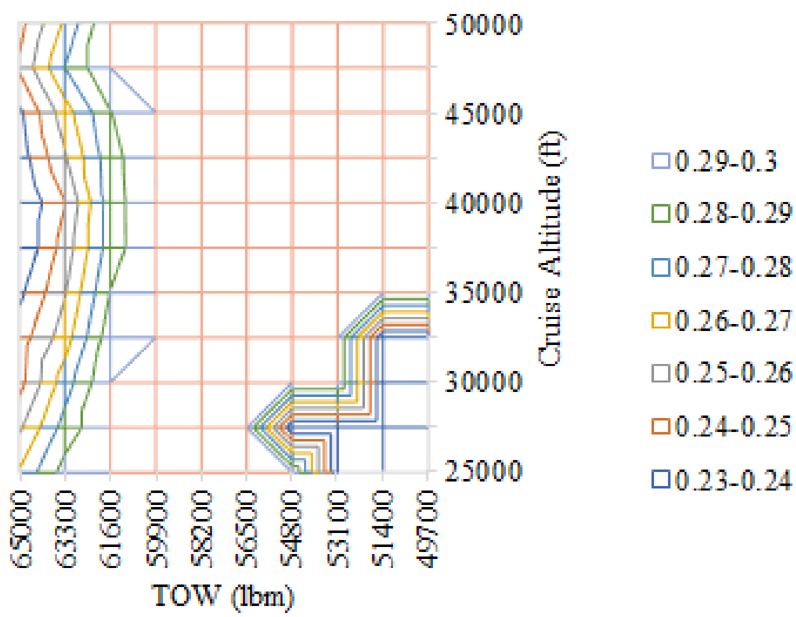


Figure 84: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 01/20/19

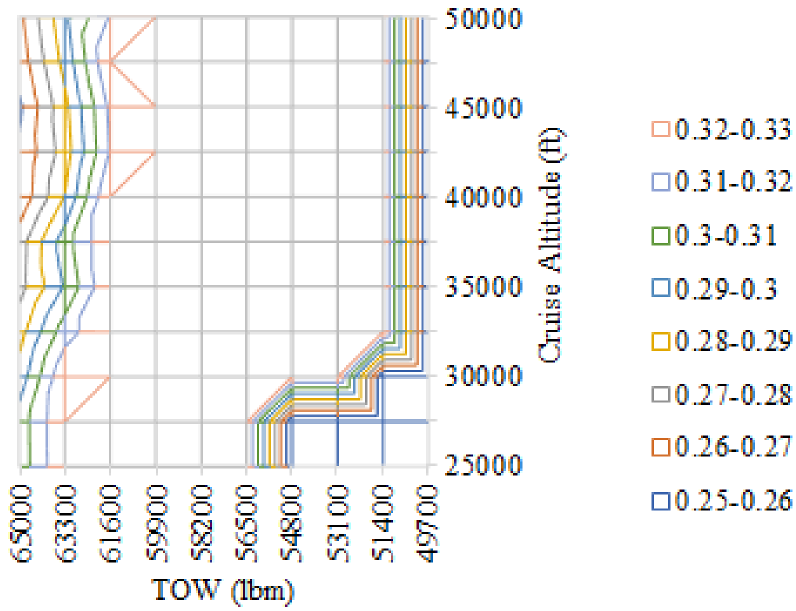


Figure 85: *Aeris* Fuel Burn/Kilopound-Mile for OAK to DVN on 04/20/19

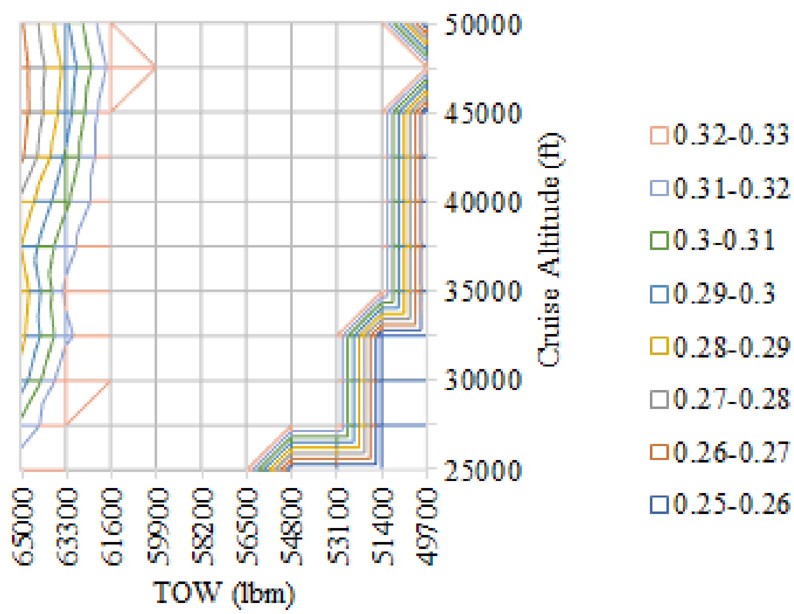


Figure 86: *Aeris* Fuel Burn/Kilopound-Mile e for OAK to DVN on 11/20/18

From the pure payload economy perspective, the trends that appeared in the passenger economy (figure 81 to figure 83) reappear. Since the *Aeris* is not passenger limited, the payload economy does not provide a particularly different vision of how the *Aeris* wants to be operated. It does confirm that the flight altitudes will radically change depending on the season.

More importantly, the payload economies of the *Aeris* were generated to compare against the Airbus *A320*. Looking at the payload economies of the Airbus *A320* in figure 75 to figure 77, the Airbus has more distortion in the optimal flight altitude based upon TOW than the *Aeris*. The *Aeris* seems to have a very flat structure at all TOWs; it prefers a single altitude depending on the day, whereas the Airbus *A320* drifts to lower altitudes at higher payloads.

For both the Airbus *A320* and the *Aeris*, there are clear benefits in optimizing cruise altitude for en-route winds. However, it seems that the *Aeris* has the most to lose from not optimizing its cruise altitudes, as its design cruise altitude is significantly higher than the jet-stream winds. Due to its design, it appears far more sensitive to the impact of winds, and thus has much more motion in terms of its flight conditions to maximize its usage of the en-route weather.

Looking at flight with the jet-stream leads naturally to the corollary of flight against the jet-stream. In flight with the jet-stream, both the *Aeris* and the Airbus *A320* are incentivized to fly closer to the maximum winds, although the *Aeris* is more impacted than the Airbus *A320*. However, flight against the jet-stream leads to an implicit design philosophy clash: is it better to fly below the jet-stream or above it when flying against the direction of the winds?

A320 Trades: DVN to OAK

When flying against the winds, it can be expected that both the Airbus *A320* and the *Aeris* have a net loss in terms of their mission economies. When flying with the winds, the aircraft to have the best economies when flying near the jet stream. However, when flying against the jet-stream the aircraft is incentivized to flight away from the jet-stream. This creates two possible options: flight above or flight below the jet-stream.

The Airbus *A320* cannot fly above the jet-stream. In theory, this limits its ability to maneuver around the jet-stream winds as it can only get away from the jet-stream by flying below it. However, lower-altitude flight comes with a cost in increasing skin-friction drag. Therefore, the *A320* must balance the impact of the winds against the impact of skin-friction losses.

To get a feel for where the Airbus *A320* wants to fly from a day-to-day perspective, same series of simulations were performed for the Airbus *A320* over the week of 09/08/19-09/12/19 as above. However, this time the flight direction was reversed so that the Airbus *A320* flies from Davenport to Oakland. For these trades, the fuel economy (credit SR) has been plotted in figure 87 to figure 91.

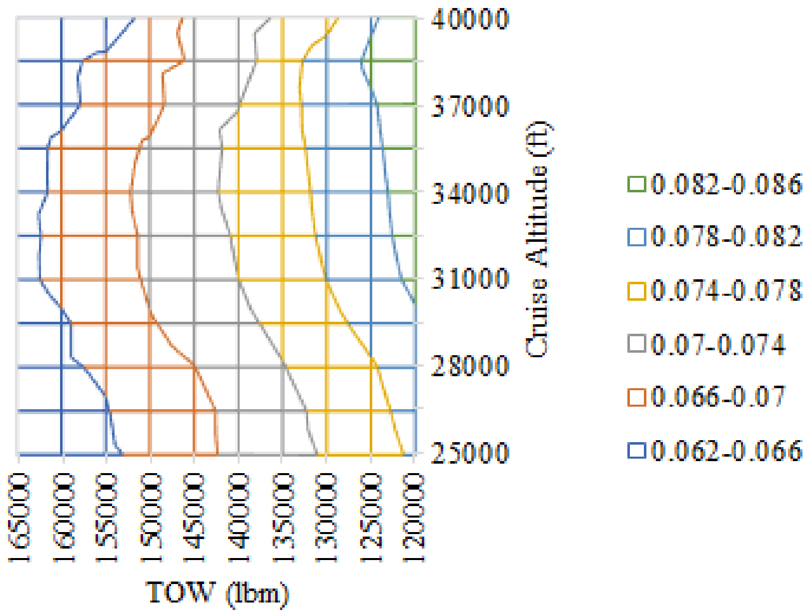


Figure 87: *A320* Credit SR for DVN to OAK on 09/08/19

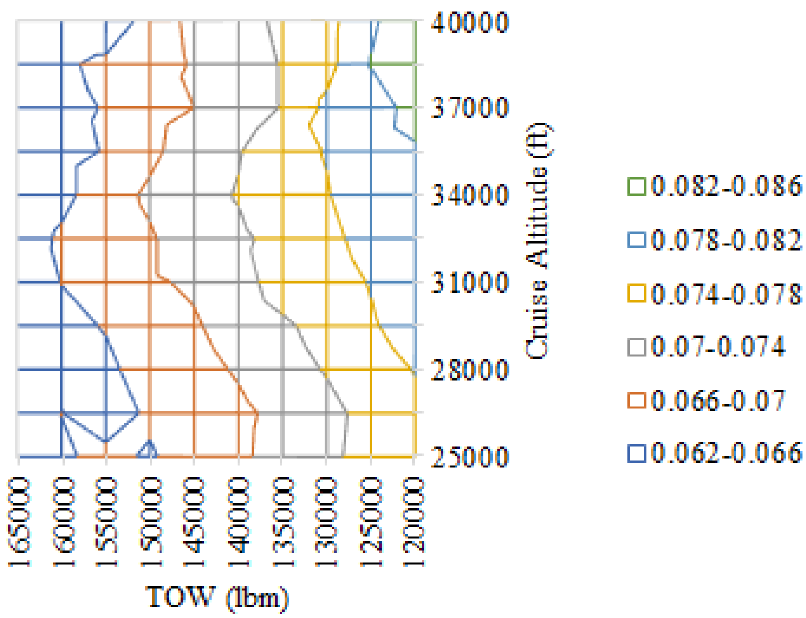


Figure 88: *A320* Credit SR for DVN to OAK on 09/09/19

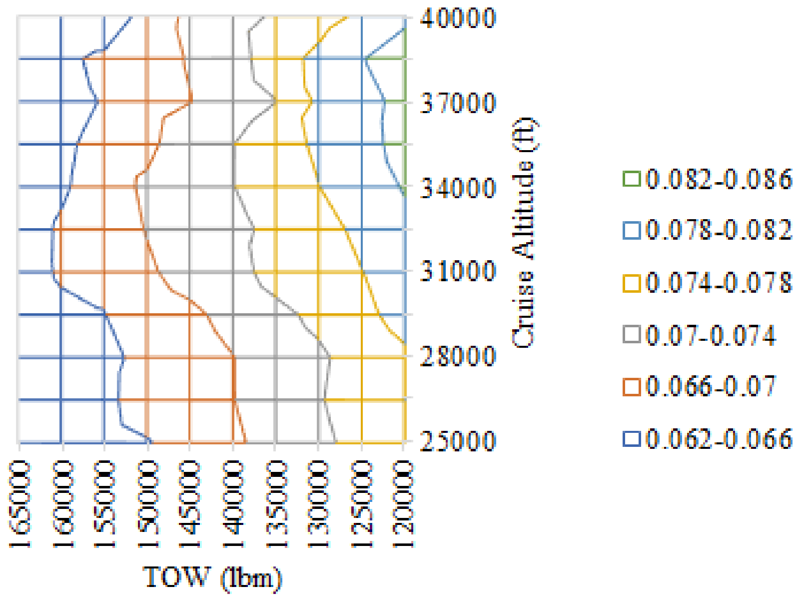


Figure 89: *A320* Credit SR for DVN to OAK on 09/10/19

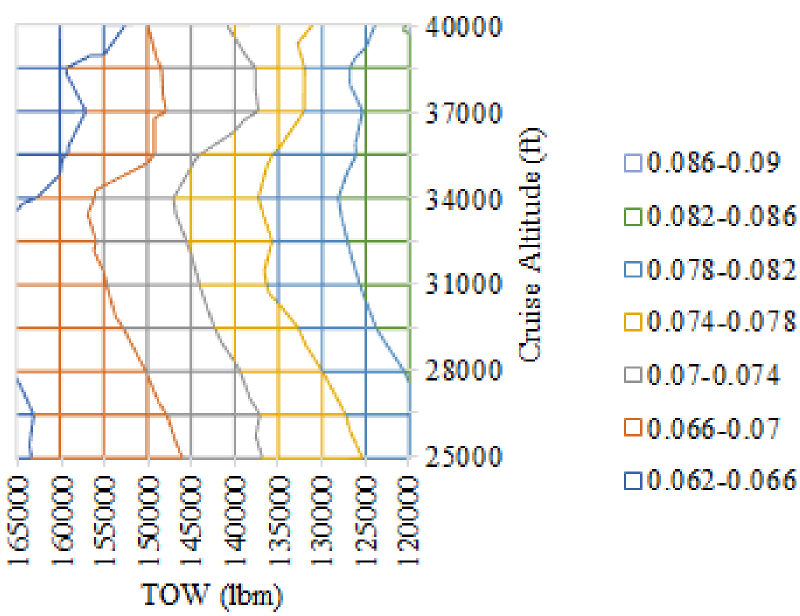


Figure 90: *A320* Credit SR for DVN to OAK on 09/11/19

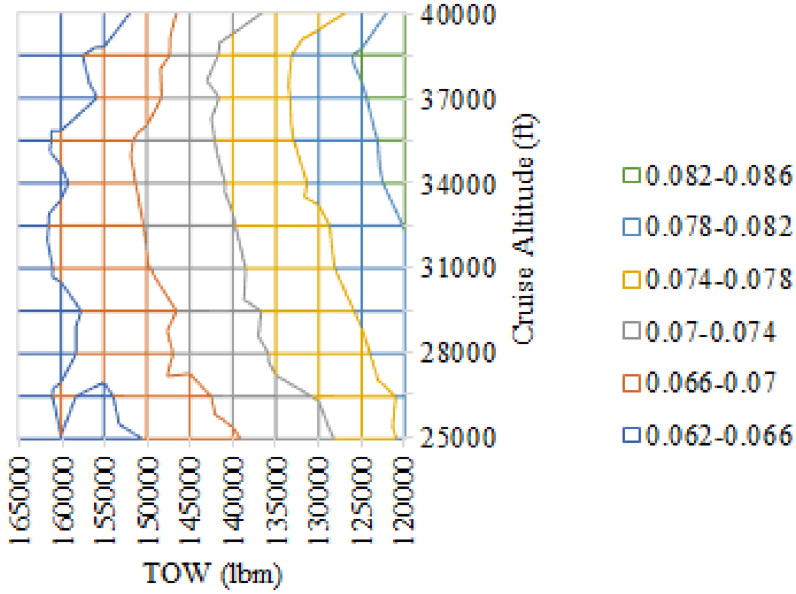


Figure 91: *A320* Credit SR for DVN to OAK on 09/12/19

From these plots, the impact of the winds is most present at higher altitudes and becomes less impactful at lower altitudes. On the 10th (figure 89) through the 12th (figure 91), the fuel economy contours curl back stronger as altitude increases. However, in some cases the contours straighten again at the highest altitude. This curling is likely caused by the interplay between skin-friction drag and winds.

In comparison to flight with the winds in figure 33 to figure 37, the best fuel economy at low weights correspond to lower altitudes when flying against the winds. September 11 (figure 90) appears to have the most extreme effect where the Airbus *A320* has an optimal fuel economy at 34000-ft (FL340) its lowest TOW. This is a 4000-ft difference from the with-winds flights, where the optimal altitude at low TOWs was found at around 38000-ft (FL380).

The shapes of the fuel economy curves are also distinctly different as compared to the Airbus *A320* baseline fuel economy curve in figure 21. Through flight against the winds, there is a lot of variance both in the shapes of the curves as well as in the gradient of the fuel economy with altitude and TOW. From a qualitative view, it appears that flight against the winds is more variable than flight with the winds.

In order to properly determine the mission economy of the Airbus *A320*, the passenger and payload economy of the aircraft when flying against the winds must also be determined. The passenger economy (fuel burn/seat-mile) of the Airbus *A320* has been graphed and can be seen in figure 92 to figure 96. Note that in these figures, the largest shown TOW corresponds to a max-filtered passenger count, and therefore implicitly carries some extra non-economic cargo. This was kept on the graphs to better show the shape and location formed by the optimal passenger economy.

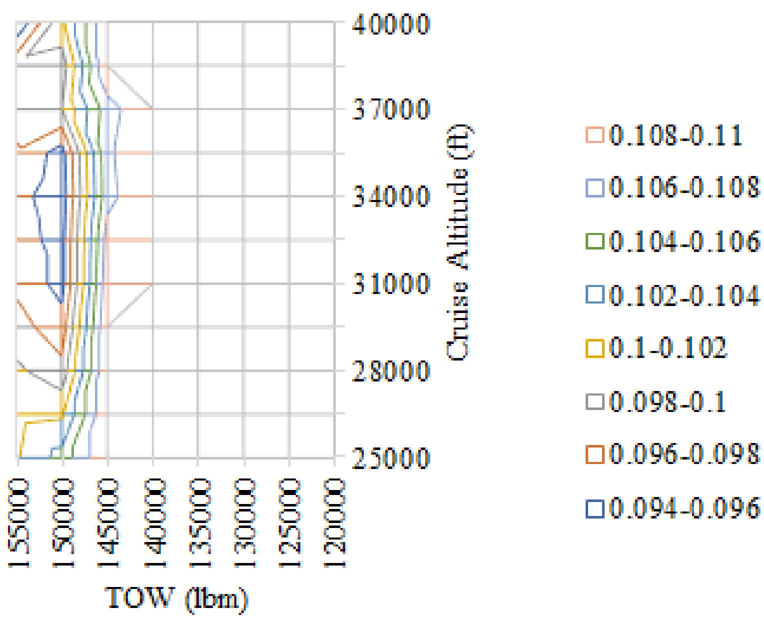


Figure 92: *A320* Fuel Burn/Seat-Mile for DVN to OAK on 09/08/19

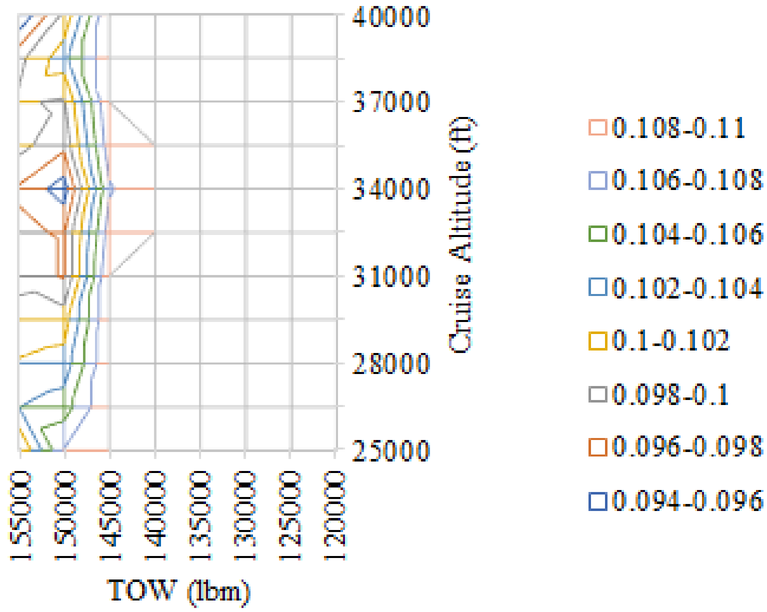


Figure 93: *A320* Fuel Burn/Seat-Mile for DVN to OAK on 09/09/19

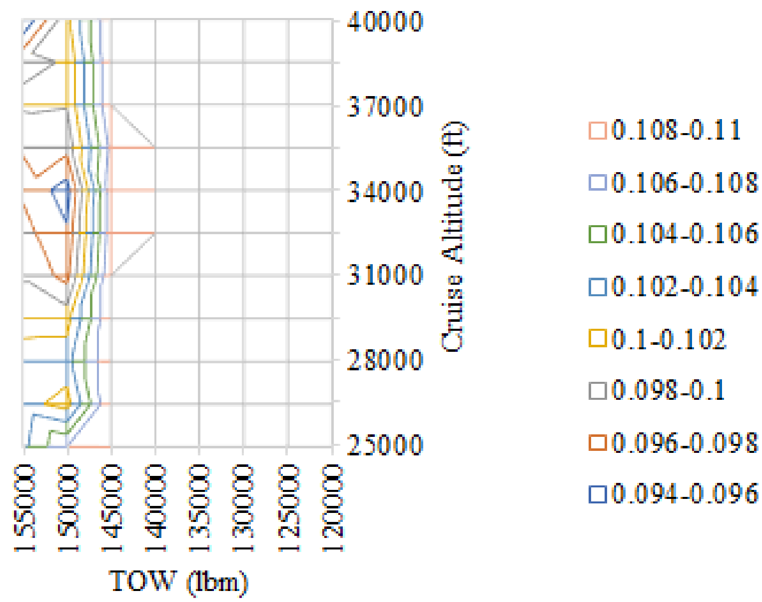


Figure 94: *A320* Fuel Burn/Seat-Mile for DVN to OAK on 09/10/19

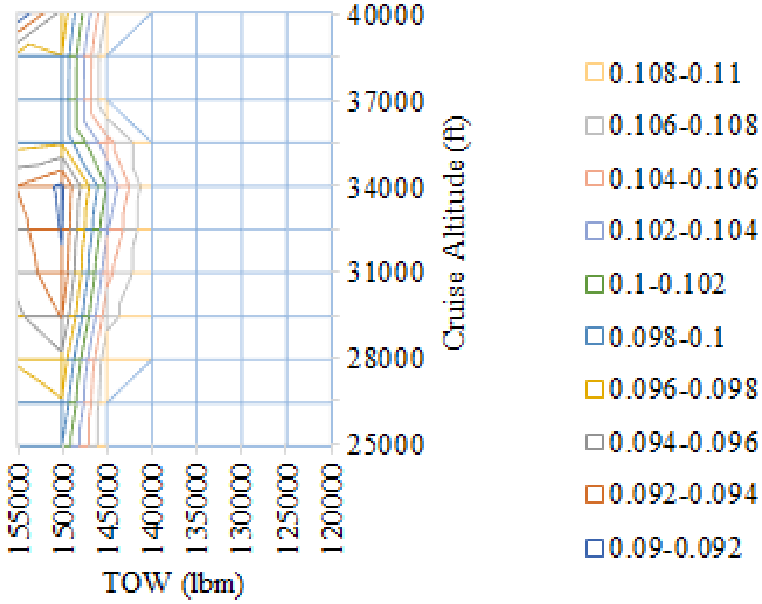


Figure 95: *A320* Fuel Burn/Seat-Mile for DVN to OAK on 09/11/19

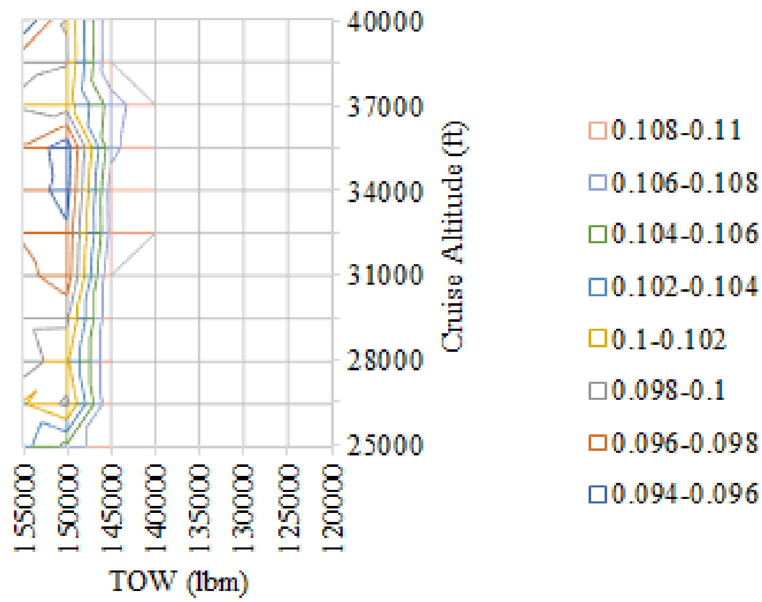


Figure 96: *A320* Fuel Burn/Seat-Mile for DVN to OAK on 09/12/19

From the passenger economy perspective, the optimal cruise altitude when passenger limited occurs at 34000-ft (FL340) for the studied week. However, when comparing the shapes of the passenger economy contours to those when flying with the winds, an inversion of the shapes appears. When flying with the winds, although the Airbus *A320* obtained optimal economy at 34000-ft (FL340), the aircraft had a wider range of good passenger economy above 34000-ft (FL340) than below. However, the favorable range is shifted downwards below 34000-ft (FL340) when flying against the winds.

There is also some variability in the location of the optimal passenger economy altitude. Although almost all plots show the best at 34000-ft (FL340), on September 12 the range actually centers around 35000-ft (FL350). Although the winds in general are found at higher speeds at higher altitudes, it seems once again that a day-to-day view of winds can show nuances that might counter our expectations.

The payload economy will likely follow a similar pattern to the passenger economy. The full payload economy (fuel burn/kilopound-mile) of the Airbus *A320* has been plotted in figure 97 to figure 101.

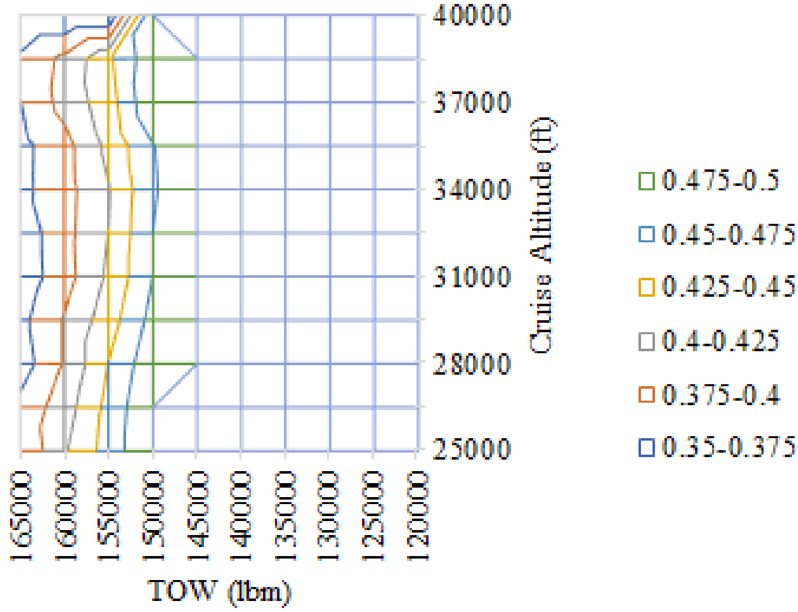


Figure 97: *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/08/19

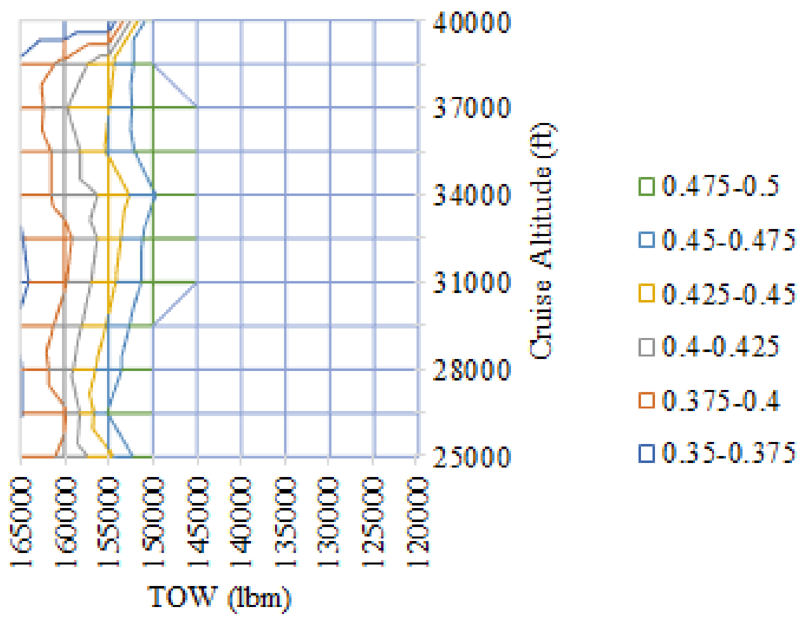


Figure 98: *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/09/19

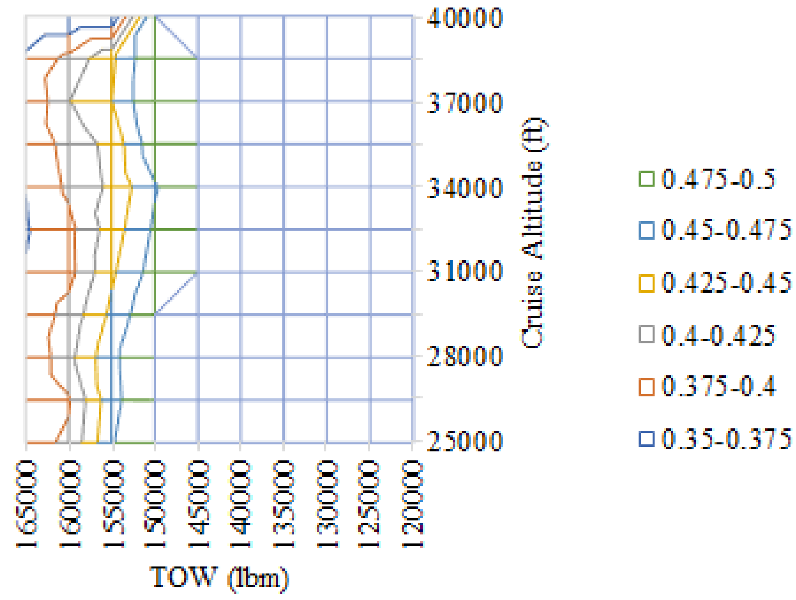


Figure 99: *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/10/19

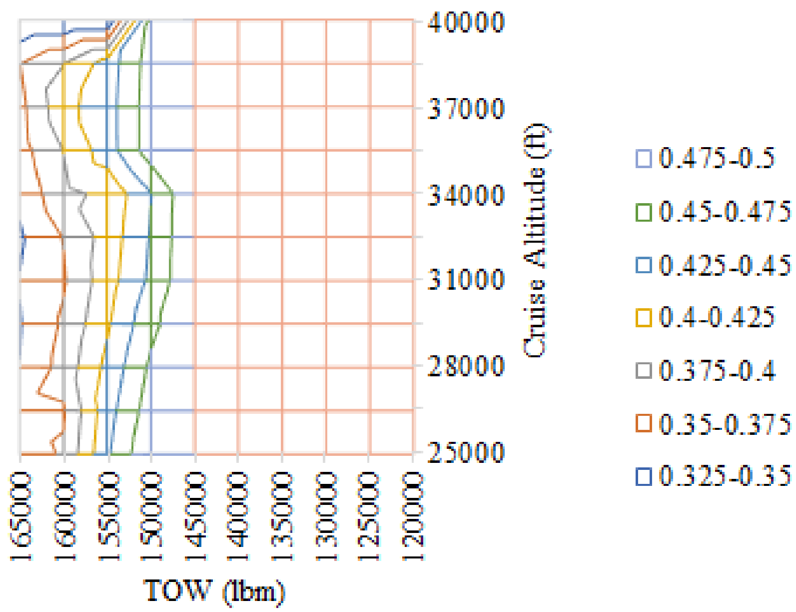


Figure 100: *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/11/19

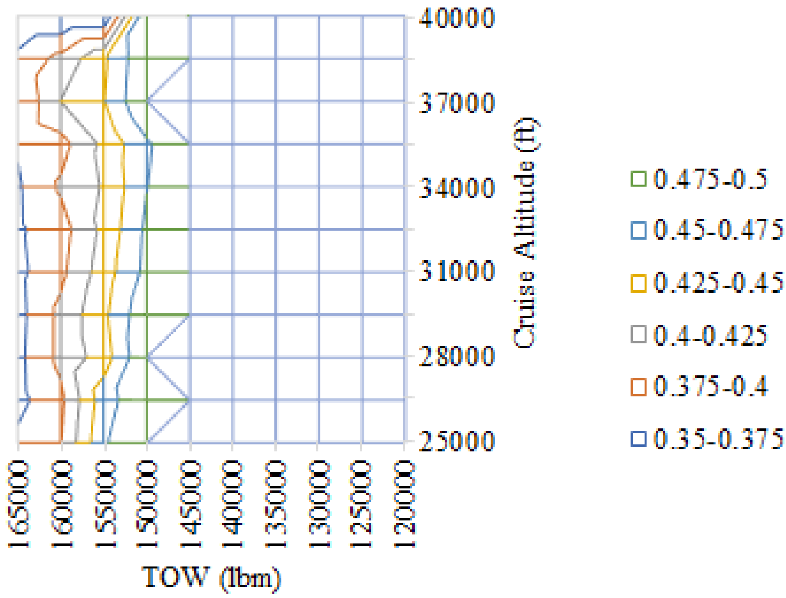


Figure 101: *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/12/19

From the payload economy plots, an optimal payload economy is reached at maximum TOW with flight altitudes of ~32000-ft (FL320). There is some variance between the days, however the impact of the winds seems severely muted (again due to the lower flight altitude of the *A320*). In comparison, flight with the winds has an optimal altitude of ~33000-ft (FL330). Thus, it appears that the impact of the winds only causes a variation of 1000-ft on a daily basis for the Airbus *A320*. From this initial perspective on winds, it appears that the design of the Airbus *A320* has made it inherently resistant to changes in optimal flight conditions based upon winds, because it's drag penalties at flight above and below this altitude both follow rapid expansion that overwhelms the effects of the winds.

The variability of the winds shows up as variance in terms of the shapes of the payload economy contours. From a day-to-day basis, the gradient in terms of altitude and TOW changes quite heavily, where some days the aircraft has a wide range of altitudes corresponding to similar economy, while others it has a narrow region. September 12 (figure 101) shows a reduction in sensitivity to winds as compared to the 10th and 11th (figure 99 and figure 100). On some days, a small switchback also appears at much lower altitudes, and the contours are very rough. For the Airbus *A320*, flight against the winds appears to show up as a large amount of "noise" within the graphs that blur our understanding of its performance from its baseline.

Aeris Trades: DVN to OAK

The *Aeris* poses a very different situation when flying against the winds as compared to the Airbus *A320*. Since the *Aeris* is capable and designed to fly at 50000-ft (FL500), the impact of flight for flying above the jet-stream can be determined, as opposed to the Airbus *A320* which is limited to flight below the jet-stream.

To see exactly how the *Aeris* compares to the Airbus *A320* when flying against the winds, the same against-winds missions were performed for the *Aeris*. Through the weekly lens, a sense of how the *Aeris* changes in terms of its flight economy on a day-to-day basis is obtained. To that end, the fuel economy (credit SR) of the *Aeris* has been plotted to see its changes from 09/08/19 to 09/12/19. These can be seen in figure 102 to figure 106.

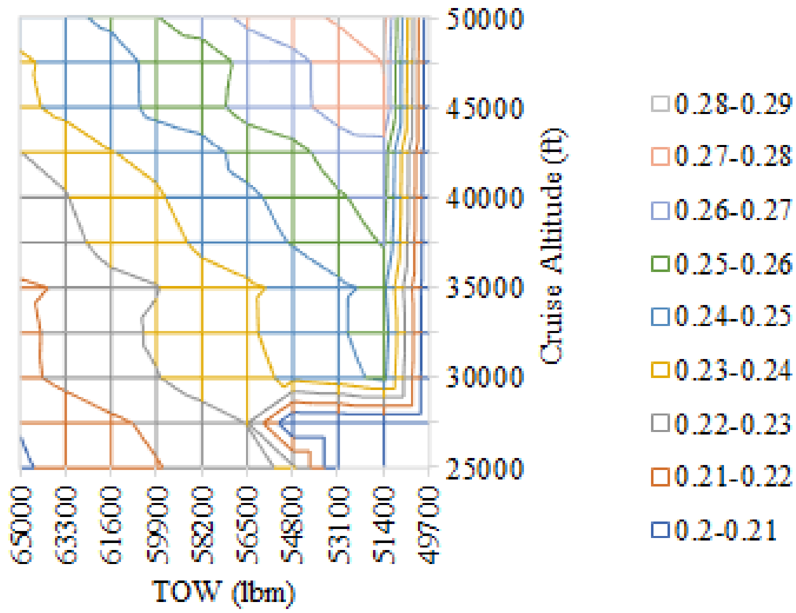


Figure 102: *Aeris* Credit SR for DVN to OAK on 09/08/19

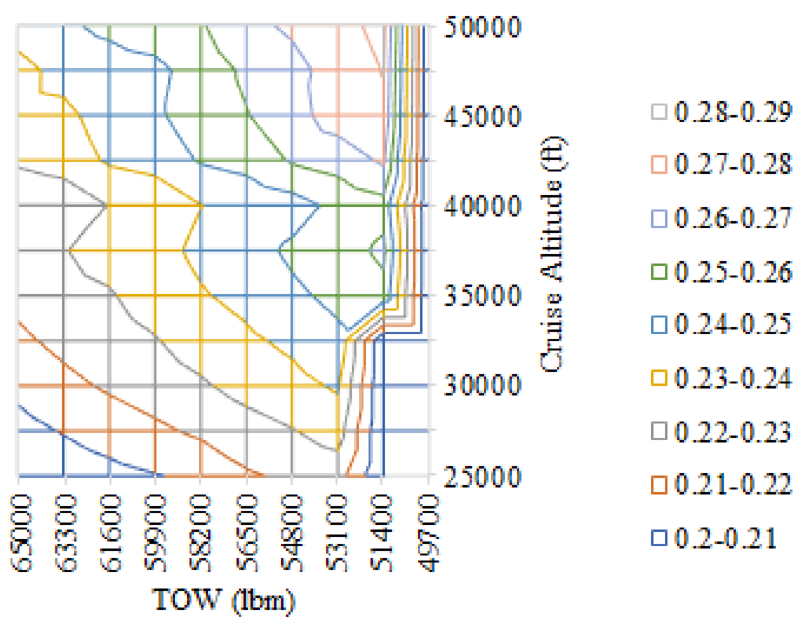


Figure 103: *Aeris* Credit SR for DVN to OAK on 09/09/19

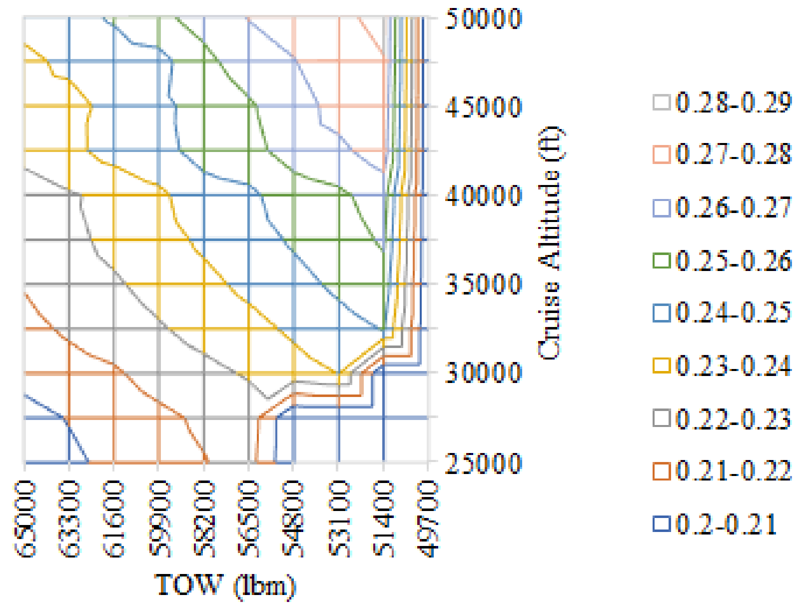


Figure 104: *Aeris* Credit SR for DVN to OAK on 09/10/19

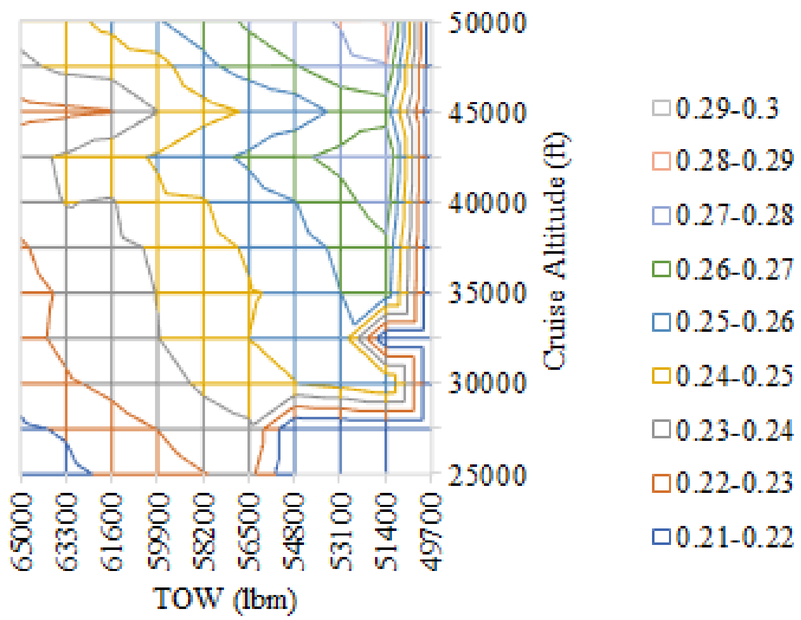


Figure 105: *Aeris* Credit SR for DVN to OAK on 09/11/19

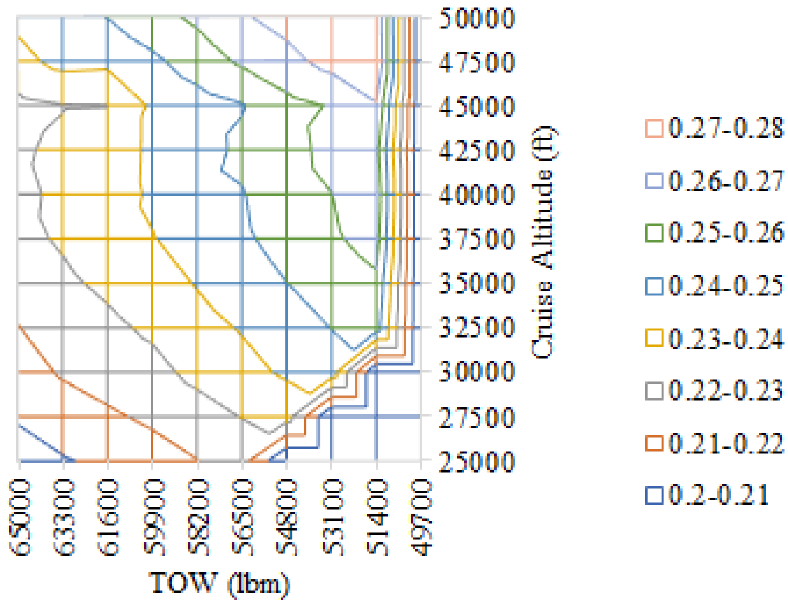


Figure 106: *Aeris* Credit SR for DVN to OAK on 09/12/19

From the fuel economy charts, major differences are found between how the *Aeris* is impacted by winds as compared to the Airbus *A320*. At lower altitudes, the fuel economy curves tend to follow a similar trend as to the *Aeris*'s standard day fuel economy curves in figure 24. However, as the altitudes approach those of the jet-stream, the curves start to curl back, giving a local maximum just underneath the winds. The fuel economy improves once again with altitude once past the core of the jet-stream, finally providing the best fuel economy at the highest altitude of 50000-ft.

The location of the switch-back seems to change heavily on a day-to-day basis. On September 8th the switchback occurs at ~35000-ft (FL350). The 9th and 10th show a switchback at 40000-ft (FL400), while the 11th and 12th show a switchback at 45000-ft (FL450). Looking at the winds charts in figure 27 to figure 32, this switchback follows the drift of the winds, where early in the week high winds were found at lower altitudes, but later in the week the high winds were found at higher altitudes.

Comparing the figures to the baseline in figure 24, the contours are also seen to be highly distorted for flight above 40000-ft (FL400). In the baseline, the contours straighten out at ~45000-ft (FL450). However, flight against the winds causes the contours at the jet-stream to curl back on themselves, leading to the switchbacks. This results in a very strong fuel economy relationship with altitude once the *Aeris* climbs above the switchback, which is in direct contrast to the baseline where the altitude relationship becomes less strong above 45000-ft (FL450).

From all the days tested, the *Aeris* can still power above the winds of the jet-stream, which hints that its best cruise altitude for mission economy is likely at 50000-ft (FL500) when flying against the winds. To prove this, the passenger economy (fuel burn/seat-mile) of the *Aeris* has been plotted in figure 107 to figure 111.

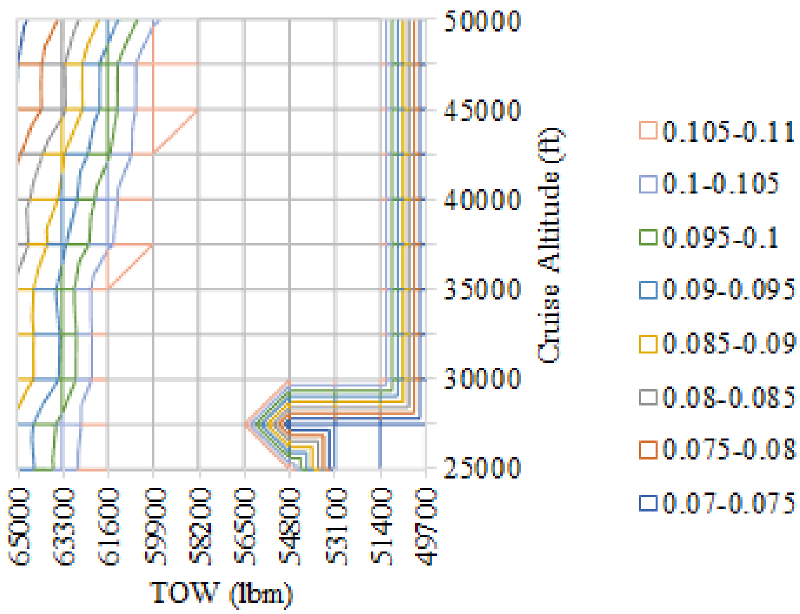


Figure 107: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on

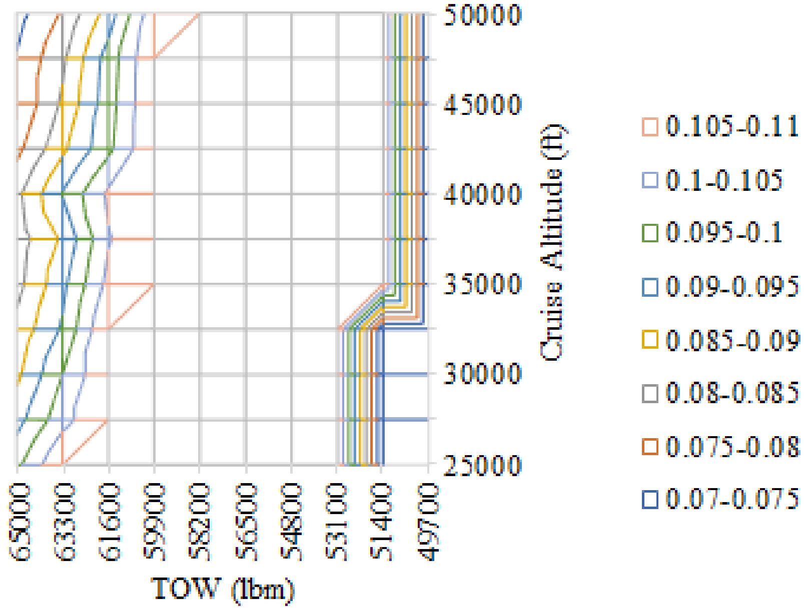


Figure 108: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on

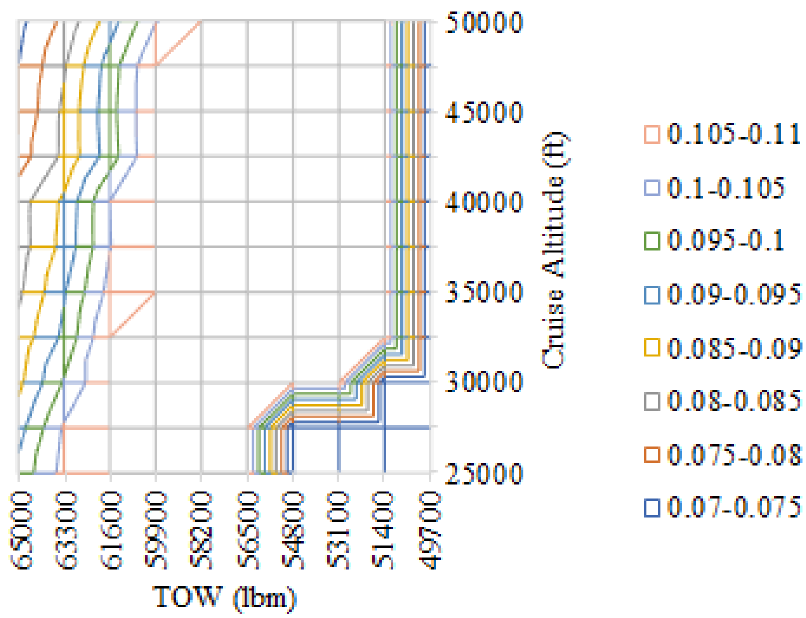


Figure 109: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 09/10/19

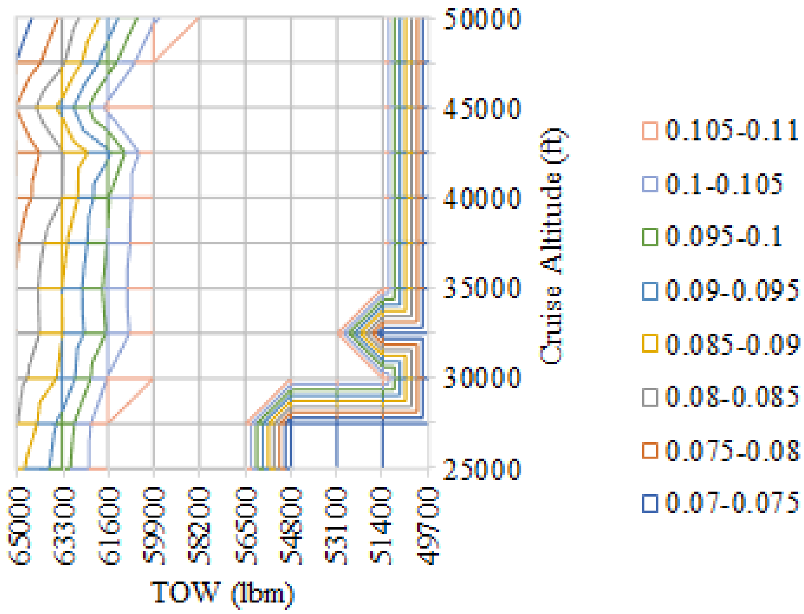


Figure 110: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 09/11/19

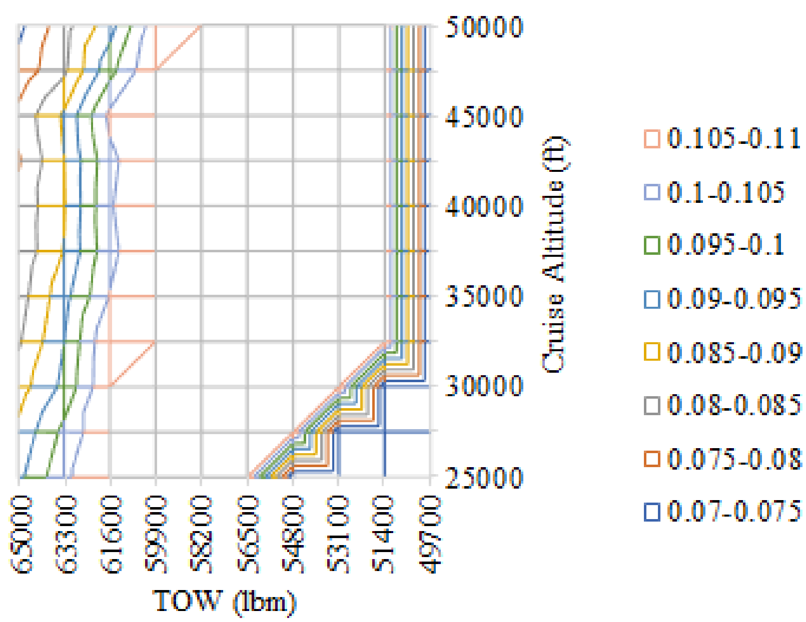


Figure 111: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 09/12/19

As expected, the optimal passenger economy (fuel burn/seat-mile) is found at a maximum TOW and at the maximum cruise altitude. However, the passenger economy curves are far more sensitive to changes in passengers than to changes in altitude even when flying against the jet-stream. The impact of the jet-stream can be noticeable when the winds are at higher altitudes though, as the *Aeris* develops a noticeable switchback occurring on the 11th and the 12th at 45000-ft (FL450). The *Aeris* is more sensitive to the impact of winds the higher the winds are located.

In comparison to the *Aeris*'s baseline passenger economy in figure 25, the economy-altitude relationship is much stronger at higher altitudes with flight against the wind. This means that the *Aeris* becomes especially sensitive to altitude changes in its cruise when flying against the winds than if there were no winds. This feedback from the winds poses a strong operational incentive to prevent reducing altitude in cruise as much as possible when flying into strong headwinds.

To understand the overall payload economy (fuel burn/kilopound-mile) of the *Aeris* when flying against the winds, it has been plotted in figure 112 to figure 116.

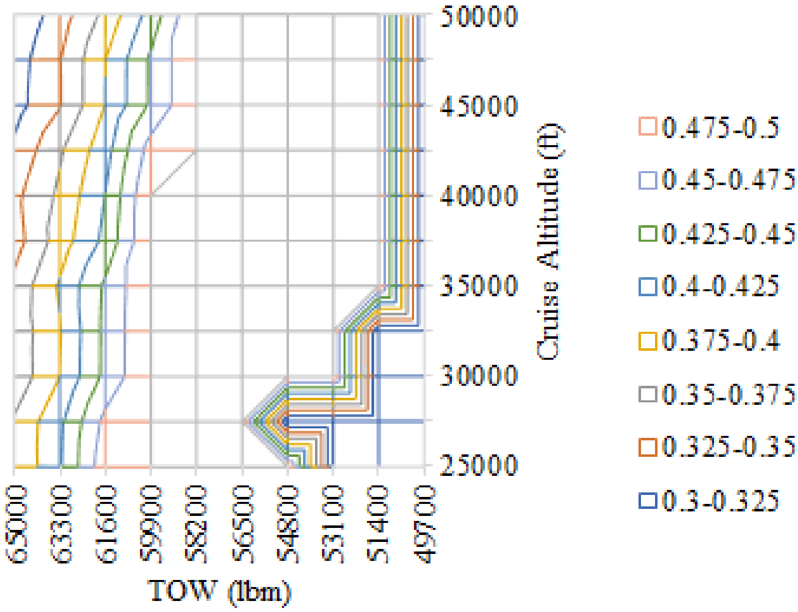


Figure 112: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/08/19

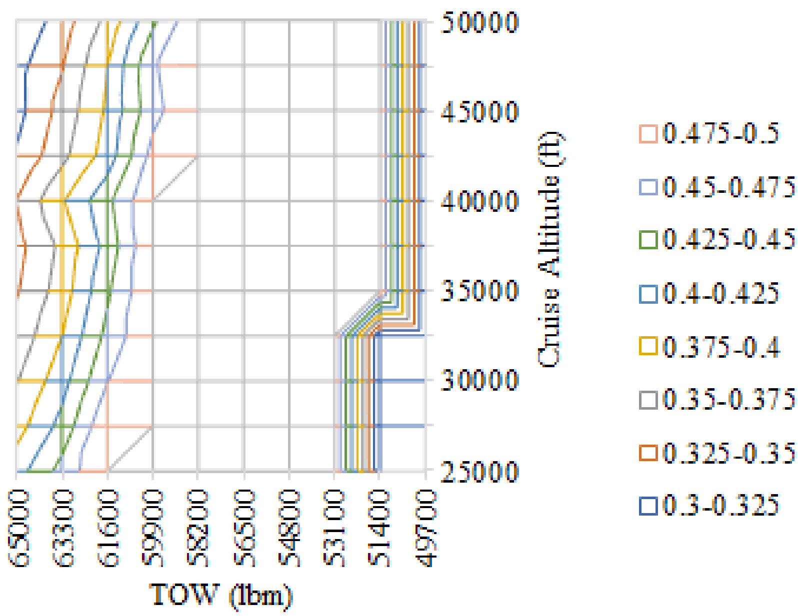


Figure 113: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/09/19

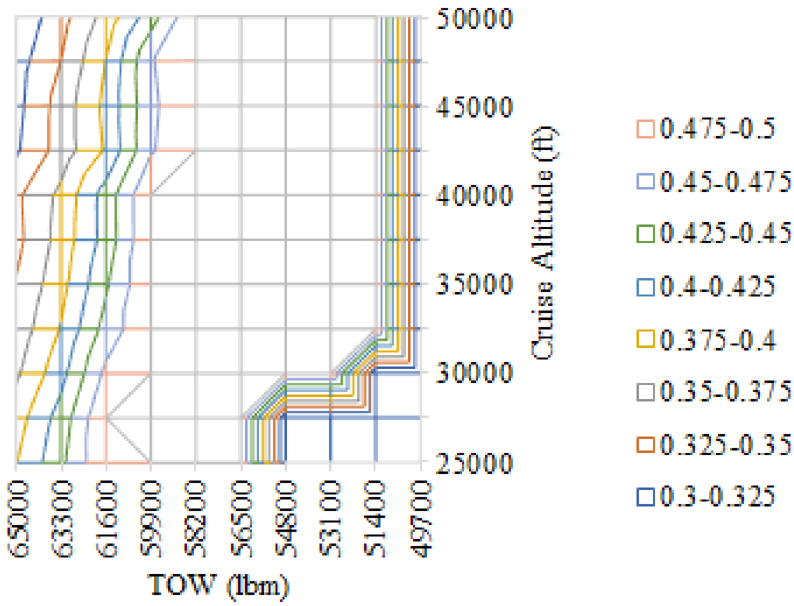


Figure 114: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/10/19

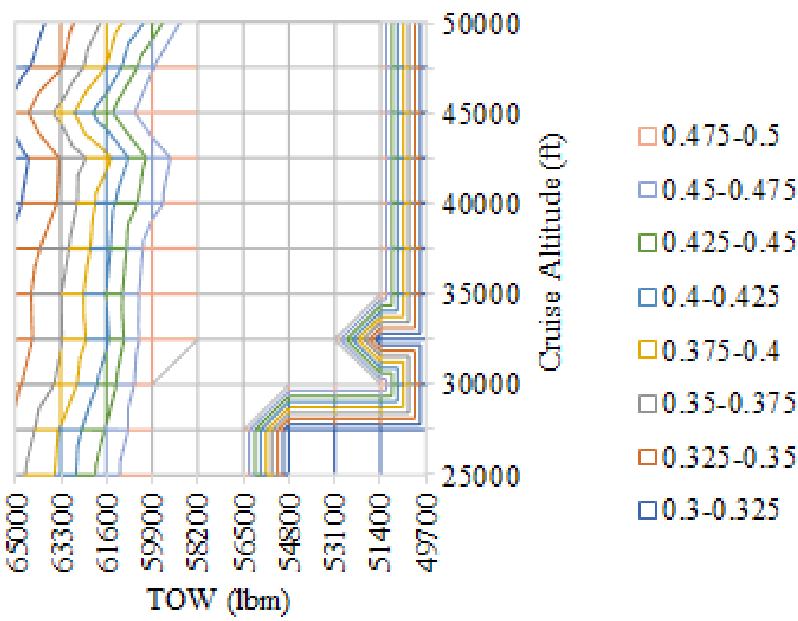


Figure 115: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/11/19

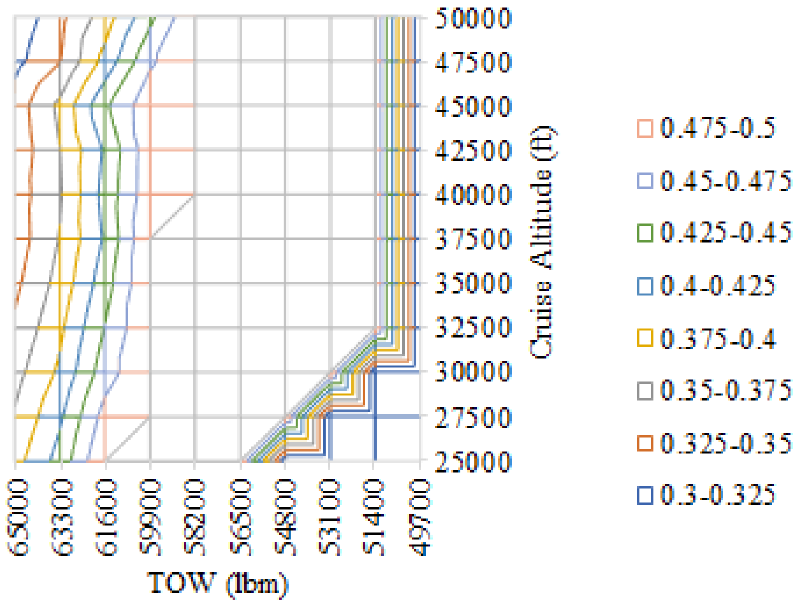


Figure 116: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 09/12/19

The payload economy of the *Aeris* shows the same trends as the passenger economy. The optimal payload economy of the *Aeris* is found at maximum cruise altitude and TOW and the curves are more sensitive to payload differences than altitude differences, although the payload economy is more sensitive to winds at high altitudes above 45000-ft (FL450) than normal. The impact of the winds at higher altitudes can especially be seen in figure 115 and figure 116.

Contrary to the Airbus *A320*, it appears that the *Aeris* does not want to fly below the winds for optimal payload economy. The only time that flight below the maximum winds seems comparable in payload economy is on September 11th, and that is when the winds are found at ~45000-ft. The presence of switchbacks does indicate strongly that close attention needs to be payed to the operational planning of the *Aeris* to ensure the aircraft spends as little time in those areas as possible.

A320 Seasonal Trades: DVN to OAK

The effects of changing atmospheric conditions on a day-to-day basis upon the mission economy for both the *Aeris* and the *A320* have been documented. This leads to questions about seasonal effects on the economy for both aircraft. For this, the same series of seasonal trades were performed as with flight with winds, except this time on the return route.

For the Airbus *A320* in flight with the winds, significant positive impact is seen in January, and less impact in April and November. In the new trades, the impact of the winds is negative rather than positive. In figure 117 to figure 119, the fuel economy (credit SR) of the Airbus *A320* in flight against the winds on January 20, 2019, April 20, 2019 and November 20, 2018 is shown.

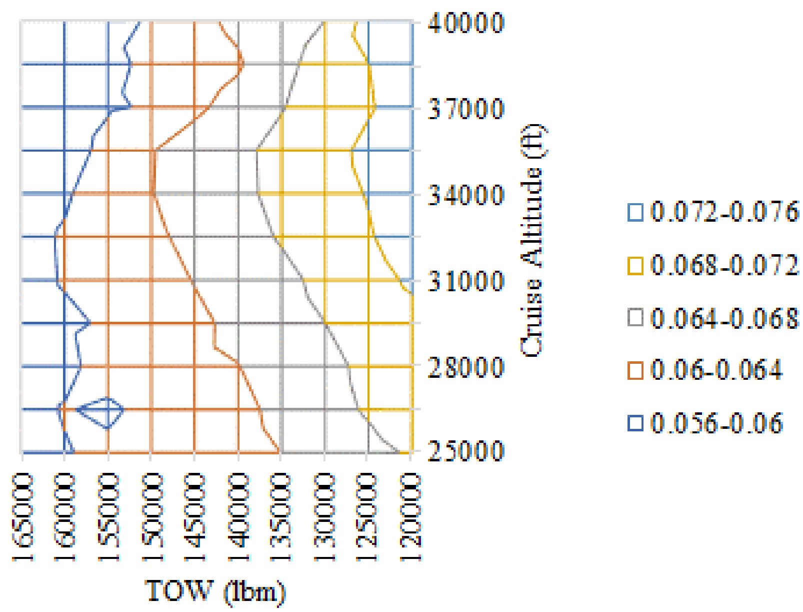


Figure 117: Airbus *A320* Credit SR for DVN to OAK on 01/20/19

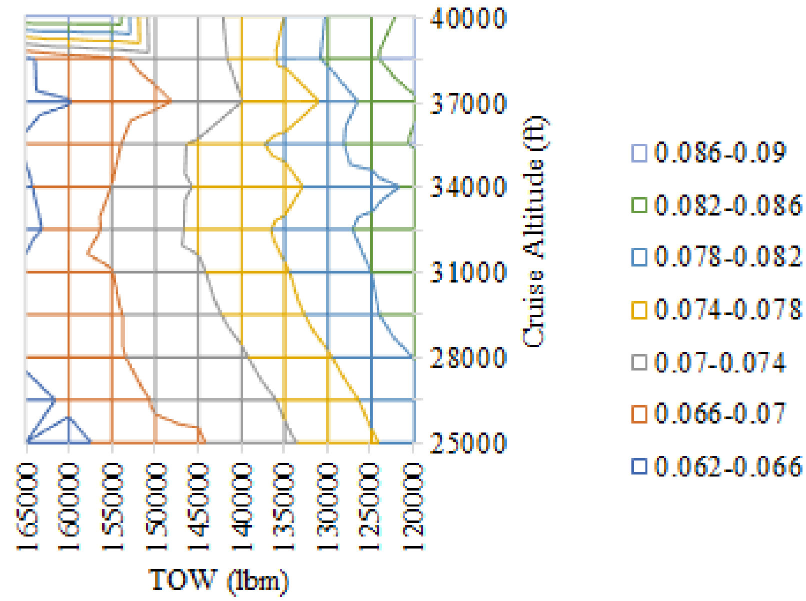


Figure 118: Airbus *A320* Credit SR for DVN to OAK on 04/20/19

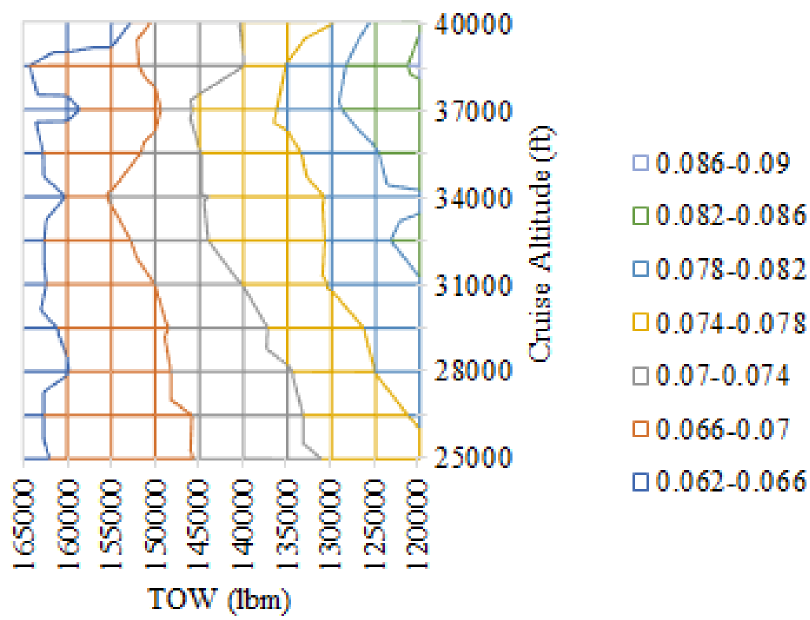


Figure 119: Airbus *A320* Credit SR for DVN to OAK on 11/20/18

The fuel economy plots of the Airbus *A320* are far less uniform than in its baseline in figure 21. In January, the overall fuel economy is far worse as compared to its standard day fuel economy. However, the curves are much wider than the standard day and even the other days in this trade. In April and November, the curves are also very jagged in shape. Despite the overall winds being less strong during these months, they appear to add more variability to the economy of the flights, and thus add a lot of noise to the contours of the graphs. In some sense, this means that it may be more important to closely watch the winds in these months as it is more difficult to predict exactly where the optimal altitude might be for fuel economy.

In April and November, switchbacks also occur at lighter TOWs at around 34000-ft (FL340). This effect seems to be dampened with increasing TOW, which suggests that the increased induced drag at that altitude begins to dominate the fuel economy decrease over the winds at a TOW of ~140000-lbm. The best fuel economy altitude also drops heavily as the TOW increases.

The effect of the winds on the passenger economy (fuel burn/seat-mile) can be seen in figure 120 to figure 122. Once again, the graphs were limited to the TOW that yielded the max passengers. However, like above, these TOWs often implicitly included non-economic cargo and thus have an “artificially” smaller passenger economy. They were left in to better show the optimal passenger economy location.

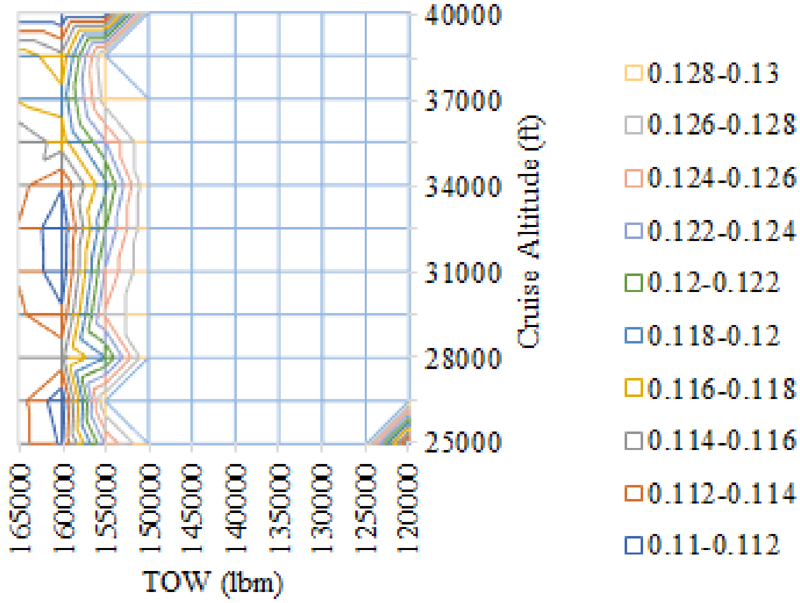


Figure 120: Airbus *A320* Fuel Burn/Seat-Mile for DVN to OAK on 01/20/19

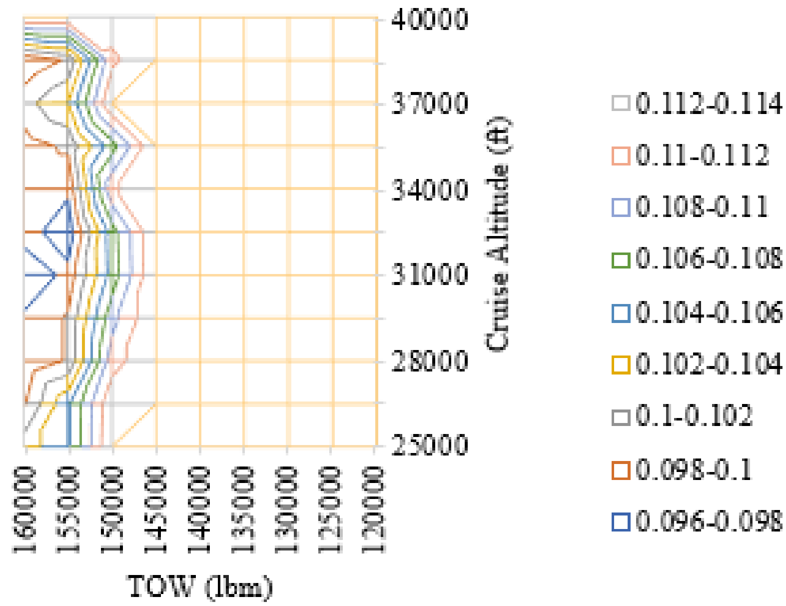


Figure 121: Airbus *A320* Fuel Burn/Seat-Mile for DVN to OAK on 04/20/19

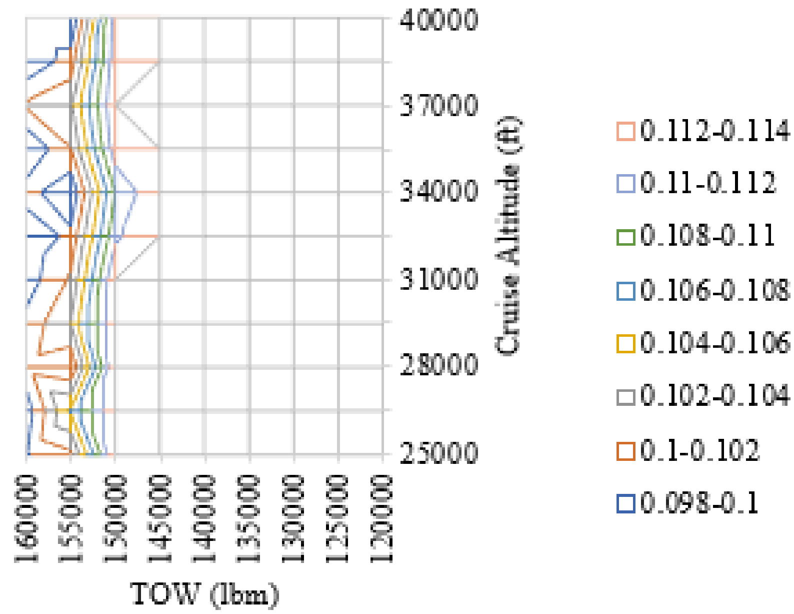


Figure 122: Airbus *A320* Fuel Burn/Seat-Mile for DVN to OAK on 11/20/18

From the passenger economy plots, the optimal flight altitude in January can be seen to be very low at ~32000-ft (FL320). In April, two peaks of similar economy with two different target sets of TOWs and flight altitudes are found. November shows the most variation in terms of the flight altitudes, with altitudes ranging from 26000-ft (FL260) to 36000-ft (FL360) having similar levels of passenger economy. As seen in the fuel economy graphs, April and November show the most noise within their contours. Although the overall impact of the winds is smaller in these months, the variance within the performance tradespace increases.

The full payload economy (fuel burn/kilopound-mile) of the Airbus *A320* has been plotted in figure 123 to figure 125.

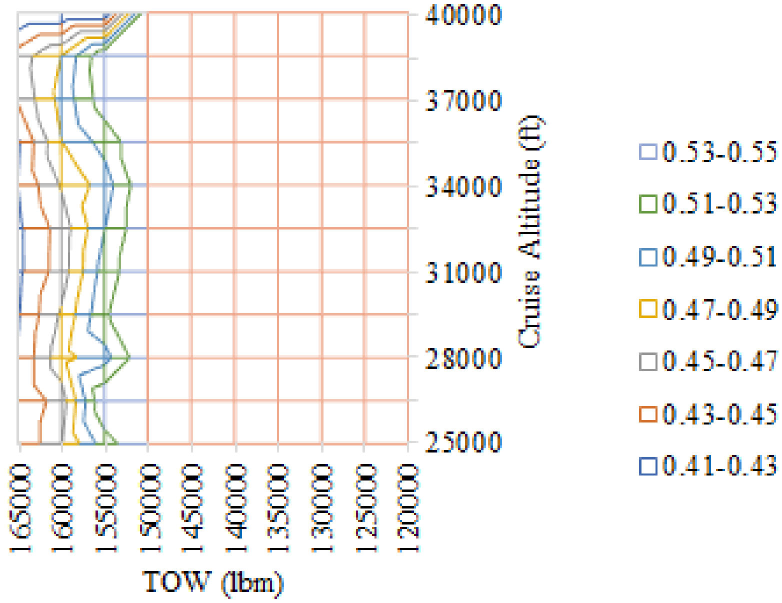


Figure 123: Airbus *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 01/20/19

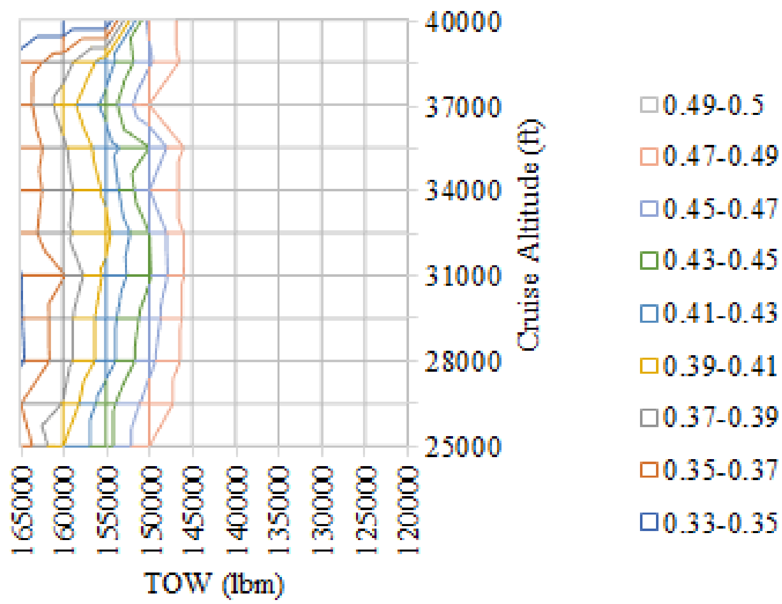


Figure 124: Airbus *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 04/20/19

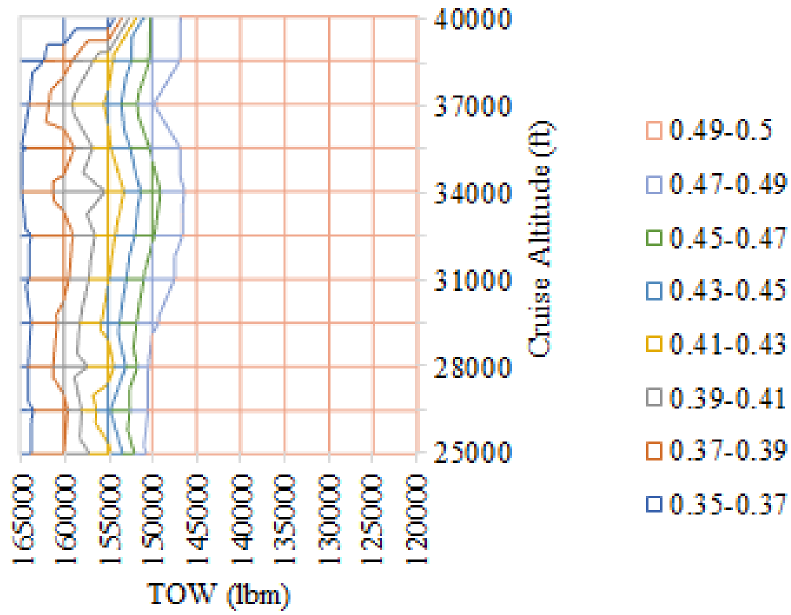


Figure 125: Airbus *A320* Fuel Burn/Kilopound-Mile for DVN to OAK on 11/20/18

It appears that the multiple peaks found in the passenger economy plots are not found in the payload economy plots. Instead, the payload economy plots tend to favor flight at lower altitudes. In January, the optimal altitude is found at ~29000-ft (FL290). In April, the optimal altitude is found around 31000-ft (FL310), and in November the optimal altitude is at 32000-ft (FL320). The payload economy plots also seem to be far less sensitive to changes in altitude than to changes in payload, with similar payload economies spanning a wide range of altitudes at high TOWs. As the TOW decreases, more variation in terms of the altitude impact appears, but the direct impact of the winds is still highly muted.

The noise seen in the fuel economy and the passenger economy graphs appear to show up again in the payload economy graphs as well in the form of added “jaggedness”.

Although it is clearer where the optimum flight altitude is located, flight performance on the boundary of these curves becomes hard to predict. Considering the large variability within the tradespace, it presents a strong argument that careful attention to daily winds will allow operators to better predict where they should fly and where they should avoid.

Aeris Seasonal Trades: DVN to OAK

From a seasonal perspective, it appears that there is significant variation in terms of the mission economy curves for the Airbus *A320*, but less so in terms of where the optimal mission can be found. The primary difference for the Airbus *A320* is that it wants to fly at lower altitudes when flying against the winds. In contrast, for the daily missions, the *Aeris* wants to fly as high in altitude as possible.

To confirm the tendency of the *Aeris* to fly at high altitude against the winds, the same seasonal trade was performed for the *Aeris* as above for the Airbus *A320*. The fuel economy (credit SR) of the *Aeris* can be seen in figure 126 to figure 128.

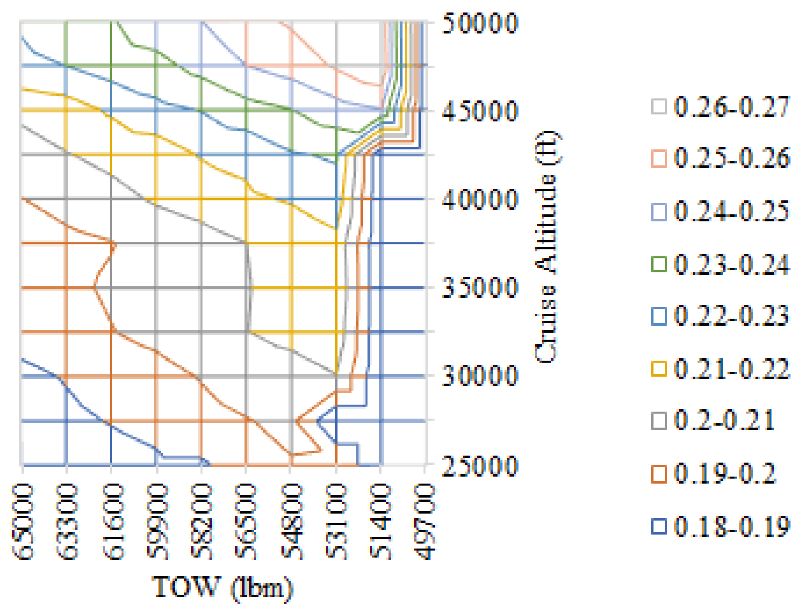


Figure 126: *Aeris* Credit SR for DVN to OAK on 01/20/19

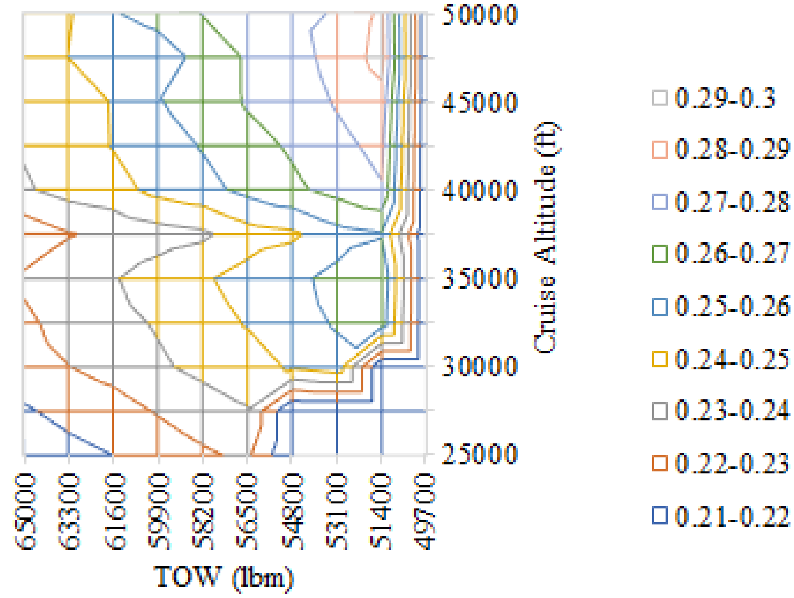


Figure 127: *Aeris* Credit SR for DVN to OAK on 04/20/19

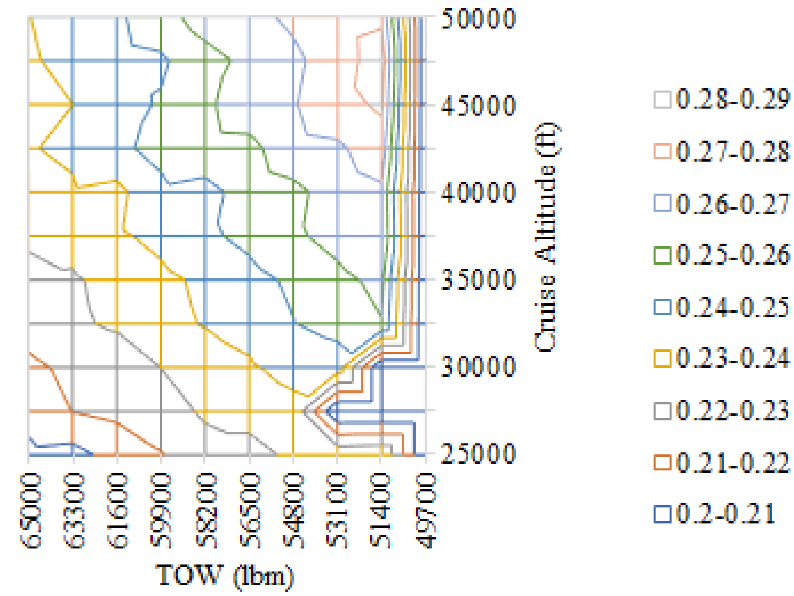


Figure 128: *Aeris* Credit SR for DVN to OAK on 11/20/18

From the fuel economy plots, the effect of the winds creates bumpy distortions and occasional switchbacks like those seen in the daily trades. The shape of the fuel economy curves in January also differ compared to April and November. The curves in January are far more sensitive to changes in altitude than in the other tested days.

Looking at the winds in January, it is not hard to see why, as a peak wind of more than 100-kts occurs at altitudes of 45000-ft (FL45). Below the jet-stream, altitude becomes far less significant in terms of fuel economy change. Overall though, the *Aeris* still has the best fuel economy at its cruise ceiling of 50000-ft (FL500).

April and November show a distinct amount of variation as well. However, while April (figure 127) has a very strong switchback at 38000-ft (FL380), no switchback is seen in November (figure 128). Instead, November shows much more variability in the contour lines themselves, where the edges of the contour lines are extremely jagged. Just as in the Airbus *A320*, November especially has a significant amount of added variability to the overall tradespace. This hints to a nature of the winds as being very difficult to predict, and once again brings evidence that aircraft operators have a strong incentive to use daily winds to predict their aircrafts' performance.

The passenger economy (fuel burn/seat-mile) of the *Aeris* for flight against the winds on the seasonal days has also been plotted in figure 129 to figure 131.

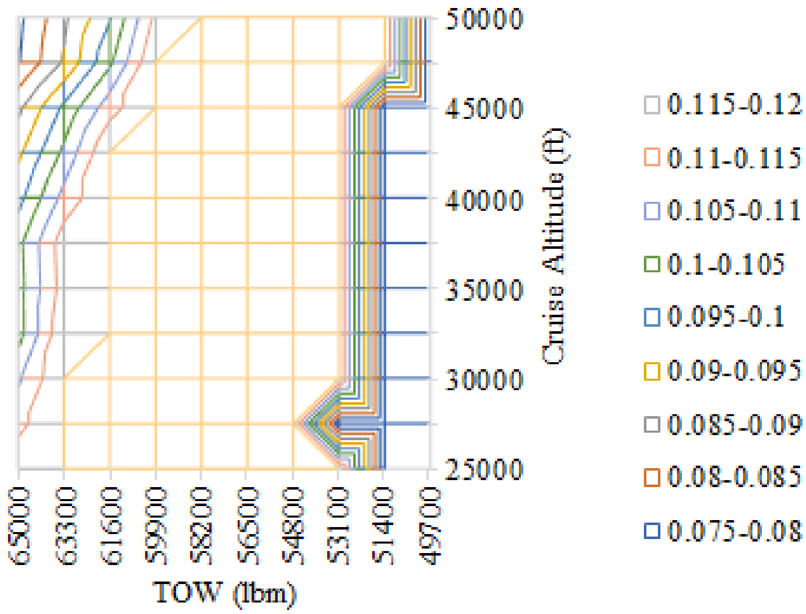


Figure 129: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 01/20/19

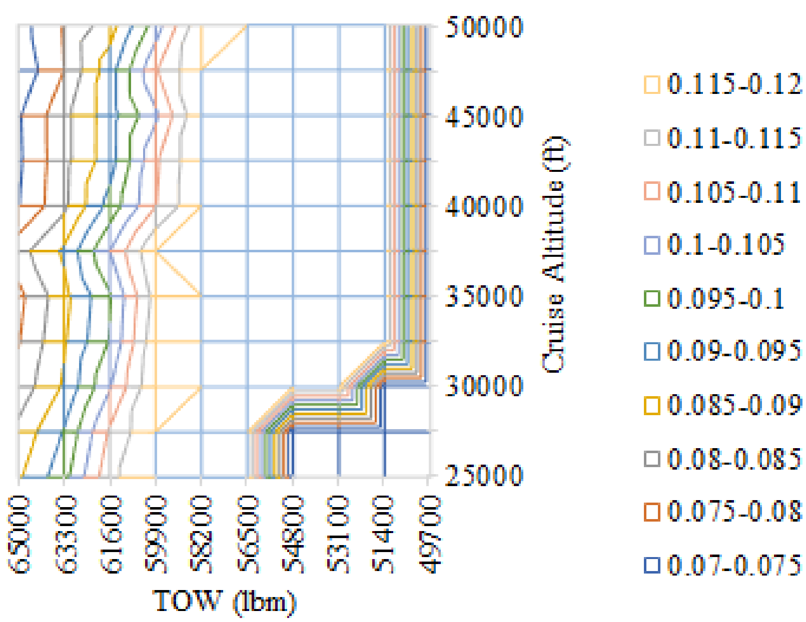


Figure 130: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 04/20/19

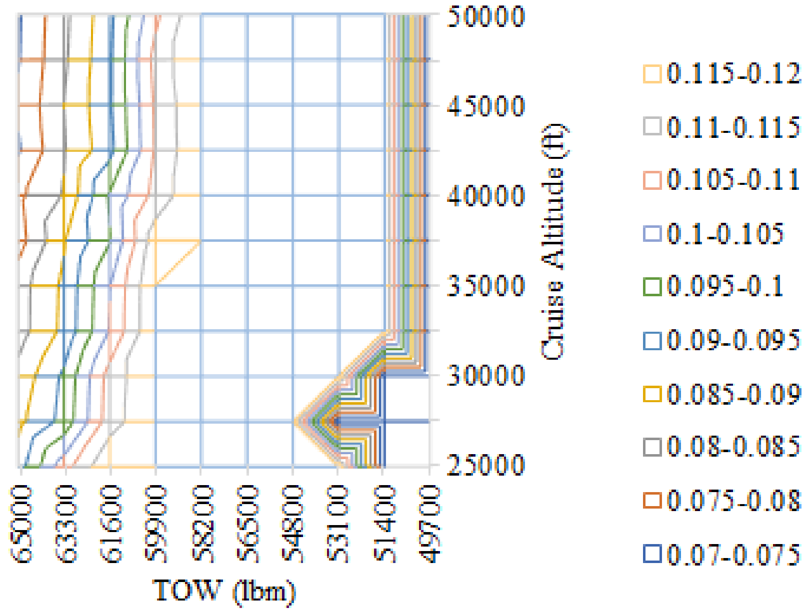


Figure 131: *Aeris* Fuel Burn/Seat-Mile for DVN to OAK on 11/20/18

From the passenger economy plots, the *Aeris* finds its best mission economy at its ceiling altitude when flying against the winds. In January, the passenger economy is much more sensitive with respect to flight altitude as compared to April and November. The shape is also comparable to those seen in the September trades in figure 108 to figure 111, once again showing the bi-annual similarities of the effect of winds on aircraft performance.

From the passenger perspective, it seems that passenger economy shapes in April and November are most similar to the *Aeris*'s baseline passenger economy in figure 25. However, November once again shows a significant jagged nature especially at 40000-ft (FL400) and below. It seems that the noise in the fuel economy plot shows up as the jagged edges, justifying that the winds add to noise both in the fuel economy and the passenger economy.

The total payload economy (fuel burn/kilopound-mile) of the *Aeris* has also been plotted for these trades and can be seen in figure 132 to figure 134.

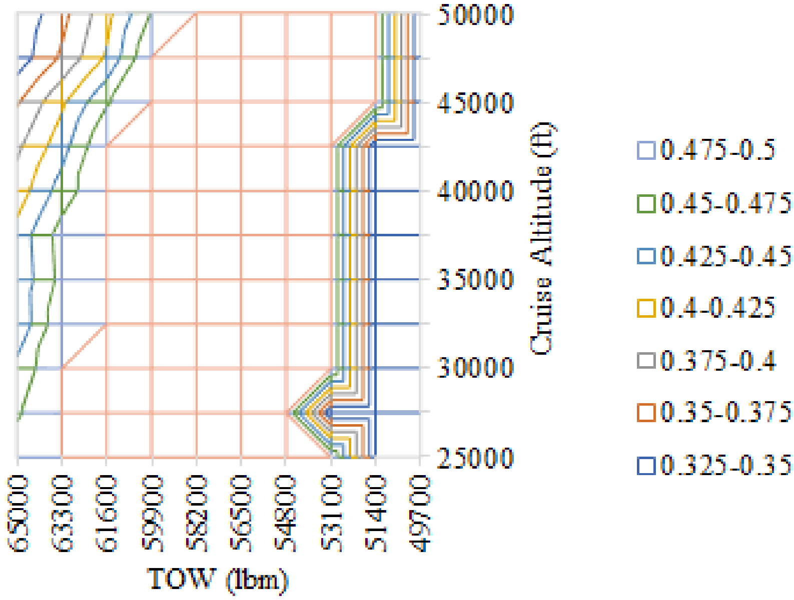


Figure 132: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 01/20/19

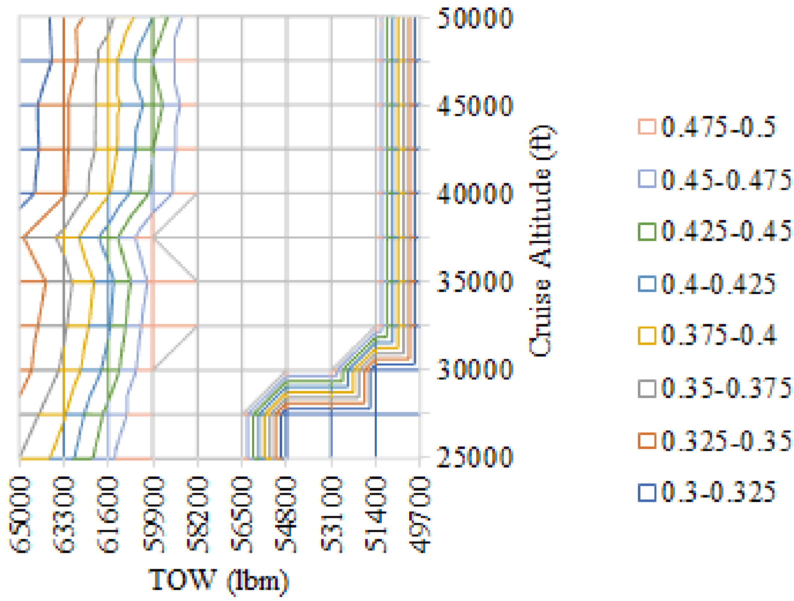


Figure 133: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 04/20/19

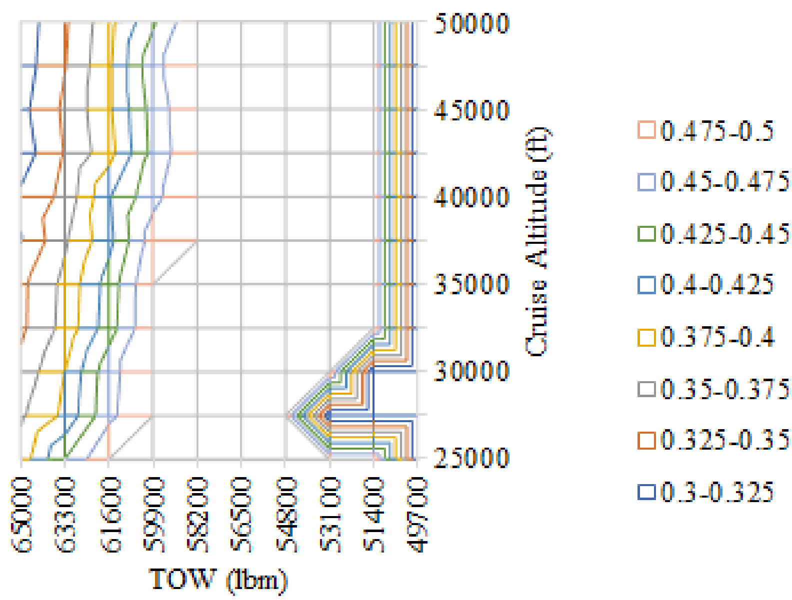


Figure 134: *Aeris* Fuel Burn/Kilopound-Mile for DVN to OAK on 11/20/18

The *Aeris* payload economy plots show the same trends as the passenger economy plots. Flight with stronger winds leads to more significant changes in payload economy with altitude, and all plots show the *Aeris* favors flight at maximum TOW (corresponding to max payload capacity) and cruise altitude. The effect of winds also show up not just in the overall magnitude of the operational economies but also as a form of noise that makes it more difficult to accurately predict the aircraft's behavior just from the baseline.

In general the *Aeris*'s payload economy is more sensitive to altitude changes than the Airbus *A320*'s payload economy for all tested dates. Furthermore, the *Aeris* wants to fly at maximum cruise altitude for all TOWs, while the Airbus *A320* has a very noticeable degradation in flight altitude with increasing TOW.

From the contour plots alone, a very different picture forms in terms of how the *Aeris* and the Airbus *A320* want to fly. The Airbus *A320* appears to have best payload economy when heavily loaded, where the wing appears to be overloaded as compared to its size. This reduces the *A320*'s optimal flight altitude, as any attempt at increasing it would be met with massive increases in induced drag that overshadow the drag benefits from flight in thinner atmosphere. The *Aeris* wants to fly at its design cruise altitude of 50000-ft when flying against the winds. Thus, the *Aeris* appears to be tailored to optimal wing loading when flying against the winds.

CHAPTER 7: QUANTITATIVE DIFFERENCES

A quantitative analysis on the performance of the *Aeris* and the Airbus *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 Airbus *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 $TOW = OEW + PYLD + FuelBurned + FuelReserved$. 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 Airbus *A320*, the best fuel, passenger, and payload economies and their percent difference from the standard design mission are tabulated in table 3. The same is done for the *Aeris* and can be seen table 4.

Table 3: *A320* OAK to DVN Best Economies

Test Point	Max SR (nM/lbm)	Max SR Delta from Design	Max Fuel Economy (lbm/seat -nM)	Fuel Economy Delta from Design	Max Payload Economy (lbm/kilopound -nM)	Payload Economy Delta from Design
Design	0.09554	0.00%	0.08967	0.00%	0.33231	0.00%
1/20/19	0.11196	17.19%	0.07817	12.82%	0.26911	19.02%
4/20/19	0.10042	5.11%	0.08555	4.60%	0.30995	6.73%
9/8/19	0.10430	9.17%	0.08039	10.34%	0.29706	10.61%
9/9/19	0.10491	9.81%	0.07957	11.26%	0.29113	12.39%
9/10/19	0.10591	10.86%	0.07946	11.39%	0.28749	13.49%
9/11/19	0.10230	7.08%	0.08158	9.02%	0.30199	9.12%
9/12/19	0.10437	9.25%	0.08041	10.32%	0.29750	10.47%
11/20/18	0.09850	3.10%	0.08616	3.91%	0.31468	5.30%
Average	0.10408	8.94%	0.08141	9.21%	0.29611	10.89%

Table 4: *Aeris* OAK to DVN Best Economies

Test Point	Max SR (nM/lbm)	Max SR Delta from Design	Max Fuel Economy (lbm/seat-nM)	Fuel Economy Delta from Design	Max Payload Economy (lbm/kilopound-nM)	Payload Economy Delta from Design
Design	0.30775	0.00%	0.06701	0.00%	0.28071	0.00%
1/20/19	0.36758	19.44%	0.05459	18.53%	0.22721	19.06%
4/20/19	0.32692	6.23%	0.06210	7.32%	0.25838	7.95%
9/8/19	0.33941	10.29%	0.05999	10.47%	0.25200	10.23%
9/9/19	0.33756	9.68%	0.05972	10.88%	0.25027	10.84%
9/10/19	0.34469	12.00%	0.05952	11.18%	0.24960	11.08%
9/11/19	0.34283	11.40%	0.05968	10.93%	0.25083	10.65%
9/12/19	0.33579	9.11%	0.05991	10.60%	0.25179	10.30%
11/20/18	0.33441	8.66%	0.06313	5.79%	0.26426	5.86%
Average	0.34115	10.85%	0.05983	10.71%	0.25054	10.75%

Based upon the values in table 4, 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%. The Airbus *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%.

Looking at table 4, the actual gain in passenger economy is also significant for the *Aeris*. In January, the *Aeris* reaches a passenger economy of 0.055 lbm/seat-nM, which is 18.5% smaller than the design passenger economy of 0.067 lbm/seat-nM. This shows potential for a nearly 20% improvement from the pure baseline passenger economy. The Airbus *A320* shows a similar story, where it reaches a passenger economy of 0.078 lbm/seat-nM in January providing a 12.8% improvement upon its baseline passenger economy of 0.09 lbm/seat-nM.

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 1/kilo-nM is reached in January, as opposed to its design point of 0.28 1/kilo-nM leading to a 19% improvement in payload economy. The Airbus has an overall optimum payload economy of 0.27 1/kilo-nM, which is also a 19% improvement from its design payload economy of 0.33 1/kilo-nM.

A direct comparison between the *Aeris* and the Airbus *A320* shows which aircraft performs better overall with real-world atmospheric conditions. Table 5 to table 7 show the direct comparison of the *Aeris*'s best fuel economy, passenger economy, and payload economy against the Airbus *A320*'s. The tables also show the percent difference of the *Aeris* for each day against the design reference difference between the *Aeris* and the Airbus *A320*.

Table 5: *Aeris* vs Airbus 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 Airbus Passenger Economy (Fuel Burn/Seat-Mile) Comparison for OAK to DVN

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.06701	0.08967	0.02266	25.27%	0.00%
1/20/19	0.05459	0.07817	0.02358	30.17%	19.38%
4/20/19	0.06210	0.08555	0.02344	27.40%	8.45%
9/8/19	0.05999	0.08039	0.02040	25.37%	0.42%
9/9/19	0.05972	0.07957	0.01985	24.95%	-1.28%
9/10/19	0.05952	0.07946	0.01994	25.09%	-0.69%
9/11/19	0.05968	0.08158	0.02189	26.84%	6.21%
9/12/19	0.05991	0.08041	0.02051	25.50%	0.91%
11/20/18	0.06313	0.08616	0.02304	26.73%	5.80%
Average	0.05983	0.08141	0.02158	26.37%	4.36%

Table 7: *Aeris* vs Airbus 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%

In comparing the actual values, the *Aeris* has a better payload economy than the Airbus *A320* under every condition. At the optimal point, the *Aeris* is almost 15% more economic to fly than the Airbus *A320*, even though the Airbus *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 Airbus

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 Airbus *A320* has been shown to be overloaded in these trades. Adding more payload will drive the Airbus *A320* to a lower altitude and further away from the jet-stream core, hurting its mission economy further when weather is involved.

However, this comparison is not quite appropriate, as the *Aeris* and the Airbus *A320* were designed for different missions. 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 table 5 to table 7. In general, the *Aeris* yields better fuel economy and passenger economy performance when flying with the winds than the Airbus *A320*. However, the Airbus *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 benefit more from flight with the winds than the *Aeris*. When the Airbus is passenger constrained, it performs worse than the *Aeris*. This nuance makes it difficult to say which aircraft is better designed for the winds.

The same quantitative perspective must also be performed for flight against the winds. For this, table 8 and table 9 show the relative differences in fuel economy, passenger economy, and payload economy for the Airbus *A320* and the *Aeris* as compared to their design mission.

Table 8: *A320* DVN to OAK Best Economies

Test Point	Max SR (nM/lbm)	Max SR Delta from Design	Max Fuel Economy (lbm/seat-nM)	Fuel Economy Delta from Design	Max Payload Economy (lbm/kilopound-nM)	Payload Economy Delta from Design
Design	0.09554	0.00%	0.08967	0.00%	0.33231	0.00%
1/20/19	0.07474	-21.77%	0.11038	-23.09%	0.42580	-28.13%
4/20/19	0.09166	-4.06%	0.09619	-7.27%	0.34623	-4.19%
9/8/19	0.08486	-11.17%	0.09477	-5.68%	0.35930	-8.12%
9/9/19	0.08442	-11.64%	0.09497	-5.92%	0.36968	-11.25%
9/10/19	0.08332	-12.78%	0.09500	-5.95%	0.37296	-12.23%
9/11/19	0.08996	-5.84%	0.09154	-2.09%	0.34664	-4.31%
9/12/19	0.08511	-10.91%	0.09473	-5.64%	0.36671	-10.35%
11/20/18	0.08934	-6.48%	0.09782	-9.09%	0.35584	-7.08%
Average	0.08543	-10.58%	0.09692	-8.09%	0.36790	-10.71%

Table 9: *Aeris* DVN to OAK Best Economies

Test Point	Max SR (nM/lbm)	Max SR Delta from Design	Max Fuel Economy (lbm/seat-nM)	Fuel Economy Delta from Design	Max Payload Economy (lbm/kilopound-nM)	Payload Economy Delta from Design
Design	0.30775	0.00%	0.06701	0.00%	0.28071	0.00%
1/20/19	0.26909	-12.56%	0.07872	-17.48%	0.32873	-17.11%
4/20/19	0.29344	-4.65%	0.07120	-6.25%	0.29882	-6.45%
9/8/19	0.28326	-7.96%	0.07326	-9.33%	0.30334	-8.06%
9/9/19	0.28292	-8.07%	0.07316	-9.18%	0.30254	-7.78%
9/10/19	0.28098	-8.70%	0.07346	-9.63%	0.30433	-8.42%
9/11/19	0.29101	-5.44%	0.07194	-7.36%	0.30244	-7.74%
9/12/19	0.27953	-9.17%	0.07365	-9.91%	0.30596	-8.99%
11/20/18	0.28526	-7.31%	0.07447	-11.13%	0.31023	-10.52%
Average	0.28319	-7.98%	0.07373	-10.03%	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, however the Airbus *A320* sees less impact on its passenger 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 passenger economy differences are worse for the *Aeris* than the Airbus *A320* almost entirely across the board, however 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 Airbus *A320*. Although the *Aeris* appears to have the best relative difference in terms of the payload economy, depending on the wind profile the Airbus *A320* might be slightly less affected.

This perspective only looks at the relative differences from each aircraft to their design points, however, and does not directly compare their economies. To that end, table 10 through table 12 show the direct comparison of the Airbus *A320* and *Aeris* mission economies to determine which design provides superior economic performance when flying against the winds.

Table 10: *Aeris* vs Airbus 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 11: *Aeris* vs Airbus Passenger Economy Comparison for DVN to OAK

	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.06701	0.08967	0.02266	25.27%	0.00%
1/20/2019	0.07872	0.11038	0.03165	28.68%	13.49%
4/20/2019	0.07120	0.09619	0.02498	25.98%	2.80%
9/8/2019	0.07326	0.09477	0.02151	22.69%	-10.19%
9/9/2019	0.07316	0.09497	0.02181	22.97%	-9.12%
9/10/2019	0.07346	0.09500	0.02154	22.67%	-10.27%
9/11/2019	0.07194	0.09154	0.01960	21.41%	-15.28%
9/12/2019	0.07365	0.09473	0.02108	22.25%	-11.95%
11/20/2018	0.07447	0.09782	0.02335	23.87%	-5.55%
Average	0.07373	0.09692	0.02319	23.93%	-5.12%

Table 12: *Aeris* vs Airbus Passenger Economy Comparison for DVN to OAK

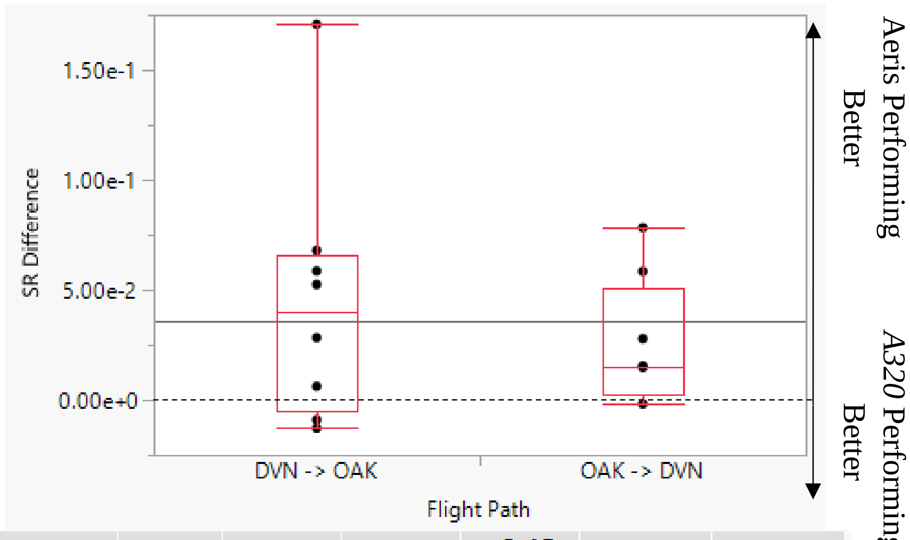
	Aeris	*A320*	Difference to *A320*	Percent Difference from *A320*	*Aeris* Percent Difference against Design Difference
Design	0.28071	0.33231	0.05160	15.53%	0.00%
1/20/2019	0.32873	0.42580	0.09707	22.80%	46.82%
4/20/2019	0.29882	0.34623	0.04741	13.69%	-11.81%
9/8/2019	0.30334	0.35930	0.05596	15.57%	0.31%
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 Airbus *A320*, the *Aeris* is still more economic 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 Airbus *A320*. It appears that the strategy of the Airbus *A320* in flying below the jet-stream results in less capability 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 is not entirely proper. To this end, the "*Aeris* Percent Difference against Design Difference" column determines whether the *Aeris* has better relative performance in the presence of winds as compared to the Airbus *A320*. Positive percentages denote that the *Aeris* performs better in winds than the Airbus *A320*, and negative percentages denote that the Airbus *A320* performs better than the *Aeris*.

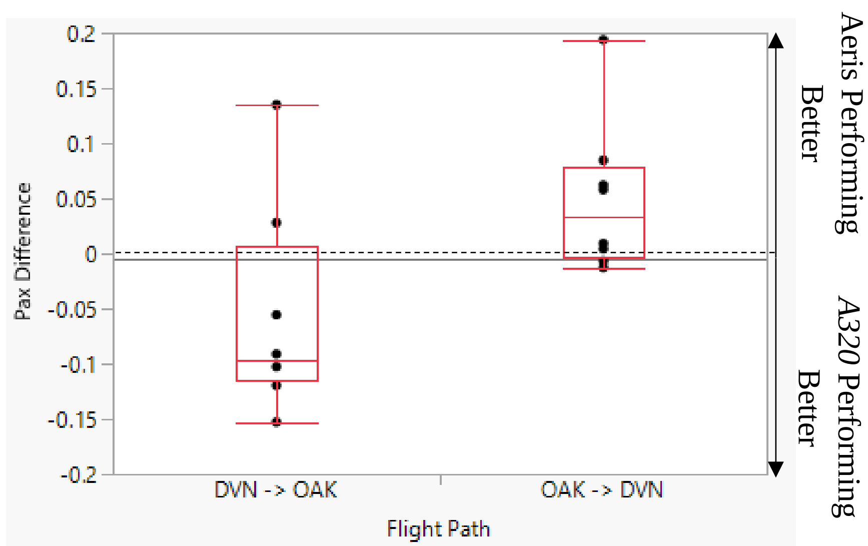
From this perspective, the effect of winds and temperature deviation once again get more nuanced. There is a spattering of positives and negatives for the fuel economy, passenger economy, and payload economy. The real-world atmosphere creates a highly variable effect upon the performance *Aeris* and the Airbus *A320*, making it difficult to know exactly which one will benefit more from the winds on any given day. In general, the *Aeris* nets better relative performance in its fuel economy and its payload economy, while the Airbus *A320* nets better passenger economy performance when flying against the winds. This is in direct contrast to flight with the winds, where the *Aeris* performed better in the passenger economy perspective than the Airbus *A320*.

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, passenger economy differences, and payload economy differences against the design difference. These can be seen in figure 135, figure 136, and figure 137 respectively. Note that the dashed line represents the 0% mark.



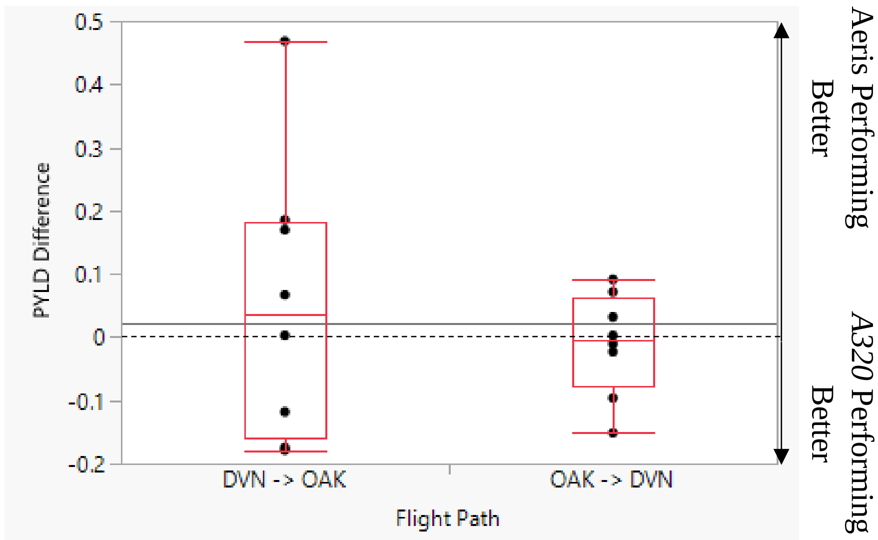
Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DVN -> OAK	8	0.0453018	0.0592716	0.0209557	-0.00425	0.094854
OAK -> DVN	8	0.0257897	0.0284846	0.0100708	0.001976	0.0496034

Figure 135: Statistical Analysis on Fuel Economy (nM/lbm) Difference against Design Difference



Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
DVN -> OAK	8	-0.057582	0.0944218	0.0333831	-0.13652	0.021357
OAK -> DVN	8	0.0490103	0.0686919	0.0242863	-0.008418	0.1064382

Figure 136: Statistical Analysis on Passenger Economy (lbm/seat-nM) Difference against Design Difference



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 137: Statistical Analysis on Payload Economy (lbm/kilopound-nM) Difference against Design Difference

From the statistical viewpoint, the variability 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 passenger economy shows the opposite case, where flight against the winds is significantly more negative than flight 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 Airbus *A320* under all studied conditions. However, from a passenger 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 Airbus *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. However, it does provide insight as to how each aircraft is affected, and it appears that the passenger economy has the most difference between flight with the winds and flight against the winds.

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 Airbus *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 Airbus *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.

CHAPTER 8: CONCLUSION

From the trades for flight from Oakland to Davenport and back, real-world atmospheric conditions add a large amount of variability to the fuel economy, passenger economy, and payload economy of both the *Aeris* and the Airbus *A320*. This indicates that the real-world weather has a significant effect upon the performance of aircraft, and also indicates the difficulty in predicting real-world performance from standard day conditions. The effect of winds provides major differences both qualitatively in the shapes of the economy contours, as well as quantitatively with major differences in terms of optimal economy values.

For mission planning, it is clear that flight with the winds provides major benefits as opposed to flight against the winds. However, since the wind speeds, directions, and altitudes will differ from day to day, there is a strong incentive to provide real-time weather updates to predict and optimize the performance of the aircraft. From an operational viewpoint, optimizing flight with the winds has the potential to save up to 10% in terms of the overall payload economy as compared to the flying the design reference mission (as can be seen with the *Aeris* flying with the winds in January: figure 84). In contrast, depending on the day flight against the winds may see as much as 25% degradation in performance as predicted from the baseline mission, even when optimized. Differences of +/-10% are common depending on flight with or against the winds.

This presents a very strong argument that aircraft operators need to use daily or real-time weather to predict aircraft performance. The variability added by winds and temperature is massive and depends heavily upon the route of travel. Through the qualitative analysis, both the Airbus *A320* and the *Aeris* have major changes not only in their optimal cruise altitudes but also throughout all studied altitudes and TOWs. This also suggests that careful investigation of climb performance and routing needs to be investigated as well, since the performance contours show major changes in terms of how the aircraft responds at different altitudes. Considering that this thesis only studied one main route, it is very likely that different routes will show different performance contours which heightens the need to use real-world conditions for aircraft operation planning.

The design aspect is trickier as the variance within the *Aeris* and the *A320* do not make a particularly compelling argument about whether either are better designed for interaction with weather. On the whole, the design of the *Aeris* appears to have some advantages depending on the day and direction, but due to the wide spread it cannot be stated for certain. The variability does hint at using statistical analysis methods, however. From the basic statistical analysis done in the quantitative analysis portion of this thesis, it appears that more data points need to be established to get a better understanding of what aircraft is 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 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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