

Aircraft Operations Based Mission Requirements

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The mission capabilities of aircraft in the current commercial fleet are a combined result of many factors. The launch customer for each aircraft has a voice in determining the requirements. The manufacturer desires to best position the aircraft in the market considering their own aircraft and their competitors aircraft it will replace and compete with. Consequently, anyone considering the development of an aircraft to compete with or replace an aircraft in-service must do more than simply choose to meet the capabilities of that aircraft. This is especially true when unconventional systems are considered; the fundamental tradeoffs for these systems may dramatically alter the cost/benefit for a given capability set. Data representing current operational practice for two aircraft in the commercial fleet are presented with an intent of establishing requirements for future aircraft.

I. Introduction

THE aircraft design process has historically been viewed as starting with a statement of specifications or requirements for a new vehicle.^{1,2} This mode of operation was largely reinforced by the government acquisition and systems engineering processes.³ Recent design texts emphasize the importance of questioning the requirements,⁴ but the process of setting the requirements is generally considered beyond the scope of the aircraft design process.

Proper establishment of the requirements has profound implications for the capabilities of the vehicle and its potential for success. Setting the requirements for a complex system reduces the available design freedom and commits a significant fraction of the overall cost at a time when relatively little is known about the eventual design.⁵ In the defense sector, there are organizations whose whole primary purpose is to model, trade, and establish requirements for future vehicles. In the commercial sector, the voice of the customer is critical, but the airframer has the ultimate responsibility for setting the requirements for its future products; setting the requirements well can dominate the conceptual design process.⁶

Identifying and understanding the active constraints and requirements for a given design is critical to its success. To improve on an optimal design problem, attention must be focused on the active constraints. Advanced concepts and technologies can have dramatic impact on the character of the vehicle; this impact can change which requirements truly drive the aircraft design. When performing aircraft advanced concept or technology studies, the choice of requirements which constrain and guide the design must be considered from a fundamental level.

It can be expected that the capability trade studies performed by militaries and commercial airframers would be very tightly guarded. By definition, these studies make clear the chosen tradeoffs and thereby the strengths and weaknesses of a proposed design. This information has obvious value to any competitor or adversary. Whether because of the sensitive nature or because little academic work has been done in this area, there are very few publications available which discuss how requirements are set when considering a new vehicle.

One may conceive of many ways to trade and set the requirements for a new commercial aircraft. In an ideal world, the requirements would be traded in an environment that quantified their effect on the aircraft design and its life cycle cost carrying these calculations through to return on investment. This environment would perhaps use a game theory approach to consider not just the aircraft design, but the design and composition of the future fleet while including various sociopolitical and economic scenarios as well

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as various scenarios representing the actions of competitors and partners in the marketplace. Unfortunately, such an environment would be extremely complex to create, maintain, and use during the earliest phases of design. Furthermore, the accuracy and utility of such an environment is surely reduced when considering revolutionary concepts and technologies far into the future.

Likewise, one may conceive of a military analog to this ideal environment. Work has been done to simultaneously model the design, technologies, and requirements for a proposed aircraft;⁷ such a model would enable concurrent trade studies through a unified decision space. Work has also been done to use campaign analysis to arrive at a high-level system effectiveness metric for military aircraft.⁸ Despite these efforts, it is not clear from available publications that these methods have been broadly adopted or are representative of current practice.

For better or worse, establishing requirements usually remains beyond the scope of the aircraft design process. While industrial designers working towards major products may be privy to requirements rigorously established by other groups, the academic and research communities usually have no such organization to rely upon. Consequently, many design studies start from the perspective of replacing an in-service aircraft. The existing aircraft's capabilities, market, and use guide the requirements and assumptions applied to the replacement design. This is frequently a reasonable approach when the replacement aircraft is similar to the in-service aircraft. However, when the replacement aircraft under consideration is dramatically different in concept or technology, this approach may inappropriately influence the new design leading to concepts which are infeasible or inviable.

In this study, data describing the operational use of aircraft is used to establish design requirements based on how in-service aircraft are actually used – not how they could be used. This allows the simplified perspective of replacing an existing aircraft (or class), but it focuses on replacing the aircraft utility – not its capability. This approach is meant to improve the justification used in establishing the requirements without the complexity implied by the ideal environments discussed above.

II. Example Aircraft

For this paper, the capabilities of two aircraft in commercial service were selected for consideration, the Cessna 208 and the Boeing 737-700. A larger, intercontinental aircraft was not selected because the data sets used primarily cover domestic United States transport. The Cessna 208 is one of the smallest aircraft in regular commercial operation today; more than 2,000 have been built. It is popular for a number of missions including inter-island passenger service in Hawaii, charter passenger and cargo service in Alaska, and regularly scheduled cargo feeder operation by FedEx. The Boeing 737-700 is a workhorse of the domestic air fleet and is representative of a wide range of narrow body transport aircraft; more than 1,100 737-700's have been built.

In this study, aircraft use is further limited to the consideration of particular launch customers; while not necessary, doing so helps limit the scope of this work and clarifies the analysis. The FedEx Corporation will be considered the launch customer for the Cessna 208 replacement. FedEx participated in the development of the dedicated cargo variants of the aircraft and has taken delivery of 300 airframes. Southwest Airlines Corporation will be considered the launch customer for the Boeing 737-700 replacement. Southwest was the launch customer for the 737-300, 737-500, and 737-700 aircraft; recently, Southwest was named the launch customer for the planned 737-MAX family of aircraft.⁹

III. Aircraft Operations Data Sources

Operational record keeping is a fundamental part of aviation. As a private pilot, I log every flight, its conditions, length, number of landings, equipment used, destination, purpose of trip, and anything of note. Thorough operational record keeping extends to the equipment; logs record operations, consumables use, and maintenance of aircraft, engines, propellers, and avionics. Commercial and military operators undoubtedly compile vast records of the operations of their fleets. Unfortunately, this data is generally not compiled, aggregated, and made available in the open in a way which is useful to the aircraft designer. In this paper, some data sets compiled for other uses are explored as an aid to the aircraft design process.

III.A. Ames Seed Day

The NASA Airspace Systems Program¹⁰ commissioned the creation of a set of representative air traffic days to support modeling and simulation of the domestic United States air transport network. Actual air traffic data from as-flown ETMS data was gathered by Metron Aviation¹¹ and compiled into a set of representative days of high and low volume with good and bad weather. September 26, 2006 was selected as a high volume day with good weather to serve as the ‘seed day’ for creation of alternative scenarios. This day includes 84,168 flights over 39 hours of air traffic for the continental United States; this includes six hours of traffic before the day of interest, 27 hours of traffic on the day of interest, and six hours of traffic following the day of interest. The day of interest is 27 hours long because it starts at midnight Eastern and extends to midnight Pacific time.

The seed day data includes records of every individual flight (takeoff to landing) from the perspective of the air traffic management system; military flights and general aviation VFR flights which did not request flight following are not included. The data set includes operator, equipment used, origin and destination airports, cruise speed and altitude, and route followed. The data does not include any record of the payload (freight/mail/passengers) carried or purpose for the flight.

III.B. BTS Database

The Department of Transportation (DOT) Bureau of Transportation Statistics (BTS) requires transport operators (truck, ship, rail, and air operators) to report aggregated records of freight, mail, and passengers transported. This data for air transport is readily available from online databases dating back to October 2002.¹²

In this study, the complete segment data set for all carriers for 2009 was used;¹³ 2009 was the most recent complete-year data set available at the time of this study. The 2009 data set represents more than ten million flights. This database combines operations into monthly totals for every operator, city pair, and equipment combination; consequently, if a record represents thirty flights, only average values for those flights can be considered. The DOT uses its own coding system to identify the aircraft type for each data record; cross-referencing the aircraft type to other data sets can sometimes be problematic.

III.C. Airport Databases

A number of freely available airport databases were used in this study. By far, the OurAirports¹⁴ database was the most complete, with 43,832 records at the time of access. The OurAirports database is created and maintained primarily through user contributions; it includes most general interest information about the included airports, but it does not include detailed information about the runways at each airport. Various data sources use either the ICAO airport code or the local airport code to identify airports. The OurAirports database contains both kinds of codes where appropriate; this information was used to standardize and convert airport lookup as required.

The length of the longest runway at as many airports as possible was compiled from three smaller databases. The FAA provides online access to a database of airport data;¹⁵ at the time of access, this database included record of runway length at 19,836 airports. The *Airports in Canada* web site¹⁶ is maintained by an aviation enthusiast. At the time of access, this database included record of runway length at 1,504 runways. This data was based on official Canadian government information available from NAV CANADA.^{17, 18} Finally, the avionics company Sandel provides a database of 11,704 worldwide public airports with runways 2,500 ft. or longer.¹⁹

III.D. Operator Annual Reports

The Securities and Exchange Commission (SEC) requires all publicly traded companies to file an annual report on the financial and operating statistics of the company. Companies use the annual report as an opportunity to reach out to investors – sometimes providing significantly more than the SEC required information. Because a fleet of aircraft represents a significant capital expense and asset, fleet size and composition is often reported in the annual report.

The operating statistics reported by the FedEx Corporation²⁰⁻²² include the fleet size and composition of their entire air fleet; this data has been summarized in Table 1 below. FedEx currently operates 252 Cessna 208 aircraft. In general, the number of aircraft of a particular type operated by FedEx is fairly stable. When

a new aircraft is acquired, purchases are spread over a few years. A stable number of aircraft are operated for a number of years until the aircraft are ready for replacement. Transition to a new type is also spread over a few years.

Table 1. History of the FedEx fleet.

	727-100	727-200	757-200	DC10-10	DC10-30	MD10-10	MD10-30	MD11	777F	A300-600	A310-200/300	C208A	C208B	F-27	ATR-72	ATR-42	SD3-60
1998	68	95	-	47	22	-	-	25	-	24	39	10	251	32	-	-	0
1999	68	95	-	58	22	-	-	28	-	31	39	10	251	32	-	-	0
2000	66	95	-	69	22	-	-	30	-	36	41	10	251	32	-	-	11
2001	52	95	-	48	22	3	2	34	-	37	46	10	248	32	-	-	11
2002	42	95	-	48	19	11	5	39	-	37	50	10	248	32	-	-	11
2003	28	94	-	48	17	19	5	42	-	43	51	10	247	30	-	8	1
2004	19	94	-	39	17	27	5	42	-	44	51	10	246	27	2	22	-
2005	18	94	-	30	17	36	5	57	-	47	62	10	246	17	2	29	-
2006	13	94	-	25	14	41	6	58	-	53	65	10	243	9	11	29	-
2007	1	94	4	14	13	49	7	58	-	60	66	10	243	8	13	29	-
2008	-	90	12	5	12	58	8	58	-	68	66	10	243	5	13	29	-
2009	-	79	24	1	6	57	12	57	-	71	56	10	242	-	13	26	-
2010	-	77	36	-	2	58	15	59	6	71	49	10	242	-	13	26	-

Although this information was not always provided, the annual reports currently provided by the Southwest Airlines Corporation²³ include fleet size and composition as well as a handful of aircraft utilization metrics which will be discussed later.

III.E. Plane Spotting Enthusiasts

There is a distributed worldwide community of aviation enthusiasts who enjoy plane spotting – the observation, logging, and often photography of aircraft. The internet has provided means for these enthusiasts to form communities and combine their efforts. In addition to aircraft sightings, plane spotters use aircraft registration, transfer of ownership, accident reports, and any other available information to compile their histories. One small group of plane spotters is working to compile complete service histories of commercial aircraft.²⁴ Their data set was used as the basis of building a complete history of Southwest Airlines’ fleet; this history includes the N-number, serial number, date of entry to service and exit from service of every aircraft Southwest has ever flown. Exit from service was sometimes approximated as the date of transfer of ownership or change in registration; consequently, the greatest inaccuracies in this history are at the end of service for aircraft which spent significant time in storage before being transferred.

Figure 1 depicts the complete history of the Southwest Airlines fleet. The lines are drawn from the combined plane spotting data – plotted at the end of each month. The diamonds reflect the fleet history reported in the company annual reports. The aircraft types are indicated by the FAA designation, 733 represents the 737-300 and 737 represents the 737-700. The history includes two brief periods where Southwest operated a small number of 727-200 aircraft.

Southwest’s history of continuous growth results in a much more volatile fleet history than for the FedEx Cessna 208. Although the 737-300 fleet has an extended period of constant size, purchases were spread over a period of nearly 15 years and only ceased when acquisition of the 737-700 started. In the coming years, it is evident that Southwest’s continued growth and the advancing age of their 737-300 and 737-500 aircraft will require a high rate of aircraft acquisition. The data presented here does not reflect the ongoing merger between Southwest and AirTran Airways; the AirTran fleet consists of 88 717-200 and 52 737-700 aircraft.

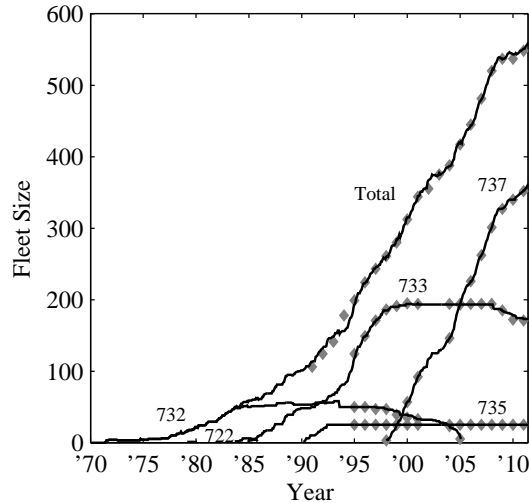


Figure 1. History of the Southwest airlines fleet.

IV. FedEx Cessna 208 Operations

A number of aircraft utilization metrics were calculated for the fleet of FedEx Cessna 208's. All aircraft operations reported to the BTS in 2009 were combined and divided by the aircraft fleet size reported in the company's annual report. The calculated utilization metrics were summarized in Table 2. The BTS only requires reporting of transport flights, so maintenance, training, and repositioning flights do not appear in these utilization metrics. Furthermore, FedEx appears to primarily operate the feeder fleet on weekdays, while the daily utilization metrics were calculated based on a seven day week.

Table 2. FedEx 2009 Cessna 208 Utilization.

Metric	Value	Units
Daily flights	1.1	-
Yearly flights	407	-
Daily utilization (BTS Ramp to Ramp)	1:09	h:m
Daily utilization (BTS Air Time)	59	m
Yearly utilization (BTS Ramp to Ramp)	421	h
Yearly utilization (BTS Air Time)	361	h

The BTS data includes the total payload flown for each record (month, operator, equipment, city pair) as well as the number of flights included in that record. This data was expanded by assuming that each flight in a record carried the average payload of the record. An empirical cumulative distribution function (ECDF) of the payload carried was plotted as Figure 2(a). It is evident that the FedEx Cessna 208 fleet carried less than 1920 lb. 95% of the time and less than 1500 lb. 66% of the time.

A set of similar ECDFs was constructed to study the distribution of distance flown by the FedEx Cessna 208's. Curves based on both the BTS data and the Seed Day data were plotted as Figure 2(b). Despite the three year separation between the data sets and dramatic difference between the time period covered (one day vs. one year), the curves essentially agree. Based on the more recent BTS data, the FedEx Cessna 208 fleet flew less than 300 nmi. 99.5% of the time and less than 200 nmi. 91% of the time.

The payload/range operation of the FedEx Cessna 208 fleet based on the BTS data was plotted in Figure 2(c). Due to the bivariate nature of this data, a plot of the cumulative distribution can not be created. Instead, a grey-coded histogram was constructed where the darkest areas represent the most likely regions of operation. This kind of plot will be called an empirical joint probability density function (EJPDF). The advertised payload/range performance for four variants of the Cessna 208 were also included in Figure 2(c)

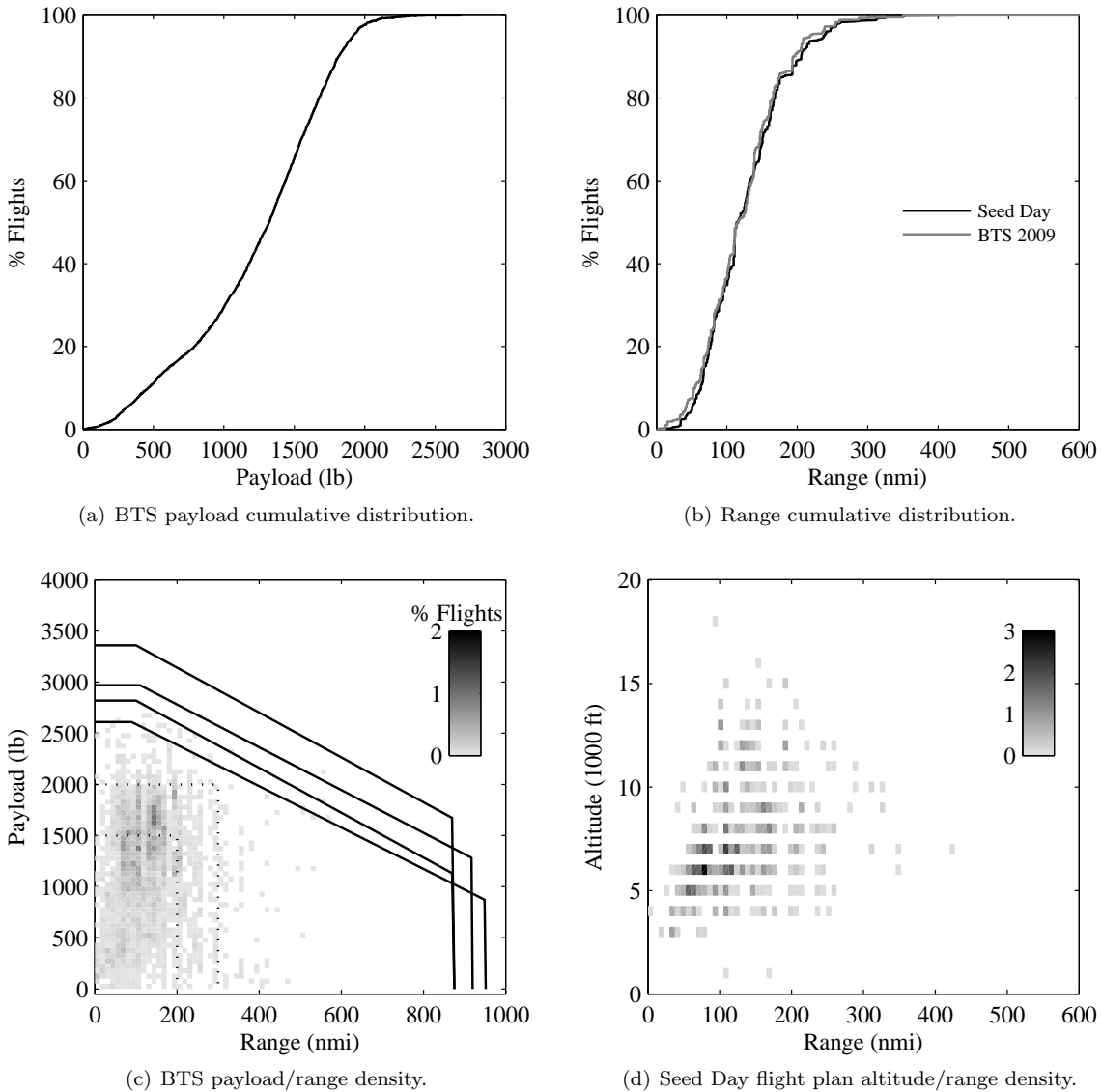


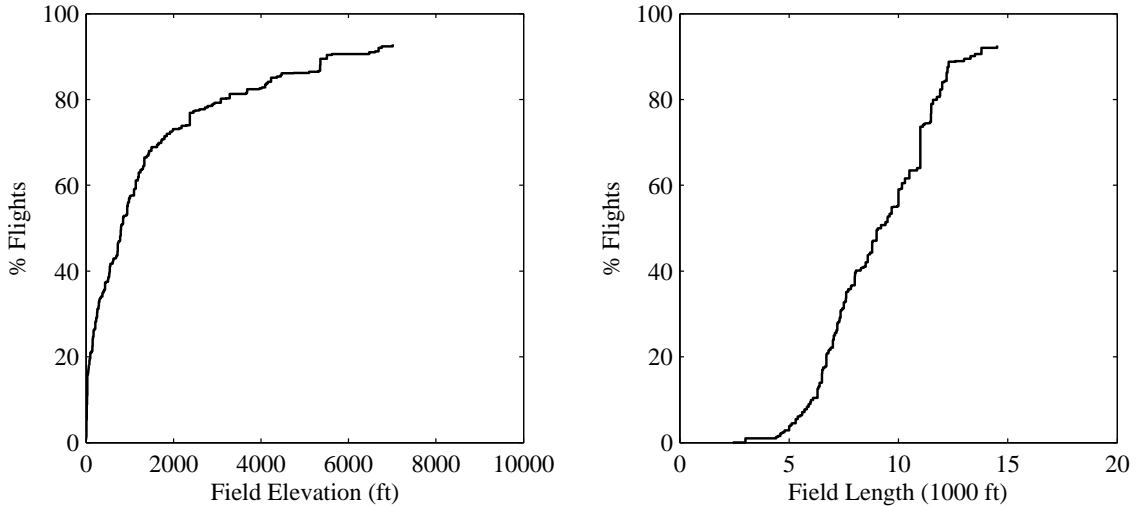
Figure 2. FedEx Cessna 208 payload, range, and altitude operations.

as the solid lines. Despite much greater operational capability, the highest density of Cessna 208 flights are approximately 175 nmi. long and carry about 1700 lb. of payload.

The flight plan altitude/range operation of the FedEx Cessna 208 fleet based on the Seed Day data was plotted as a EJPDF in Figure 2(d). The highest density of flights are between 5,000-7,000 ft. Although very short flights are not flown at high altitude, there is no strong trend for longer flights to be flown at high altitude.

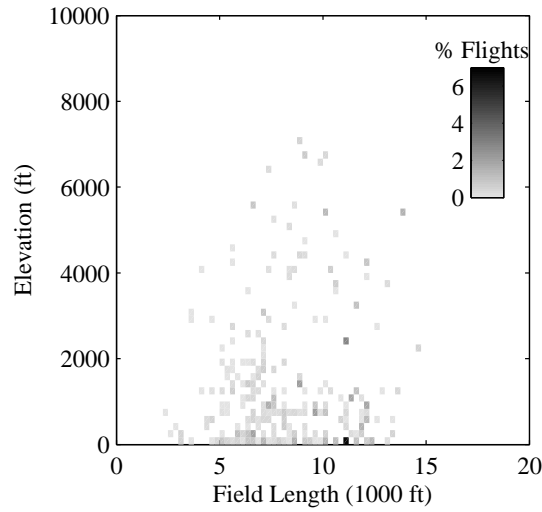
The range of airfields used by the FedEx Cessna 208 fleet were explored in Figure 3. All of the airfields utilized by the flights in the BTS data set were looked-up in the combined runway length data set. The airfield elevation and runway length were plotted as ECDF's in Figures 3(a) and 3(b) respectively. About 7% of the airfields used did not match any record in the runway length data set; this omission resulted in the gap at the top of each ECDF curve presented.

Although the Cessna 208 is renowned for its short field capability, FedEx's operations with the aircraft do not appear to require that level of performance. Most of the airfields used are at relatively low altitude, with 80% at less than 3,000 ft. elevation and 86% at less than 5,000 ft. Likewise, most takeoffs and landings occur from relatively long runways, less than 3% of operations occur from runways less than 5,000 ft. in



(a) Field elevation distribution.

(b) Field length distribution.



(c) Field length/elevation density.

Figure 3. FedEx Cessna 208 field operations.

length and less than 10% of operations occur from runways less than 6,000 ft. in length.

The combined density of the elevation/runway length operation of the FedEx Cessna 208 was plotted as an EJPDF in Figure 3(c). Although most flights clearly occur from airports at low elevation, in general, the high elevation airports do not have the shortest runways used.

IV.A. Proposed Requirements

A designer considering the design of a Cessna 208 replacement with FedEx as a launch customer may consider designing the replacement aircraft to a set of requirements less than the Cessna 208's full capabilities. Such a vehicle may be smaller and cheaper than the aircraft it replaces, or the reduced set of requirements may enable consideration of alternative advanced concept aircraft which may not feasibly be designed to match the Cessna 208's performance in every way.

FedEx may be reasonably expected to purchase between 250 and 300 replacement feeder aircraft. The FedEx feeder operation demands relatively light aircraft utilization; the aircraft should be able to sustain two flights per day and if the vehicle cruises at a similar speed, it will accumulate approximately 500 flight

hours per year. The vehicle could be designed to carry 2,000 lb. of payload 300 nmi. or, if a more aggressive reduction in capability is required, 1,500 lb. of payload 200 nmi. No pressurization system is required unless it benefits the concept under consideration. Finally, while the field performance is not likely to be critical, the design airfield could be taken to be 5,000 ft. long and located at 3,000 ft. elevation.

V. Southwest Boeing 737-700 Operations

A number of aircraft utilization metrics were calculated for the Southwest Airlines fleet; all aircraft in the fleet were used in these calculations, not just those for the 737-700. All aircraft operations reported to the BTS in 2009 were combined and divided by the monthly aircraft fleet size reported by the plane spotting data. The calculated utilization metrics were summarized in Table 3 along with the utilization metrics reported in the Southwest Airlines annual report. The BTS only requires reporting of transport flights, so maintenance, training, and repositioning flights do not appear in the BTS utilization metrics. Consistent with their low cost business model, Southwest Airlines maintains a high level of utilization of aircraft and high average load factor. The 76% load factor reported in the company's annual report appears to be based on seat-mile utilization rather than just seat utilization.

Table 3. Southwest Airlines 2009 Utilization.

Metric	Value	Units
Daily flights	5.7	-
Yearly flights	2076	-
Daily utilization (SWA Annual Report)	10:50	h:m
Daily utilization (BTS Ramp to Ramp)	10:14	h:m
Daily utilization (BTS Air Time)	8:47	h:m
Yearly utilization (BTS Ramp to Ramp)	3734	h
Yearly utilization (BTS Air Time)	3205	h
Passenger mile load factor (SWA Annual Report)	76.0	%
Passenger mile load factor (BTS Data)	76.0	%
Passenger load factor (BTS Data)	71.5	%

From examining the BTS data, it does not appear that Southwest Airlines carries a significant amount of cargo or mail in addition to their passengers. Consequently, it is better to use load factor as a measure of transport rather than pounds of payload. The 737-300 and 737-700 aircraft currently operated by Southwest carry 137 passengers in a single-class layout while the 737-500 aircraft can carry 122 passengers. Southwest has ordered 737-800's outfitted to carry 175 passengers; the passenger capacity for the 737 MAX order has not been announced. An ECDF of load factor for Southwest's 2009 737-700 flights was plotted as Figure 4(a).

The distribution of distance flown by Southwest 737-700's was plotted as an ECDF in Figure 4(b). The fleet flew less than 1,500 nmi. 94% of the time, less than 1,000 nmi. 85% of the time, and less than 800 nmi. 75% of the time.

The joint load factor/range density of the Southwest fleet based on the BTS data was plotted in Figure 4(c). There is a clear bias to higher load factor for long range flights which explains the discrepancy between passenger mile load factor and passenger load factor reported in Table 3.

The flight plan altitude/range operation of the Southwest Boeing 737-700 fleet based on the Seed Day data was plotted as a EJPDF in Figure 4(d). Although there are a significant number of flights below 30,000 ft. for ranges less than 500 nmi. the highest density of flights are near the certification ceiling of 41,000 ft. for flights of at least 250 nmi.

The range of airfields used by the Southwest Airlines Boeing 737-700 fleet were explored in Figure 5. All of the airfields utilized by the flights in the BTS data set were looked-up in the combined runway length data set. The airfield elevation and runway length were plotted as ECDF's in Figures 5(a) and 5(b) respectively. Runway lengths for all airports used by Southwest Airlines in 2009 were matched in the runway length data set.

The joint density of the elevation/runway length operation of the Southwest 737-700 fleet was plotted as an EJPDF in Figure 5(c). Most flights occur from airports at low elevation and there is significant bias such

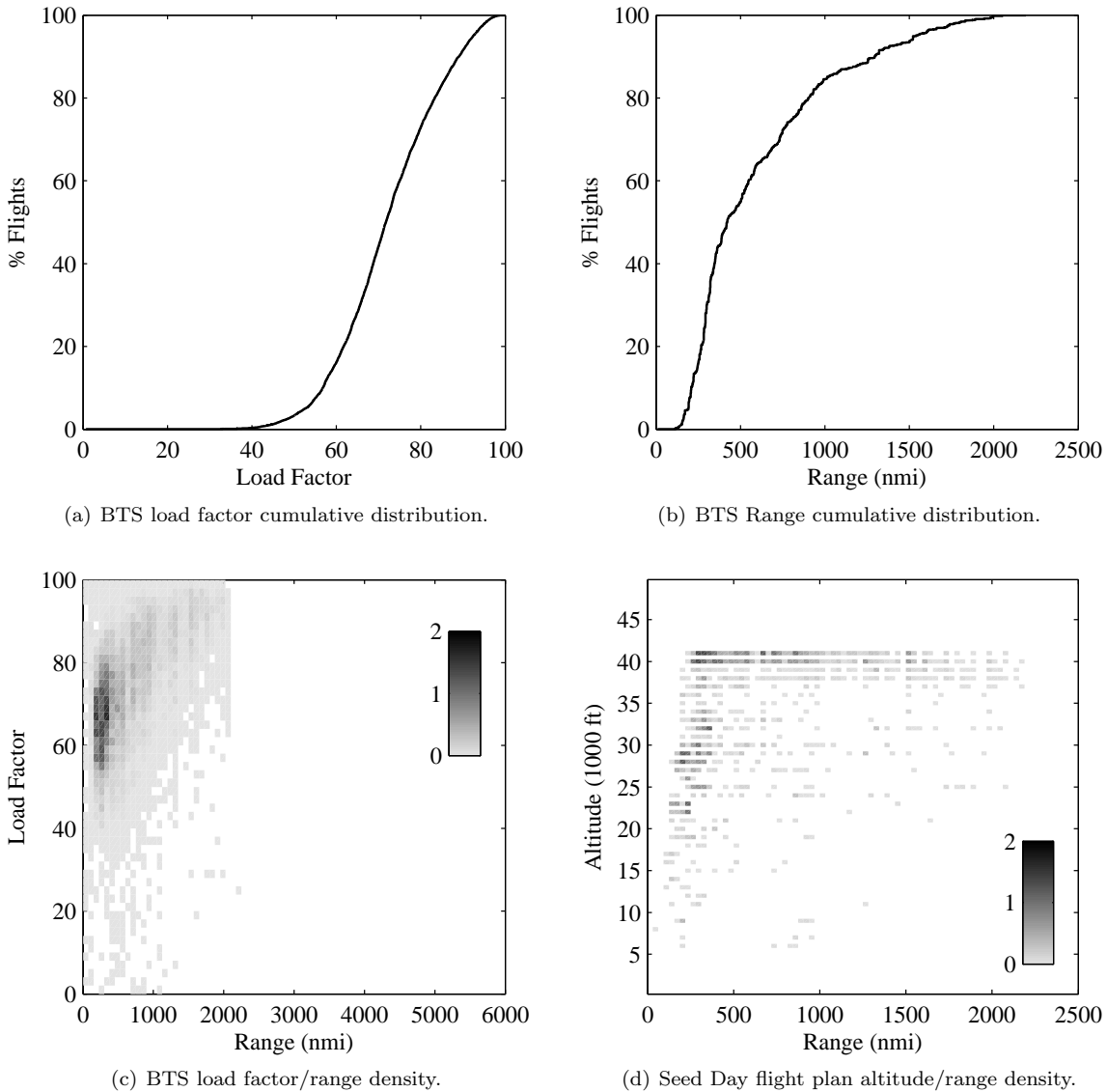


Figure 4. Southwest 737-700 load factor, range, and altitude operations.

that high elevation airfields which are utilized are likely to have long runways. Southwest often operates out of secondary airports in major cities (Dallas-Love, Houston-Hobby, Chicago-Midway); the shorter runways of these airports should be considered when designing a replacement aircraft.

V.A. Proposed Requirements

As with the Cessna 208 discussed earlier, a designer considering the design of a Boeing 737-700 replacement with Southwest as a launch customer may consider designing the replacement aircraft to a set of requirements less than the 737-700's full capabilities. Such a vehicle may be smaller and cheaper than the aircraft it replaces, or the reduced set of requirements may enable consideration of alternative advanced concept aircraft which may not feasibly be designed to match the 737-700's performance in every way.

In becoming the launch customer for the 737 MAX, Southwest ordered 150 aircraft.⁹ If an aircraft were expected to replace all of the 737-300 and 737-700 aircraft in the Southwest fleet, orders could approach 600 aircraft; or more if the airline continues to grow. Southwest's operations demand high utilization; the aircraft should be able to sustain six flights per day and will accumulate approximately 4,000 flight hours

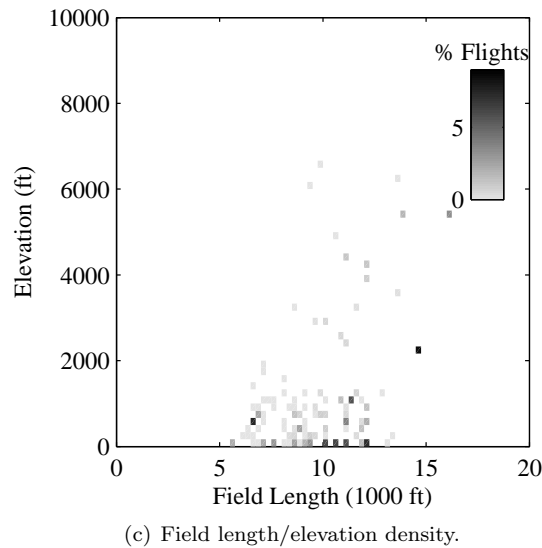
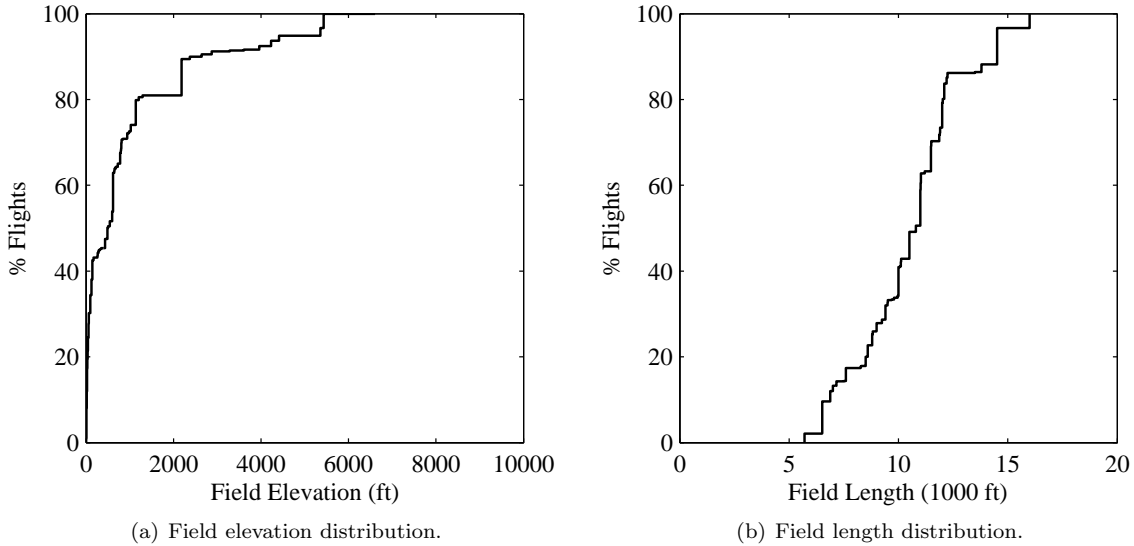


Figure 5. Southwest 737-700 field operations.

per year. The aircraft should be sized to match the 137 seat capacity of the aircraft it replaces, the aircraft must not limit load factor to less than 100%. Depending on the reduction in capability required, the aircraft could be designed to 1,500, 1,000, or even 800 nmi. Operation out of Chicago-Midway’s 6,522 ft. runway at 620 ft. elevation is likely to be most critical.

VI. Conclusions

It is possible to conduct far more sophisticated simulations and trade studies when establishing the requirements for a proposed aircraft design, but such studies are often beyond the scope of the conceptual aircraft design process. It is expected that military operators and commercial manufacturers thoroughly study the requirements before committing to develop a vehicle. However, industrial teams performing quick-look studies as well as students or researchers engaged in aircraft design seldom have the authority, skills, resources, or time to conduct sophisticated requirements trade studies. Examining the operational use of aircraft provides a simplified means of quantitatively studying aircraft requirements.

Aircraft operators and manufacturers are expected to have far more extensive operational databases for

their fleets and products, however, much information about the operation of commercial aircraft can be discerned from publicly available sources. The operational use of two commercial aircraft was studied from the standpoint of guiding the design of their replacement aircraft. This understanding of how the operators use the aircraft may enable their replacements to be smaller or less expensive than current aircraft or it may enable the design of unconventional replacements which might be otherwise unfeasible.

VII. Acknowledgements

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