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A discussion about how efficiently the major US airlines are using their domestic fleets of Boeing 737-800 aircraft

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Abstract

In order to design an aircraft with adequate operational flexibility that satisfies the requirements of several operators on a variety of routes, a civil passenger jet aircraft has to balance a range of conflicting requirements. To this end, the aim of this work is to assess how efficiently one of the world's most popular narrow-body jet airliners - the Boeing 737-800 - performs operationally in terms of its payload and range performance. The study is limited to operations in the domestic US market by the four major US airlines. Actual payload and mission length data for every flight performed in a given year of operation are obtained from the US Bureau of Transportation Statistics,T-100 Domestic Segment (All Carriers). This allows actual operational data to be plotted and assessed against the aircraft design potential, as typified by its payload-range envelope. Three main conclusions are apparent: (i) no flights are operated at either limits of maximum payload or maximum range and there is a considerable amount of unused performance potential; (ii) there is clearly scope to use a smaller aircraft type on many routes; and (iii) there is empirical evidence that shows that efficient and profitable operations occur within a very distinct area of the payload-range envelope.

1.Introduction

The United States of America boasts an extensive air transportation network that serves the largest domestic market for passenger flights in the world (Xu & Harriss 2008). This network is based predominantly on the hub-and-spoke principle, which co-exists with point-to-point services (Shaw 1993, Alderighi *et al* 2005), and flying has become the *de facto* mode of travel for trips between major cities or for distances exceeding 500km.

The major US airlines serving this domestic passenger market are American Airlines, Southwest Airlines, Delta Airlines and United Airlines[1] (Statistica, n.d.). These four airlines also happen to top the league tables for operating the four largest fleets in the world, carrying the most passengers in the world, and offering the most destinations worldwide. For their domestic passenger operations, all four airlines make extensive use of narrow-body jet aircraft, as typified by the Boeing 737 series or Airbus A320 series. These aircraft types are ideally suited to the sort of distances, passenger numbers, and flight frequencies that characterize the US domestic passenger market, and they also represent a substantial proportion of each airline's total fleet; it is noted that Southwest Airlines exclusively operates only Boeing 737 models. See Table 1 for further details.

[1] The data reported herein for the four major carriers does not include any regional subsidiaries such as American Eagle or Delta Connection.

For brevity's sake, this study is limited to a single aircraft type - the Boeing 737-800 – as operated by the four major US airlines. The 737-800 is a twin-engine jet airplane designed to operate over short to medium ranges, seating 160 passengers in a two-class layout or 184 passengers in a one-class layout (Boeing 2013). The choice of aircraft type was made on the basis it is the most widely used narrow-body jet aircraft in the current US domestic market. Clearly, it would not be so popular if it did not meet a very demanding set of market requirements.

The aim of this work is to assess how efficiently the four major US airlines are using their Boeing 737-800 types by investigating how well matched it is to its operational mission in terms of its payload and range performance. This task is made possible by the US Bureau of Transportation Statistics,T-100 Domestic Segment (All Carriers) which contains, amongst other things, all the actual operational data specifying the payload and mission lengths flown by all airlines domestically within the USA for a given aircraft type during a given month, quarter, or year of operation (US DoT BTS n.d.). When such data is plotted and assessed against the aircraft type's design potential, as typified by its payload-range envelope, an interesting pattern of usage emerges. Operational data is presented for two years, 2006 (before the global financial crisis) and 2016 (ten years later), to illustrate how the major US airlines are utilizing their domestic 737-800 fleets. This is the first known presentation of such data and it tells an interesting story.

Table 1. Summary of the four major US Airlines and their current fleets of Boeing 737-800

Airline	Total fleet size[A]	No. of Boeing 737-800[A] in service	Shortest Scheduled Leg using Boeing 737-800[B]	Longest Scheduled Leg using Boeing 737-800[B]
American Airlines, Inc.	951	304	100km (PBI-MIA[C])	4,384km (MIA-SEA)
Delta Airlines, Inc.	875	77	151km (PHL-JFK)	4,202km (LAX-BOS)
Southwest Airlines, Co.	718	191	220km (GRR-MDW)	3,938km (OAK-BWI)
United Airlines, Inc	750	141	108km (MKE-ORD)	4,580km (ORD-ANC)

A – https://www.planespotters.net/ (current April 2018).
B – (US DoT BTS n.d)
C – See Appendix 3 for a list of IATA codes for US domestic airports.

2. Background

2.1. Aircraft payload-range envelopes

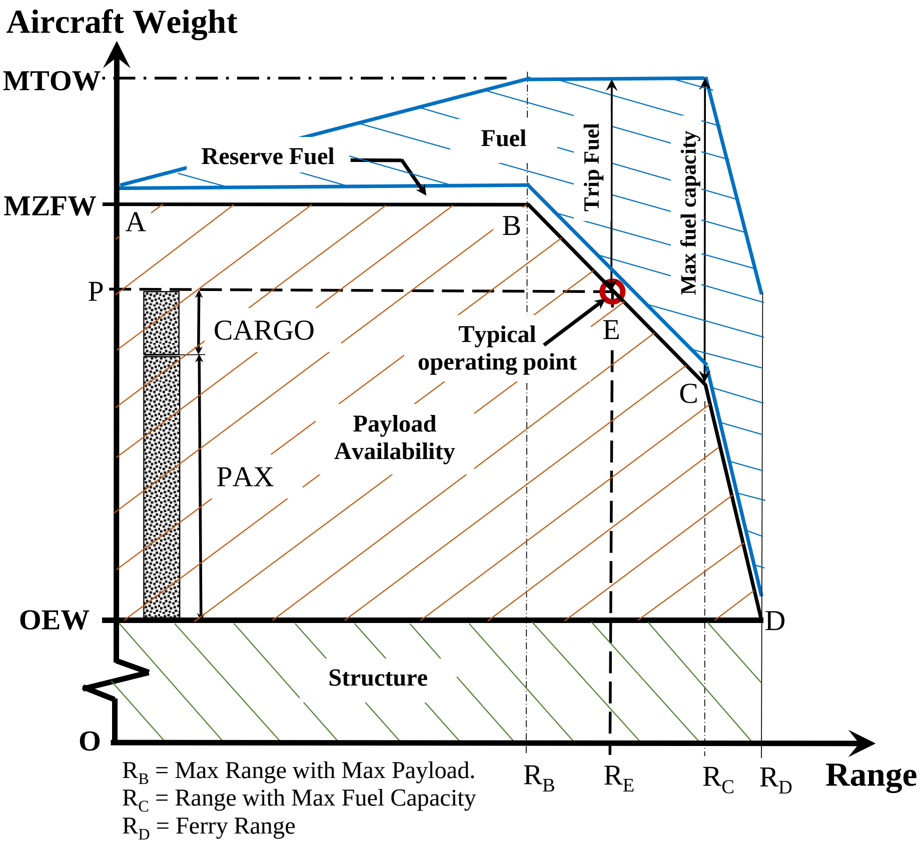
The primary means of assessing the overall performance of a civil aircraft is from its payload-range graph, which provides an envelope showing how the available payload capacity varies with flight range. Full details can be sourced elsewhere (Torenbeek 1982, Martinez-Val, Palacin & Perez 2008) and only a brief description is presented here. A typical civil aircraft weight build-up, illustrating the formation of the payload-range envelope, is shown in Figure 1. Strict definitions of the various terminology used here are provided in Appendix 2.

The horizontal line AB is fixed at the Maximum Zero Fuel Weight (MZFW) of the aircraft. In the region AB, the difference between the MZFW and the OEW equals the payload capacity. Since the fuel tanks are only partially filled in this region the full payload can be transported for ranges extending to R_B simply by increasing the fuel quantity. The gross weight of the aircraft increases along line segment AB as fuel is added but remains less than the Maximum Take Off Weight (MTOW) value until Point B is reached. At B the aircraft

weight reaches its limit, set by the MTOW value, and this point also represents the maximum possible flight range R_B that the aircraft can attain with its maximum payload. According to Morrell (2011) this is the point of maximum operational efficiency. However, there still remains spare fuel capacity because the fuel tanks are only partially filled.
Between points B and C, the MTOW limits the gross weight of the aircraft, which remains constant in the region BC. From Point B, the range may now only be increased by exchanging fuel weight for payload weight, i.e. payload is off-loaded whilst fuel is added, thus maintaining a constant gross weight. Point C occurs when the fuel tanks are completely full, a limit that is set by the aircraft's fuel tank capacity.

In the region CD, further increases in range can now only be achieved by progressively reducing the payload since no additional fuel can be accommodated. For commercial use the region CD is unimportant and uneconomic.

Figure 1. Generic payload-range envelope for a typical civil aircraft



With further reference to Figure 1, a typical operating point for most civil aircraft is indicated by the point E. Given the performance potential typified by the payload-range envelope, one would expect the most efficient flights to occur relatively close to the boundary line, AB-BC, with Point B representing the theoretical point of maximum operational efficiency (Morrell, 2011). Refer also to the discussion in Section 4.1, Figure 6(a) and 6(b). However, for domestic operations in a country the size of the USA, routes vary wildly in both leg distance (range) and passenger demand (payload), meaning that in practice most of the area beneath the bounding envelope is representative of "typical" missions. Whether such missions are actually economical and profitable for the airlines, remains to be seen. Clearly all airlines will try to use the aircraft type that is best-suited to the route in question.

2.2. How is "operational efficiency" defined?

Whilst there are various measures of aircraft efficiency as discussed by Hileman et al (2008), the most widely used metric of efficiency is given by:

(Total payload carried x great circle range) / fuel burnt. Units [kg-km/MJ].

This metric provides a measure of productivity or useful work done (payload moved a given distance) per unit of fuel energy consumed by the aircraft (Nangia 2006, Hileman et al 2008). Whilst the payload and range (distance) for a given flight are readily available from the T100 database, there is no available data for the corresponding amount of fuel burnt at the airline and aircraft type level – this data, if it does exist, remains company confidential to the Airline and/or Boeing. It is also noted that the fuel burn varies significantly as a function of both the payload carried and the mission range for a given trip, and less so with a variety of other operational factors that cannot easily be predicted[2] . The lack of aircraft-specific fuel burn data[3] prevents a quantitative determination of efficiency herein, which is noted as a limitation of this work.

Hence the term "efficiency", as used in this paper, must be understood to be a qualitative measure rather than a quantitative one. The qualitative assessment used herein is based on the premise that short range flights with any payload fractions are understood to be inefficient since most of the flight is spent climbing and descending, as are long range flights with low payload fractions due to the significant fuel mass required. Conversely, medium range flights with modest to high payload fractions – representing the optimum design point(s) for the aircraft - are known to be more efficient (Torenbeek 1982, Park & O'Kelly 2014).

2.3. Bureau of Transportation Statistics, T-100 Domestic Segment (All Carriers)

The Bureau of Transportation Statistics is a US Department of Transport database freely available to the general public that provides a wealth of data on commercial aviation, multimodal freight, and transportation economics (US DoT BTS n.d.). The Air Carrier Statistics database, referred to as Form 41 Traffic, contains domestic and international airline market and segment data. Certificated U.S. air carriers report monthly air carrier traffic information using Form T-100. The data is collected by the Office of Airline Information, Bureau of Transportation Statistics.

[2] These operational factors include the cruising altitude (often decided by ATC controllers, not the aircrew), en-route traffic conditions (which means the cruising altitude can change several times during a single flight), airport restrictions on climb-out to minimise the noise footprint (which means more fuel is consumed because the flaps must be extended for a longer time), and, of course, the fact that in straight and level cruise conditions, the fuel consumption reduces as the plane gets lighter as it gradually burns its own fuel (which is a key assumption used in deriving the Breguet Range equation).

[3] Although some predictive work on passenger aircraft fuel burn has been reported (Nangia 2006, Hileman et al 2008), it is of a generic nature and is not relevant to the current work.

2.3.1 T-100 Domestic Segment (All Carriers)

The T-100 Domestic Segment (All Carriers) provides the source information for this study, since it contains domestic non-stop segment data reported by both U.S. and foreign air carriers, including: carrier, origin, destination, aircraft type and service class for transported passengers, freight and mail, available capacity, scheduled departures, and departures performed, when both origin and destination airports are located within the boundaries of the United States and its territories. It should be noted, however, that when considering a given type of aircraft, such as the Boeing 787-800 this database does not distinguish between types that come with differently tuned CFM56-7 turbofan engine variants, different weight variants, or the later models that are equipped with blended or split scimitar winglets.

2.3.2 Data filtering and manipulation

The US domestic data used in the current work were filtered by year, aircraft type and airline to provide the following information:

- Year: User specified (2006 and 2016 chosen).
- Carrier: American Airlines, Southwest Airlines, Delta Airlines and United Airlines.
- Origin: All domestic US.
- Destination: All domestic US.
- Distance: the distance of a flight segment between the points of origin and destination. This is given in statute miles and converted to *km*. (1 mile = 1.6093km).
- Aircraft type: Item ID 614 denotes a Boeing 737-800.
- Transported passengers: the number of passengers on each flight was rendered a weight in *kg*, using the industry standard average weight of 100kg per person, including his/her checked baggage. AC120-27E (Par 201) recommends allotting a weight of 220lbf per passenger for aircraft operation (AC120-27E 2005).
- Freight and mail: the weight of both freight and mail is given in *lbf*. This is summed to give a weight in *lbf* and then converted to *kg*. (1 lbf = 0.4535 kg). The freight and mail weight was added to the passenger weight to obtain the total payload in *kg* per flight.
- Departures performed: for a specified time period, the T-100 database sums the payload (passengers, freight and mail) for a regular repeated flight segment service. Hence the total payload was divided by the number of departures performed to obtain an average value per flight in *kg*.

2.4. Methodology

The title problem was investigated using secondary data. This enabled a deductive approach to be used based on proven quantitative methods. The data for this study were obtained from the aircraft manufacturer’s Airplane Characteristics for Airport Planning manual (Boeing, 2013) which furnished basic information about the Boeing 737-800 and its payload-range envelope, and the US DoT T-100 database (US DoT BTS n.d.), which was the source of all the operational data. All subsequent data manipulation followed standard statistical procedures.

3. Results

3.1. Operational performance data in 2006

The payload-range operational data for domestic US flights in the year 2006 - before the advent of the global financial crisis - is plotted for two of the four major US airlines in Figure 2. The reason only two airlines are shown is simply because neither United Airlines nor Southwest actually owned and operated any Boeing 737-800 types in 2006. United Airlines began operations with this type in 2010 (Planespotters n.d.) followed by Southwest in 2012

(World Airline News 2012). The clustered data points in Figure 2 show the actual operational payload-range parameters for the whole year 2006. It is noted that a single point may represent a large number of flights between the same points of origin and destination, such as those on a regular daily shuttle service. For reference purposes, these data points are bounded by the actual payload-range envelope of the Boeing 737-800, denoted by the line segments *A-B-C-D*, as explained in Appendix 1.

In 2006, Delta operated some 73,144 non-stop flight segments using its fleet of Boeing 737 800s, compared with American Airline's 68,885 flights. Delta Airlines usage shows a more uniform coverage within the payload-range envelope than American Airlines, suggesting a broader domestic route network. It is noted both carriers fall short of the full payload potential for any flights, achieving a near-constant ceiling just above 15,000kg. This may be due to an operational policy intended to minimise wing fatigue damage during the ground-air-ground cycle and hence mitigate maintenance overheads, but it may also reflect operational contingencies such as airport congestion, airline fuel reserve policy, or allowances for Air Traffic Control routing. Regarding range, it is evident the Boeing 737-800 is eminently well-suited to the domestic US network, since no routes flown stray into the "uneconomic" region *C-D* of the payload-range envelope.

Figure 2(a). Delta Airlines domestic US operations using Boeing 737-800s in 2006

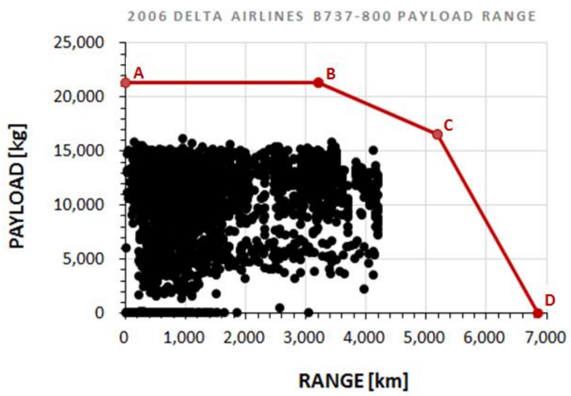


Figure 2(b). American Airlines domestic US operations using Boeing 737-800s in 2006

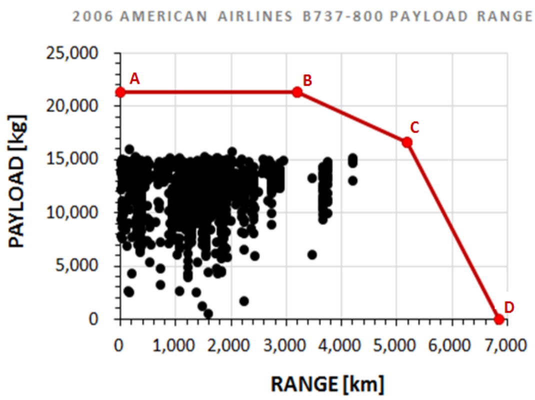


Figure 3 shows the same plots, but this time statistically decomposed into 200km range increments with average payloads and corresponding frequencies. The histogram is based on 200km range increments, with the first bin running from 100km – 299km and centred at 200km, the second bin running from 300km – 499km and centred at 400km and so forth. Note each range increment in the histogram and the corresponding payload-range chart are aligned. It is interesting to note that both airlines exhibit distinctly different modes of operation, reflecting their respective route network and service frequency.

Figure 3(a). Delta Airlines domestic US operations in 2006 – Average Payload Frequency Histogram

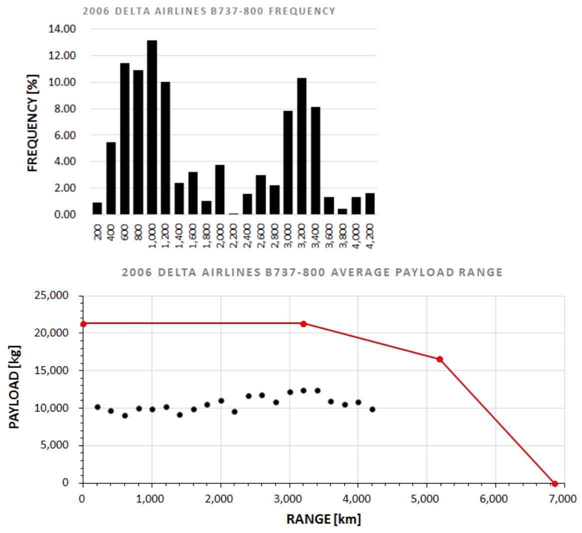
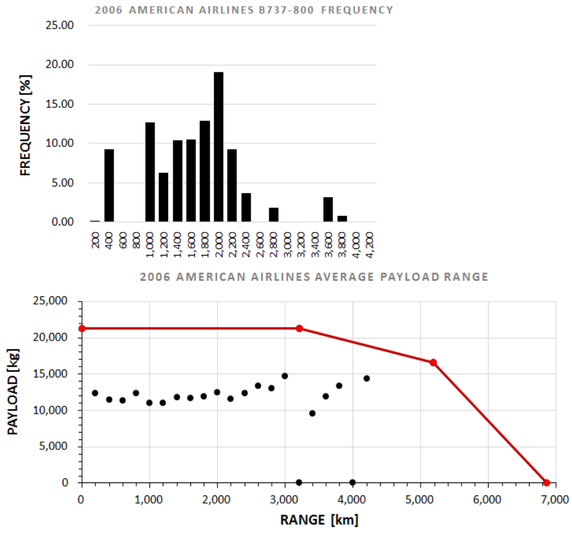


Figure 3(b). American Airlines domestic US operations in 2006 – Average Payload Frequency Histogram



Delta Airlines' operations exhibit a clear bi-modal distribution centred on short-haul routes of just under 1,000km with an average payload of just 10,000kg and again on longer haul routes of approximately 3,200km with an average payload of 12,000kg. It is noted that there is a slight increase in the average payload at greater ranges, indicating that longer routes are flown with more passengers and/or cargo. In contrast, American Airlines shows a more normal distribution of frequencies centred nearer 2,000km with an average payload of 12,000kg.

3.2. Operational performance data in 2016

The payload-range data for domestic US flights using Boeing 737 800s in the year 2016 is plotted for each of the four major US airlines in Figure 4. These illustrate the movements of a large cross-section of the travelling public within the USA some 8 years after the global financial crisis. American Airlines operated 278,051 flights, a massive increase compared with its performance in 2006. United Airlines and Southwest operated 117,203 and 194,447 flights respectively. Only Delta Airlines saw a reduction in its flights compared with 2006, operating some 65,523 non-stop flight segments. Compared with 2006 data, it is apparent that the overall total number of flights in the US domestic market has increased, reflecting the addition of new routes and a growth in the frequency of connecting services. Although all four legacy airlines suffered significant losses and restructuring during and just after the global financial crisis (OIG 2012) they have nonetheless returned to profitability through this increased level of market growth (Delta Airlines Inc. 2016, American Airlines Inc. 2016, United Airlines, Inc, 2016, and Southwest Airlines, Co. 2016).

Figure 4(a). Delta Airlines domestic US operations using Boeing 737-800s in 2016

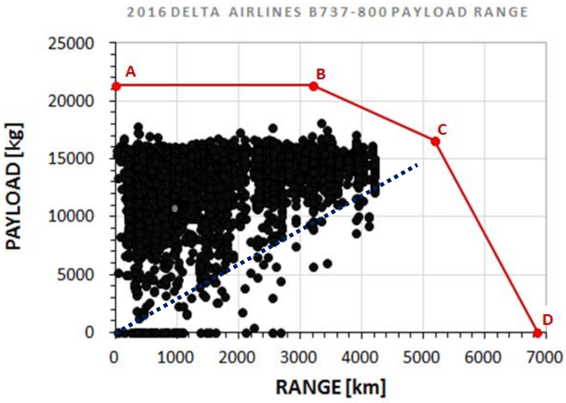


Figure 4(b). American Airlines domestic US operations using Boeing 737-800s in 2016

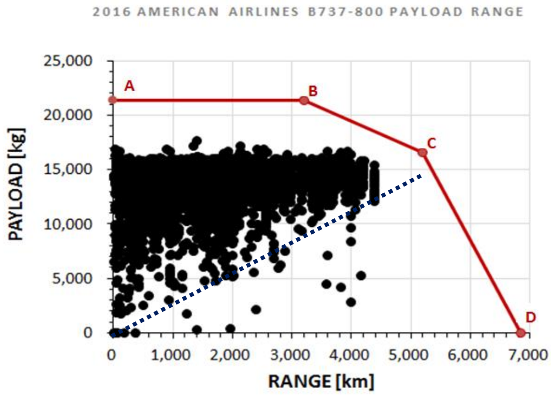


Figure 4(c). United Airlines domestic US operations using Boeing 737-800s in 2016

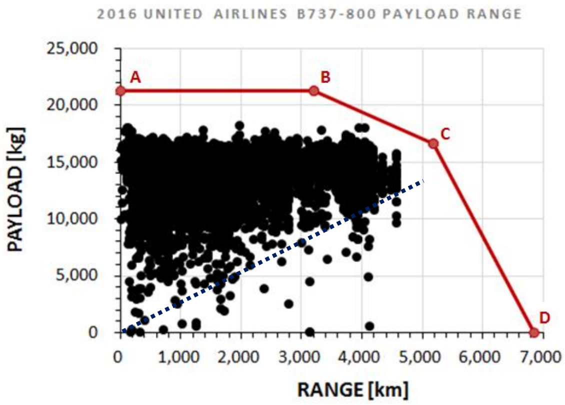
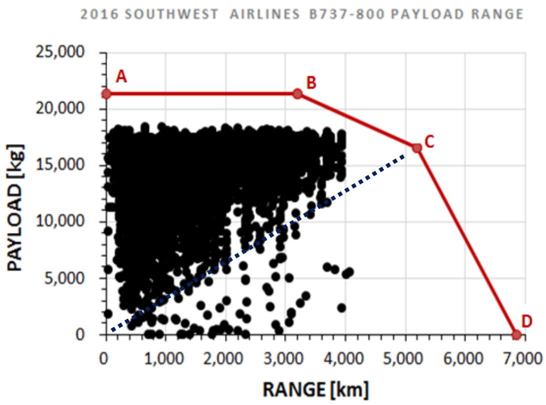


Figure 4(d). Southwest Airlines domestic US operations using Boeing 737-800s in 2016



Comparing Figures 4(a) and 2(a), Delta Airline shows a marked change in operational performance, with a clear reduction in the longer range-lower payload category. This is likely a deliberate company policy to remove inefficient flights from its service network. In both 2006 and 2016, Delta also shows a large number of zero-payload ferry flights. When comparing Figures 4(b) with 2(b) American Airlines exhibits similar operational patterns but with a far denser clustering of data, reflecting the significant increase in flights that have occurred for this airline since 2006. Whilst there is no 2006 data available to compare United Airlines and Southwest Airlines, each set of 2016 data, as shown in Figure 4(c) and 4(d), displays a similar pattern, with United's extending to the greatest range of 4,580km for its flights linking Chicago and Anchorage.

For all the airlines considered in Figure 4, there is a clear demarcation of payload-range data about a diagonal line running from the origin to just below Point C in the Payload-Range diagram. (This is shown by a dotted line in Figure 4). The vast majority of operations occur above this line, which provides empirical evidence to support the notion that these flights must be profitable and to some extent efficient. It is surmised that there is more to this than purely aircraft performance capability and efficiency, as discussed in Section 4.1. The region with flight ranges less than 1,000km is known to be inefficient from a performance viewpoint simply because a significant portion of the trip is spent climbing to altitude and then descending, which is not an efficient design regimen. However, there is a compelling economic reason for airlines to operate such flights, namely to gain a share of lucrative short-haul routes such as New York – Washington DC (350km) which command very high ticket prices due to a constant high demand. Hence there is an economic imperative to offer certain services that may not use the optimum design potential of the aircraft. This is the reality of operating an airline, which goes beyond pure design potential.

The very light scattering of operational data beneath the diagonal demarcation line strongly suggests these flights are inefficient and possibly uneconomic. Most are for longer range flights with relatively low payload levels, indicating a generally inefficient operation. All carriers fall short of the full payload potential for any flights, but achieve slightly higher peak payloads than in 2006, reaching a near-constant ceiling just above 16,000kg. This is likely due to increased passenger load factors. Southwest clearly carries the highest maximum payloads of all four major airlines, peaking close to 18,000kg.

Figure 5 shows the same plots, again statistically decomposed into 200km range increments with average payloads and corresponding frequencies. It is interesting to note that all four airlines exhibit different frequencies of operation by distance, again reflecting their respective route network and service frequency. It is also surmised that seasonal effects and airport location factors could influence the heterogeneity of the payload among different periods of operation and between points of origin and destination. The most frequent flights occur at ranges between 1,500km - 2,000km, with an average payload of 13,000kg. There is a general upwards trend in the average payload with increasing range; the longest routes generally achieve a higher passenger load factor due to fewer flights being available.

Comparing Figure 5(a) with Figure 3(a), the distinctly bi-modal frequency distribution seen in 2006 has softened somewhat in the intervening 10 years; the latter pattern still exhibits a generally bi-modal shape, but the peaks are less distinct and the intervening frequency values have increased, indicating a broader spread of routes and services offered. Comparing Figure 5(b) with Figure 3(b), American Airlines has maintained a normal distribution of flight frequencies, but the 2006 sharp peak value showing 20% of flights occurred at 2,000km range has now flattened to approximately 11% spread over each range increment from 1,600km to 2,000km.

Figure 5(a). Delta Airlines domestic US operations in 2016 – Average Payload Frequency Histogram

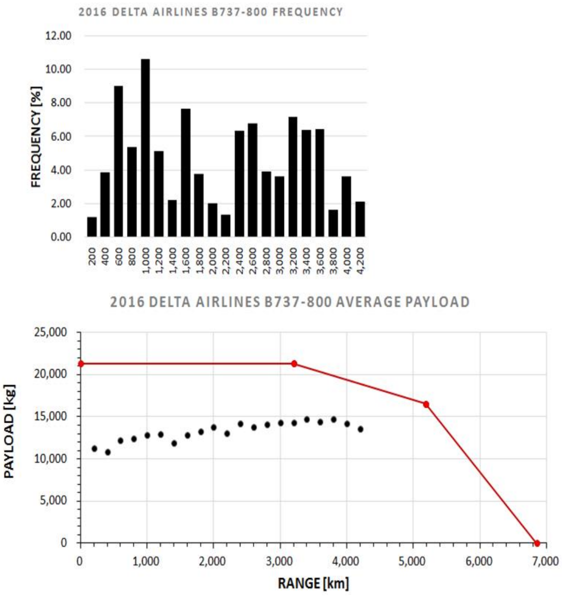


Figure 5(b). American Airlines domestic US operations in 2016 – Average Payload Frequency Histogram

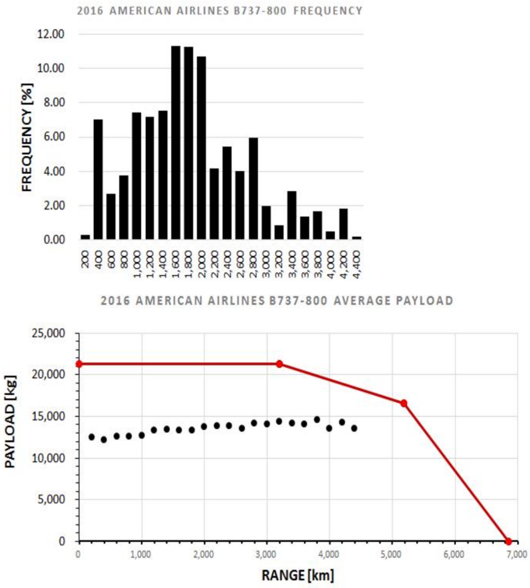


Figure 5(c). United Airlines domestic US operations in 2016 – Average Payload Frequency Histogram

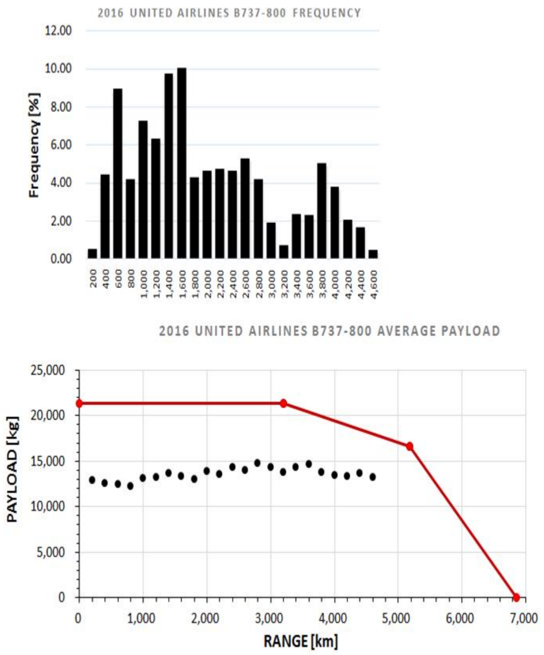
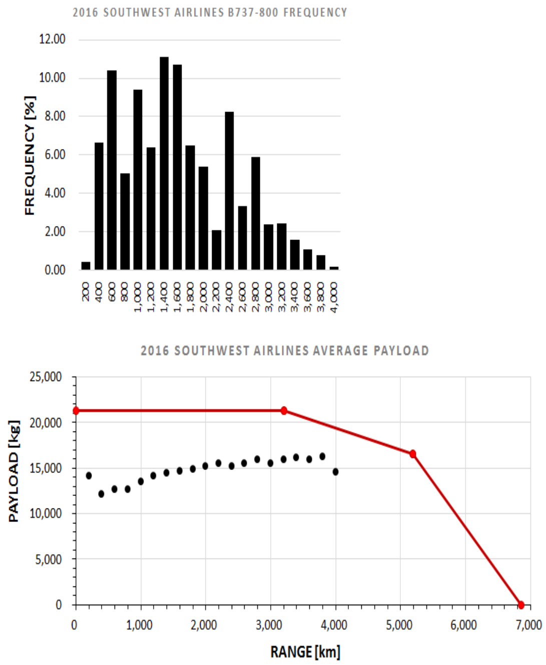


Figure 5(d). Southwest Airlines domestic US operations in 2016 – Average Payload Frequency Histogram



Figures 5(c) and 5(d) suggest United Airlines and Southwest Airlines operate a wide variety of routes with the most popular occurring between 1,400km to 1,600km, jointly accounting for just over 20% of annual flights. The corresponding payload-range data in Figures 4(c) and 4(d) suggest broadly similar patterns of operation, with Southwest achieving the higher maximum payload values.

The average payload quantities shown in Figure 3 and Figure 5 clearly highlight what amounts to an essentially unused performance potential for the aircraft when comparing actual operations to aircraft design potential. The immediate conclusion is that it would be feasible, and more efficient, to operate a smaller aircraft type over these routes.

4. Discussion and synthesis of results

4.1. Aircraft performance potential versus economic necessities

Whilst the payload range envelope represents the performance potential of a given civil aircraft, this is not the only factor that influences how the aircraft is used operationally. When an airline has one basic type of aircraft available to service domestic routes, such as the Boeing 737 or Airbus A320, it is inevitable that a reasonable proportion of missions will be conducted well off the optimum design point(s). Thus when the majority of flights involve thick (high density) shorter range operations over distances of less than 1,000km, some much less, the economic necessity of offering such a service is more of a consideration than exploiting the full performance potential of the aircraft. Clearly, from Figures 2-4 all four major US airlines fly a considerable number of short-haul routes that are inefficient from an aircraft performance perspective, but which are clearly economically profitable from a demand-driven market perspective. These aspects are illustrated schematically in Figure 6(a). It is interesting to see that the actual operational performance (see Figures 2-5) confirms this reasoning, but also fills in the payload-range diagram above a diagonal line running from the origin to just below Point C, as indicated in Figure 6(b). Hence it becomes very difficult to distinguish whether economic factors or aircraft performance factors dictate just how efficient and profitable a given route is – in reality, it will be a combination of the two.

Figure 6(a) – Expected region of the payload-range envelope for efficient operations

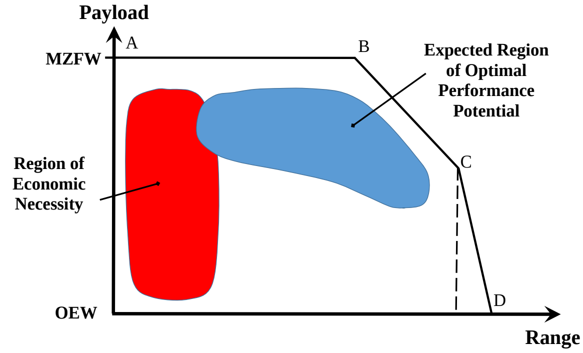
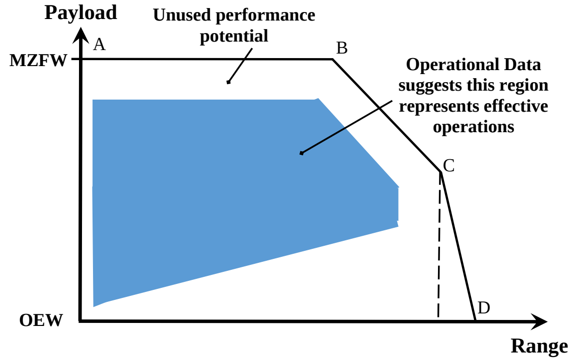


Figure 6(b) - Actual region of the payload-range envelope for effective operations



The Boeing 737-800 is the world's most popular narrow-body jet airliner, and given the profitable status of all four major US airlines (e.g., Southwest Airlines Co. 2016), it must be sufficiently economical to operate over a relatively wide range of payload-range combinations, as seen in Figures 2-5.

Whilst this work has focused on a payload-range envelope derived from the Boeing 737-800 Basic Data shown in Appendix 1, it should nonetheless be understood that this model can be purchased/leased with a number of different gross weight options - see Appendix 1 - so it is possible the airlines try to tailor different aircraft to different routes to optimise their efficiency. However, this level of detail is not present in the T-100 database (US DoT BTS n.d.). Regardless, the clustering of mission data points around 1,500km – 2,000km as shown in Figure 5, where all four major airlines have the highest frequency of operation, appears to be the "sweet spot" which maximises the effect of both economic factors and aircraft performance factors.

4.2. Environmental considerations

Aviation emissions cause greater damage to the world's climate than the same emissions made at ground level (Jardine 2005), and the environmental issues associated with aviation are well documented (Henderson, Martins, & Perez 2012,). Many studies have been conducted on aircraft noise and emissions (CO2, H2O, NOx, CO, and particulates such as SOx, and soot) showing the adverse impact they have on human health and the ecosystem (GAO 2009). From an aircraft performance standpoint, a one-size-fits-all approach is definitely not good environmental stewardship – using a Boeing 737-800 for a relatively short route with a low payload fraction will create similar amounts of noise and emissions during take-off and landing as the same aircraft operating on a much longer route with a much healthier payload fraction. In this respect, a smaller jet aircraft or a turboprop makes much more sense. As has been noted from Figures 2 to 5, the operational payload-range data suggest that modern jet aircraft, as used in the domestic US market, are oversized relative to their in-service operational requirements which results in an unnecessarily heavy aircraft that burns excess fuel on most missions. Frequent flights over short routes will also increase the Airline's maintenance burden.

4.3. "Belly hold" cargo carriage

Air cargo is also an important revenue source for airlines. American Airlines, Southwest Airlines, Delta Airlines and United Airlines all operate as a combination service provider in which passengers are seated in the main aircraft cabin and cargo is carried below in the lower deck "belly hold" compartments (Morrell 2011, Billings et al. 2003). However, it is apparent that none of these four airlines carries more than a token amount of cargo domestically – see Table 2. Clearly, given there is volumetric and payload (weight) availability, the carriage of more cargo would be one simple way in which all these airlines could obtain a greater payload fraction, and boost both profitability and efficiency.

Table 2. Belly-hold cargo carriage in 2016 for domestic flights using the Boeing 737-800 (US DoT BTS n.d.)

Airline	Total payload carried [tonnes]	Passenger payload carried [tonnes]	Freight payload carried [tonnes]	Mail payload carried [tonnes]	Total cargo carried [tonnes]	% Total cargo carried
American Airlines, Inc.	3,796,208	3,759,992	16,789	19,426	36,216	0.95%
Delta Airlines, Inc	896,782	883,264	7,409	6,108	13,518	1.51%
Southwest Airlines, Co.	2,869,132	2,845,046	24,086	0	24,086	0.84%
United Airlines, Inc	1,617,131	1,589,832	7,720	19,578	27,298	1.69%

4.4. What about Turboprops?

For airlines looking to feed their hubs on very short routes (Shaw 1993), turboprops in the 50-70 seat capacity, such as the ATR-72 and the Bombardier Q400, make better economic sense than jet aircraft. Although the jets are indeed faster, on short flights the time difference is marginal; when turboprops are flown at the correct altitude and airspeed, they are extremely efficient and burn less fuel than larger jet aircraft like the Boeing 737 or Airbus A320. Turboprops thus offer a lower hourly rate and hence a more cost-effective and environmentally attractive solution for flights under approximately 750km. Furthermore, turboprop aircraft have much shorter take-off and landing distances than the commercial jets, which means they have access to smaller regional airports thus increasing the potential for an airline to grow its route network. So it comes as something of a surprise to learn that none of the major US airlines operates turboprop aircraft. This is generally attributed to a passenger perception issue[4] - namely that turboprop flights are more cramped, less comfortable, and less safe than even small jets (New York Times, 2000). So, despite their efficiency dividends, the turboprop market in the USA seems moribund. This may explain why Delta Airlines is about to acquire a smaller state-of-the-art, fuel-efficient regional jet aircraft, the Bombardier CS100, sized for 100-133 passengers with a range up to 3,000km (Delta News Hub 2016). By introducing a new jet aircraft, which is better optimised for shorter haul flights having a lower payload capacity than the airline's current fleet of Boeing 737s or Airbus A320s, Delta will help improve both its operational efficiency and passenger appeal – something a turboprop would struggle to achieve in the current US domestic market.

[4] "*An informal survey by Delta recently found that its passengers hate turboprops so much that most are willing to drive two to five hours to avoid flying in them*". (New York Times, 2000)

5. Conclusions

This paper has provided a brief overview of the use of the Boeing 737-800 employed in domestic operations by the four major US airlines in the years 2006 and 2016. The study has focused on plotting and assessing actual operational data taken from the US DoT BTS (n.d.) against the aircraft design potential, as typified by its payload-range envelope.

Three main conclusions are apparent: (i) none of the four major US airlines operates flights at either limits of maximum payload or maximum range and there is a considerable amount of unused (wasted) performance potential; (ii) there is clearly scope to use a smaller aircraft type on many routes; and (iii) there is empirical evidence that shows that efficient and profitable operations occur within a very distinct area of the payload-range envelope which lies above a diagonal line extending from the origin to just below Point C. The lightly scattered data plotted below this “natural” diagonal suggests flights that are inefficient, uneconomic and possibly unprofitable for the airline.

Aircraft performance modelling forms the basis of an airline’s fleet planning decisions. The wrong aircraft in the wrong mission can increase the operational and financial cost for an airline (Flouris 2010). This work has shown that a one-size-fits-all aircraft is not an optimum solution in the US domestic airline market. (Similar plots showing the usage of Airbus A320 types look remarkably similar to the ones shown here for the Boeing 737, so there is little or no performance difference between the types offered by both the main aircraft manufacturers).

Whilst neither thick (high density) short range operations or thin (low density) longer range operations are particularly efficient from an aircraft performance perspective, there are economic imperatives - in the US domestic market at least - to offer the former. This work has shown that there is scope for the major airlines to consider using a smaller aircraft better-suited to serve such routes. Whilst turboprop aircraft could comfortably fulfil this requirement, and would offer reductions in fuel consumption, emissions, noise and hourly rates when compared with jet aircraft, any move in this direction would most likely result in an airline losing significant market share on account of customer resistance. For this reason alone, it seems the major carriers in the US domestic market will continue to operate jet-only services and bear the economic and environmental penalties.

Further research would be beneficial to compare and contrast the use of a particular aircraft type, such as the Boeing 737 or Airbus A320, in different air transportation markets such as Europe, China, India, and Australia. Such work could be of interest to both airlines and OEMs to better inform future designs and fleet planning. However, the lack of publicly available databases that share this information[5] is regrettable.

[5] The *Australian Bureau of Infrastructure, Transport and Regional Economics* (BITRE) database, whilst free, does not contain sufficient classes of data, such as aircraft type or passenger numbers, to permit a similar analysis of Australian operations

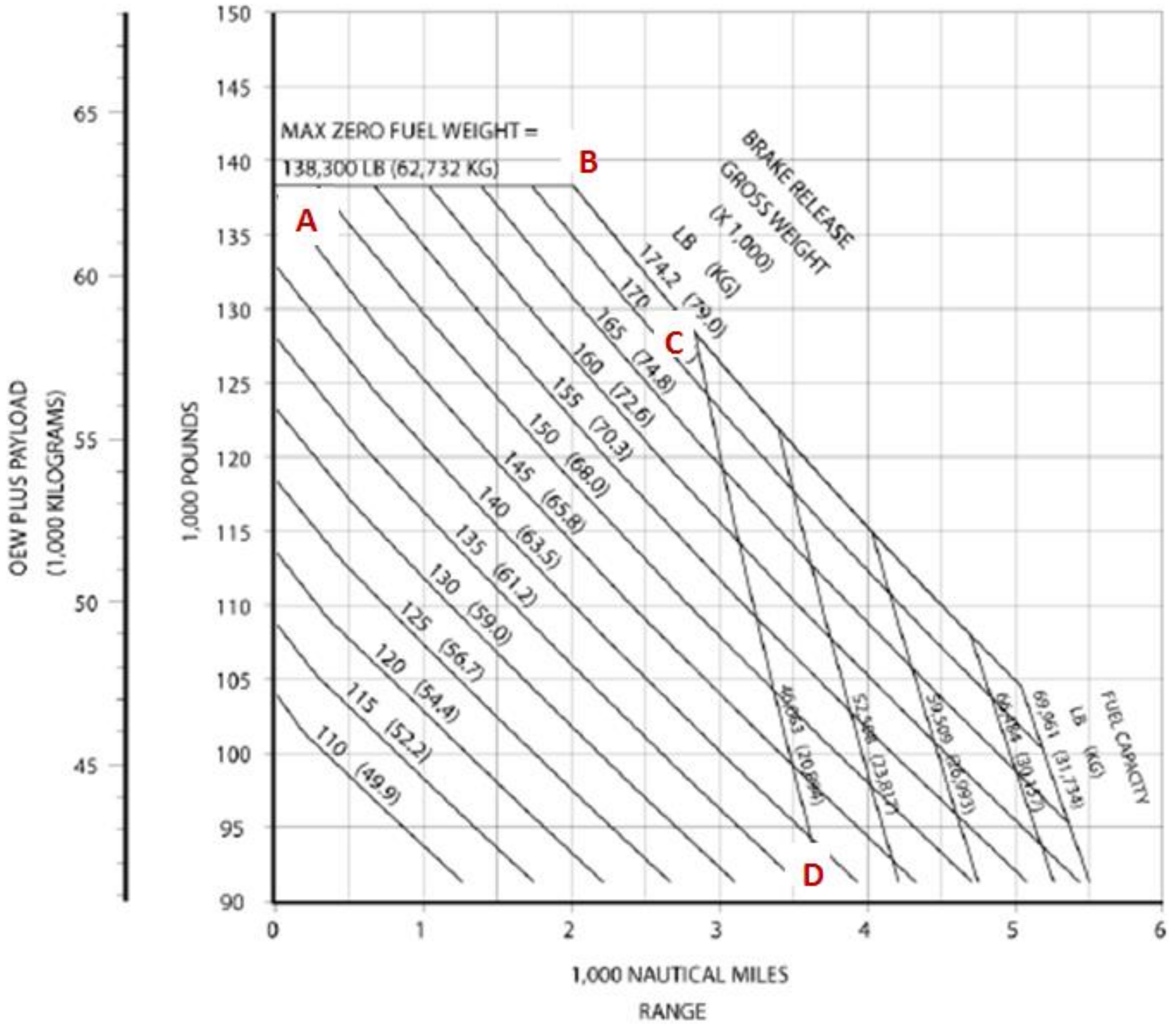
APPENDIX 1. Boeing 737-800 payload-range data

The Boeing 737-800 key payload-range parameters were sourced from Boeing (2013). The largest envelope commensurate with the aircraft basic data was used in this work, as shown in Figure A1.

Boeing 737-800 Basic Data (Boeing 2013)

MZFW = 62,732kg.
OEW = 41,413kg.
Max structural payload = 21,319kg (Payload = MZFW – OEW).
MTOW = 79,016kg. (Brake release gross weight)
Usable Fuel = 20,894kg

Figure A1. Payload Range envelope for a Boeing 737-800 (Boeing 2013)



APPENDIX 2. Key Definitions

Maximum Zero Fuel Weight (MZFW): Maximum weight allowed before usable fuel and other specified usable agents must be loaded in defined sections of the aircraft as limited by strength and airworthiness requirements.

Operating Empty Weight (OEW): Weight of structure, powerplant, furnishing systems, unusable fuel and other unusable propulsion agents, and other items of equipment that are considered an integral part of a particular aircraft configuration. Also included are certain standard items, personnel, equipment, and supplies necessary for full operations, excluding usable fuel and payload. The OEW will vary airline by airline.

Maximum Takeoff Weight (MTOW): Maximum weight for takeoff as limited by aircraft strength and airworthiness requirements. (This is the maximum weight at the start of the takeoff run.)

APPENDIX 3. IATA Abbreviations (US domestic Airports)

IATA Code	**Airport name (location)**
ANC	Ted Stevens Anchorage International Airport (Anchorage, Alaska)
BOS	General Edward Lawrence Logan International Airport (Boston, Massachusetts)
BWI	Baltimore/Washington International Thurgood Marshall Airport (Baltimore, Washington)
GRR	Gerald R. Ford International Airport (Grand Rapids, Michigan)
JFK	John F. Kennedy International Airport (New York City)
LAX	Los Angeles International Airport (Los Angeles, California)
MIA	Miami International Airport (Miami, Florida)
MDW	Chicago Midway International Airport (Chicago, Illinois)
MKE	General Mitchell International Airport (Milwaukee, Wisconsin)
OAK	Metropolitan Oakland International Airport (Oakland, California)
ORD	Chicago O'Hare International Airport (Chicago, Illinois)
PBI	Palm Beach International Airport (West Palm Beach, Florida)
PHL	Philadelphia International Airport (Philadelphia, Pennsylvania)
SEA	Seattle Tacoma International Airport (Seattle, Washington)

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