

FUEL CONSUMPTION OF THE 50 MOST USED PASSENGER AIRCRAFT AS FUNCTION OF FLIGHT DISTANCE

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Abstract

Purpose – The estimation of aircraft fuel consumption of passenger aircraft over varying flight distances is essential in flight planning and environmental assessment. The so-called bathtub curve represents fuel consumption per passenger per 100 km versus flight distance but is not discussed much. This could be changed by representing the function with a simplified analytical equation.

Methodology – Necessary for the calculation are only Maximum Take-Off Mass (MTOM), Maximum Zero-Fuel Mass (MZFM), number of seats, average mass of one passenger (including baggage) and the payload-range diagram of the aircraft. Using these numbers and the Excel table developed by Burzlaff (2017), the fuel consumption was represented as a function of flight distance and five fitted constants (a, b, c, d, e) for each of 50 of the most used passenger aircraft. The constants were fitted using Excel's Solver.

Findings – Fuel consumption represented with the bathtub curve was determined and successfully approximated for 50 aircraft, revealing minimum fuel consumption and its flight distance for each aircraft type. The analytical equation showed minimal deviation from the full model. The analytical equations were applied to an Intermediate Stop Operations (ISO) analysis. The Perth–London route was investigated. Results, showed that using a range- optimized aircraft for two legs can reduce fuel per passenger compared to a single-leg flight by 7.5%.

Research Limitations – The calculation of aircraft fuel consumption is limited only by available data. Mostly, sufficient input data is available or can be estimated.

Practical Implications – Now, absolute fuel consumption and fuel consumption per passenger and 100 km as a function of flight distance can easily be calculated. Respective solutions are given for 50 passenger aircraft. For a given flight distance, the aircraft with the lowest fuel consumption can be found.

Social Implications – Passenger aircraft fuel consumption as a function of flight distance can be discussed openly independent of otherwise missing manufacturer's data based on a simple equation.

Originality – While the bathtub curve itself is not new, this work expands its use by proposing an analytical approximate equation for fast calculations and provides results for 50 passenger aircraft.

Keywords

aircraft, passenger, fuel, consumption, flight, distance, equation, curve fitting

1. FUNDAMENTALS

There are many ways to estimate the fuel consumption of an aircraft, as it is analyzed in previously developed projects (see [1]). In this study the bathtub curve is used. This model takes into account not only the cruise-phase, but also the non-horizontal phases. It allows to estimate the fuel mass using available data from aircraft manufacturers. Furthermore, the graphic obtained helps identify the aircraft's optimal flight distance.

1.1. Breguet Equation and Fuel Mass

To calculate the range a jet powered aircraft can achieve the Breguet equation is commonly used.

$$(1.1) \quad R = \frac{V}{c} \frac{E}{g} \ln \frac{m_1}{m_2}$$

SFC (specific fuel consumption) represented in (1.1) as c and glide ratio, E are not published by the aircraft manufacturer, so the Breguet factor defined in equation (1.2) must be used.

$$(1.2) \quad B = \frac{V}{c} \frac{E}{g}$$

A rearrangement of (1.1) leads to a new definition of the Breguet factor for a simple cruise flight.

$$(1.3) \quad B = B_{cruise} = \frac{R}{\ln \frac{m_1}{m_2}}$$

The Breguet factor in (1.3) only takes care of cruise horizontal flight phases, thus we need to include also fuel consumption in non-horizontal flight phases. Mission

segment fuel fractions are defined as the quotient $M_{ff} = m_{i+1}/m_i$. All fuel fractions can be separated into two different groups: horizontal and non-horizontal flight phases. Cruise, reserve and loiter are considered horizontal flight, while take-off, climb, descent, and landing are considered non-horizontal flight phases (in short: landing and take-off, LTO).

$$(1.4) \quad M_{ff} = M_{ff,CR-RES-LOI} \cdot M_{ff,LTO}$$

The real Breguet factor is then defined as follows.

$$(1.5) \quad B = \frac{R}{\ln\left(M_{ff,LTO} \frac{m_1}{m_2}\right)}$$

We will rearrange the Breguet equation using the Breguet factor to finally calculate the fuel mass needed for the flight including all phases.

$$(1.6) \quad R = B \cdot \ln \frac{m_1}{m_2}$$

Where m_1 is the mass prior to take-off and m_2 is the aircraft mass after landing. The difference between these masses can be assumed to be the burned fuel mass m_{fuel} .

$$(1.7) \quad m_{fuel}(R) = m_2(e^{R/B} - 1)$$

1.2. Payload-Range Diagram

The manufacturer published payload-range diagrams can be used to extract the necessary data for the calculation of fuel mass and range. This chart shows the relationship between the take-off mass and the range achieved in different conditions. We will pay special attention to points A, B, C and D in Figure 1.1.

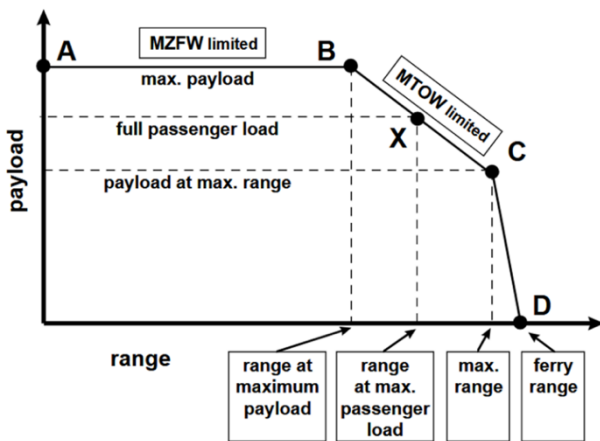


FIGURE 1.1 Payload range diagram [2]

Between points A and B we can see the performance of an aircraft loaded with the maximum payload mass. Point B corresponds to the design point, which means the range achieved with the maximum payload (also called harmonic range). At this point we reach MTOW.

Between points B and C we gradually reduce the payload and increase the fuel mass to extend the range. Point C

corresponds to an aircraft loaded with full tanks, meaning MFW but still having payload.

Between points C and D the fuel tanks remain fully loaded while payload gets reduced until point D, which corresponds to the ferry range, the maximum distance the aircraft can fly, where the aircraft has full tanks and no payload.

Table 1.1 summarizes the masses at every characteristic point of the payload-range diagram.

TABLE 1.1 Characteristic points of the payload-range diagram

	Range	Take-off	Landing weight
B	R_1	MTOW	MZFW
C	R_2	MTOW	MTOW-MFW
D	Ferry Range	OEW+MFW	OEW

$PL_1 = MPL$ and $OEW = MZFW - PL_1$ and $MFW = MTOW - (OEW + PL_2)$. Based on (1.5) we can calculate the Breguet factor of each point of the payload range diagram. As payload decreases between B and C, and C and D, a linear interpolation should be made to obtain the correct Breguet factor.

1.3. Bathtub Curve

The Excel table developed by Burzlaff [3] calculates for every point of the payload-range diagram the Breguet factor, and using (1.7) the fuel mass is obtained. Dividing by 100 km and the number of passengers, which depends on the payload at that point, the bathtub curve is generated.

As an example, we will calculate the bathtub curve of the most used airplane in commercial aviation, Boeing 737-800. Data can be extracted from the Aircraft Dataset by Kühn [4] and the document "737 Airplane Characteristics for Airport Planning" [5]. The required parameters for the calculation are summarized in Table 1.2.

TABLE 1.2 General characteristics of B737-800

MPL	21,184 kg	R_1	3,750 km
$MTOW$	79,016 kg	R_2	5,223 km
$MZFW$	62,732 kg	R_{ferry}	6,850 km
PL_2	16,716 kg	M_{cruise}	0.78
m_{pax}	95 kg	n_{seat}	160

The resulting bathtub curve is shown in Figure 1.2.

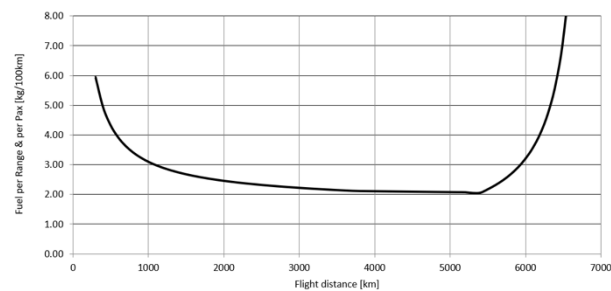


FIGURE 1.2 Bathtub curve for B737-800

As can be seen in Figure 1.2, the fuel consumption per passenger per 100 km increases at both the low and high

extremes of the curve, indicating that flying either near the aircraft's ferry range or over very short distances is not optimal. There is a broad region in the graph where fuel consumption remains nearly constant, reaching a minimum in our case at 5,300 km. To maximize fuel efficiency, the aircraft should operate within this flat region.

2. ANALYTICAL EQUATION

The fuel mass calculation presented before relies on a fairly complex equation that involves multiple interpolations of the Breguet factor, depending on the segment of the payload-range diagram under consideration. This highlights the need to derive a simplified analytical version of the curve, one that can easily be used with a pocket calculator.

As seen in Figure 1.2, the curve presents an asymptotic behavior at the beginning, where fuel consumption per passenger per 100 km tends towards infinity for very short flight distances. To approximate this behavior a term a/x is included in (2.1) with the independent variable placed in the denominator.

The curve also features a nearly constant central segment, running with a light descending slope to the horizontal axis. This section is represented in (2.1) by the constant d and the linear expression ex .

As the curve approaches the ferry range, a similar asymptotic behavior reappears, with fuel consumption per passenger per 100 km increasing sharply. To capture this effect, a term $b/(c-x)$ is included in the analytical approximation (2.1) with the constants b and c .

Together, an analytical approximation is obtained, providing the bathtub curve

$$(2.1) \quad y = \frac{a}{x} + \frac{b}{c-x} + d + ex \quad .$$

Note the units of the parameters a , b , c , d and e . Here we work with distances in km and fuel consumption per passenger in kg/(100 km). Accordingly, the units are as given in Table 2.1.

To determinate the values of these parameters, an additional table is added to the Excel file from Burzlaff [3]. This table calculates the squared error between the simplified bathtub curve and the version obtained through the full calculation. Using Excel's GRG Nonlinear Solver, this error is minimized to identify the optimal parameter values. It is important to note that obtaining a satisfactory solution requires providing reasonable initial guesses – for example, a value of d between -3 and 3, and assigning to c a value close to the ferry range.

The mean squared error (MSE) is calculated from

$$(2.2) \quad MSE = \frac{1}{N} \sum_{i=1}^N (f_i - y_i)^2 \quad .$$

Where N is the number of data points, f_i is the value returned by the model and y_i the actual value for data point i .

TABLE 2.1 Approximation parameter for B737-800

a	1,036.46 kg·km/(100 km)
b	2,331.89 kg·km/(100 km)
c	6,843.22 km
d	2.0422 kg/(100 km)
e	$-2.843 \cdot 10^{-4}$ kg/(100 km ²)
MSE	$9.953 \cdot 10^{-3}$

As shown in Figure 2.1, the approximation closely matches the computed bathtub curve overall, although it fails to capture the precise minimum in fuel consumption at 5,300 km.

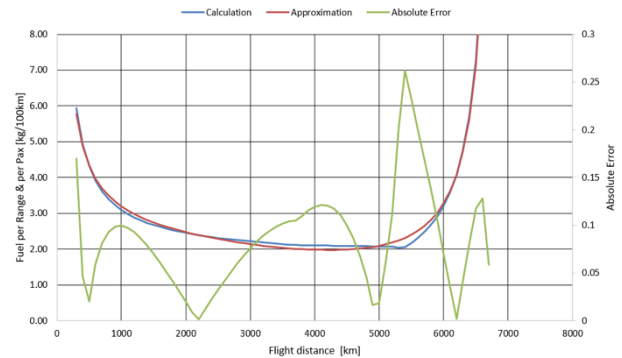


FIGURE 2.1 Bathtub curve, approximated curve and absolute error for B737-800

3. 50 MOST USED AIRCRAFT

The bathtub curve calculation is applied to the 50 most commonly used passenger aircraft, using the Excel model developed by Burzlaff [3], the extended version with the curve approximation, and data extracted from the Excel table by Kühn [4] and the Aircraft Database by Hirsch [6].

To perform these calculations, it is necessary to know the ferry range, which is not included in any of the available datasets but can easily be found in the Manuals for Airport Planning published by aircraft manufacturers. The reserves assumed in the payload-range diagram must be checked too.

The approximation method was successful for all aircraft, yielding a reasonable small margin of error.

4. APPROXIMATE PARAMETERS

The parameters of the analytical equation have been successfully calculated for the 50 most commonly used passenger aircraft. Using these data, an approximation of each of the parameters by leveraging the available values from the aircraft is attempted in order to find a simpler method to calculate the bathtub curve.

The most evident correlation is with parameter c , which consistently corresponds to the ferry range (see Figure 4.1).

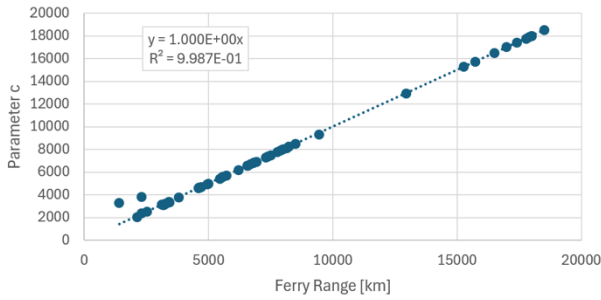


FIGURE 4.1 c versus ferry range of the most used passenger aircraft

The parameter a defines the slope of the first arm of the curve. A relationship has been found between this factor and the ratio of Operational Empty Weight (OEW) to the number of passengers. The parameter a indicates how much effort the aircraft requires to lift itself.

As the OEW is not one of the parameters required in the Excel calculation, the difference between Maximum Zero Fuel Weight (MZFW) and maximum payload is used instead (see Figure 4.2).

For parameter d , a relationship was found based on this parameter: (MTOW minus MPL) divided by the number of seats. This ratio is related to parameters b and d (see Figure 4.3 and Figure 4.4).

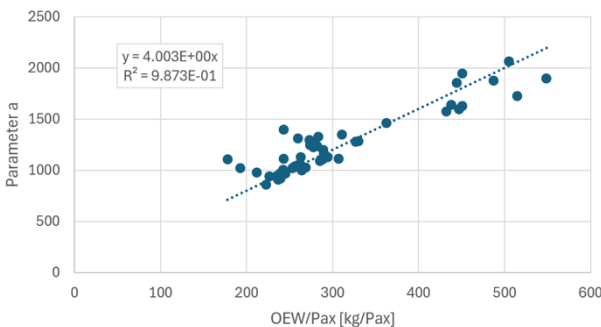


FIGURE 4.2 a versus operational empty weight of the most used passenger aircraft

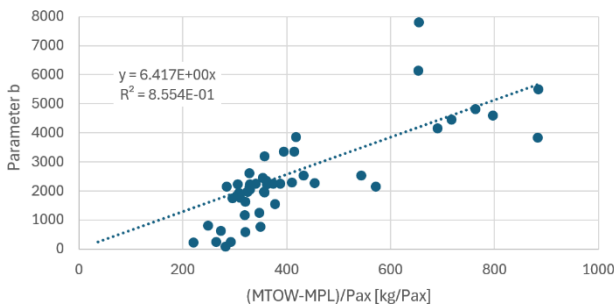


FIGURE 4.3 b versus (MTOW-MPL)/Pax of the most used passenger aircraft

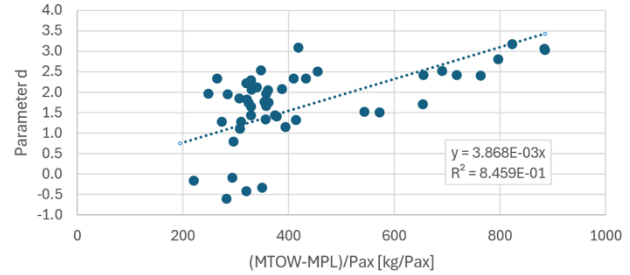


FIGURE 4.4 d versus (MTOW-MPL)/Pax of the most used passenger aircraft

No apparent relationship has been found between parameter e and any of the variables used in the bathtub curve calculation. However, it has been observed that for most aircraft, e takes negative values on the order of 10^{-4} , while for smaller aircraft – those with fewer than 50 seats – it tends to take positive values.

The approximation of the parameters is summarized in Table 4.1.

TABLE 4.1 Approximated parameters for the bathtub curve

Equation	R^2
$a = 3.989 \cdot \frac{MZFW - MPL}{n_{seat}}$	0.9879
$b = 6.443 \cdot \frac{MTOW - MPL}{n_{seat}}$	0.8602
$c = 1.000 \cdot \text{Ferry Range}$	0.9987
$d = 0.003900 \cdot \frac{MTOW - MPL}{n_{seat}}$	0.7261

5. TOTAL FUEL CONSUMPTION

The bathtub curve is a useful tool for identifying the optimal flight distance of an aircraft. However, on its own, it does not provide information on total fuel consumption as a function of range. To determine this, the value obtained from the bathtub curve must be multiplied by the flight distance and the number of passengers.

For the calculations performed in Section 3 we assumed a payload-range diagram model in which the payload is reduced first, followed by the number of passengers.

The goal is to derive the equations that define the number of passengers as a function of range, which will then allow us to calculate the total fuel consumption for a given range.

5.1. Passenger as a Function of Flight Distance

In the payload-range diagram (Figure 1.1), a reduction in payload can be observed starting from point B, which increases the range up to point C, and later to the ferry range, corresponding to an aircraft without payload. This chart does not indicate what type of payload is being reduced – whether passenger load or cargo – so we will break it down below.

As mentioned before, for the payload reduction, the first mass to be reduced is cargo and then, when there is no cargo at all, passenger mass is reduced. We will call this

point with zero cargo and full passengers R_D . Point R_D can be achieved between R_A and R_B or between R_B and ferry range R_C . We will call this scenario 1 and 2 respectively.

Scenario 1 occurs when the maximum passenger mass is higher than PL_B (see Figure 5.1), and scenario 2 occurs when the maximum passenger mass is lower than PL_B (see Figure 5.2).

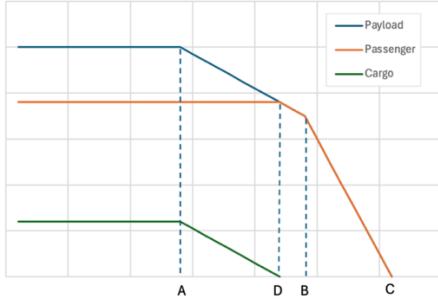


FIGURE 5.1 Detailed payload-range diagram for scenario 1

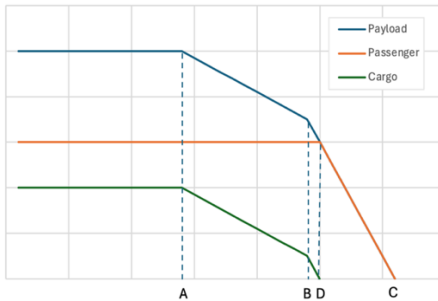


FIGURE 5.2 Detailed payload-range diagram for scenario 2

In the first scenario, passenger mass, m_{pass} can be written as a three parts function.

$$(5.1) \quad m_{pass} = \begin{cases} n_{pax} \cdot m_{pax}, & 0 < R < R_D \\ PL_A - (R - R_A) \cdot \frac{PL_A - PL_B}{R_B - R_A}, & R_D < R < R_B \\ PL_B - (R - R_B) \cdot \frac{PL_B}{R_C - R_B}, & R_B < R < R_C \end{cases}$$

In the second scenario, passenger mass can be written as a two parts function.

$$(5.2) \quad m_{pass} = \begin{cases} n_{pax} \cdot m_{pax}, & 0 < R < R_D \\ PL_B - (R - R_B) \cdot \frac{PL_B}{R_C - R_B}, & R_D < R < R_C \end{cases}$$

Dividing the passenger mass, $m_{pass} = n_{pax} \cdot m_{pax}$ by the mass of one passenger, m_{pax} , the number of passengers for a given flight distance can be calculated for both cases.

5.2. Fuel Consumption versus Flight Distance

Having the function of passengers versus flight distance, taking the values of the bathtub curve and multiplying them

by the range and the number of passengers, the absolute fuel consumption for a given range is obtained.

For the calculation of a fuel consumption diagram, the analytical approximation of the bathtub curve can also be used, instead of the full calculation, so that only the equation parameters – a , b , c , d , and e – and the characteristic points of the payload range diagram are required. Equations 5.1 and 5.2 are used before the first characteristic point.

In scenario 1, between R_B and R_D a linear interpolation is used instead of multiplying the bathtub curve with the number of passengers and range, as this would lead to a curve that doesn't match reality (see Figure 5.3). In scenario 2, after R_D the absolute fuel mass can be considered constant, the limit is achieved, because the aircraft has a limited fuel tank capacity (see Figure 5.4).

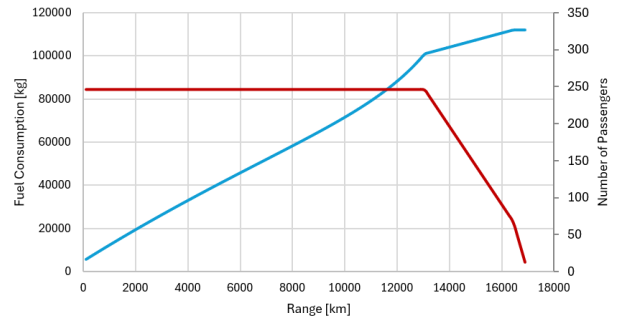


FIGURE 5.3 Passengers (red) and fuel consumption (blue) versus flight distance of A330-200 (scenario 1).

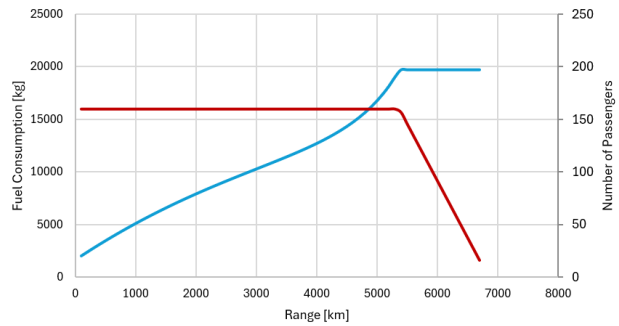


FIGURE 5.4 Passengers (red) and fuel consumption (blue) versus flight distance of a B737-800 (scenario 2).

6. INTERMEDIATE STOP OPERATION (ISO)

As an extension of the discussion on flight efficiency and fuel planning the concept of Intermediate Stop Operations (ISO) is examined – a flight strategy in which a long route is divided into two segments, with a stop for refueling.

Although not common in regular commercial service, ISO can be considered in specific cases where range limitations, payload constraints, or fuel efficiency make a continuous flight less practical.

In evaluating the feasibility and efficiency of ISO, not only

the fuel consumption must be assessed, but also economic and operational implications must be considered. The practical implementation of ISO must account for regulatory and legal considerations, particularly those related to ICAO's Freedoms of the Air.

6.1. Potential ISO Routes and Aircraft

The London–Perth connection has been selected as a relevant case study. Currently operated by Qantas as flight QFA9, this ultra-long-haul route is among the longest nonstop commercial flights in the world. Covering an actual distance of 15,190 km with a total flight time of approximately 17 hours, it serves as an ideal candidate.

Flight data is specified in Table 6.1.

TABLE 6.1 Flight information of QFA9 [7]

QFA9	
Took-off from	Perth, Australia (PER)
Landed at	London, UK (LHR)
Take-off time	WED 02-07-2025 02:17 AM AWST
Landing time	WED 02-07-2025 12:21 PM BST
Total trip time	17 h 4 min
Airline	Qantas
Aircraft	Boeing 787-9 Dreamliner
Actual distance	15,190 km
Direct distance	14,525 km

The bathtub curve for the Boeing 787-9 used in this route is shown in Figure 6.1. Minimum fuel stage length is 14,800 km, where the fuel per range and passenger is 2.14 kg/Pax/100 km. For the route studied, the aircraft is operating after its optimal point, where the fuel consumption starts to increase.

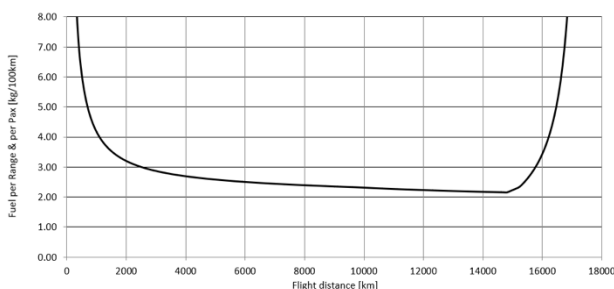


FIGURE 6.1 Bathtub curve of the Boeing 787-9

The Boeing 787-9 has a total of 290 seats. When operating the route under study, the aircraft must fly with a reduced payload, limiting the maximum number of passengers to 268. In other words, it cannot operate with a Passenger Load Factor (PLF) of 1; the highest possible PLF is 0.92. For the defined route and the actual distance, the absolute fuel consumption results in 94,129 kg.

To simplify the study, we will assume that an ISO is carried out by dividing the total distance into two equal legs of 7,595 km which would correspond to a stopover in Dubai, approximately halfway (see Figure 6.2). We will perform the same calculation again using the same aircraft.

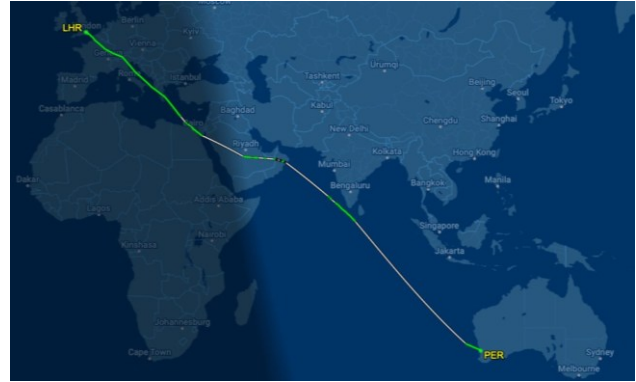


FIGURE 6.2 Flight QFA of the 2nd July 2025 [7]

The fuel consumption of each leg is now 52,921 kg. However, since we are operating in a region further to the left on the payload-range diagram, a PLF of 1 can be achieved. The total fuel consumption amounts to 105,842 kg. When divided by the 290 passengers, this results in 364.97 kg/Pax, and by the flight distance 2.40 kg/Pax/(100 km). Despite the ability to increase the number of passengers to the aircraft's full capacity, the overall fuel consumption has increased compared to the direct flight.

A different approach of the ISO would be using a different aircraft, more suitable for the reduced distance. Using the Fuel per Passenger Excel Table [8] we can find the least consuming aircraft for the desired flight distance, in our case 7,595 km.

The most suitable airplane for this leg of the route, with a fuel consumption per passenger of 121.89 kg/Pax, is the Boeing 777-200ER. Though it may seem unintuitive, extended range versions of aircraft have been used for shorter distances for their good performance. Using the B777-200ER, the absolute fuel consumption for each leg is 45,667 kg, 91,334 kg for the whole route. The route could be operated with 375 passengers, so the fuel consumption per passenger would be 243.56 kg/Pax, 1.60 kg/Pax/(100 km). Figure 5.3 shows the bathtub curve of the Boeing 777-200ER. As can be seen in the bathtub curve, for the stage length desired, the airplane operates before its minimum stage length.

It may seem that the solution to reduce fuel consumption on this route is to perform an ISO using a different aircraft. However, another possibility should also be considered: that the Boeing 777-200ER might be even more efficient when operating a direct flight. If we look at the absolute fuel consumption, we see that the fuel needed for the direct flight with the 777-200ER is 87,593 kg. Although the absolute fuel is lower than with the ISO, the number of passengers has to be reduced to 333 to achieve the whole length of the trip, so the fuel per passenger is slightly higher, 263.04 kg/Pax. This can also be seen in the bathtub curve, as the distance between Perth and London is achieved after the minimum fuel stage length, where the fuel consumption increases rapidly. The results are listed in Table 6.2.

TABLE 6.2 ISO comparison for Perth-London route

B787-9	Direct	ISO
Total Fuel [kg]	94,129	105,842
Change Percentage [%]	0	+12.44
Number of Passengers	268	290
Fuel per Passenger [kg/Pax]	351.22	364.97
Change Percentage [%]	0	+3.91
Fuel Consumption [kg/Pax/100km]	2.31	2.40
Change Percentage [%]	0	+3.9
B777-200ER	ISO	Direct
Total Fuel [kg]	91,334	87,593
Change Percentage [%]	-2.97	-6.94
Number of Passengers	375	333
Fuel per Passenger [kg/Pax]	243.56	263.04
Change Percentage [%]	-30.65	-25.11
Fuel Consumption [kg/Pax/100km]	1.60	1.73
Change Percentage [%]	-30.7	-25.1

As a conclusion of the case study, we can state that performing an Intermediate Stop Operation can lead to a higher fuel consumption, but if it is done with an aircraft especially selected for the stage length, the total fuel consumption can be reduced by 2.97% and the fuel consumption per passenger by 30.7%. The B777-200ER could have been used in the first place. The fuel consumption per passenger and 100 km could have been reduced from 1.73 kg/100 km to 1.60 kg/100 km. This is a reduction of 7.5%.

6.2. Practical Implications

Making an intermediate stop instead of operating a long-haul direct flight involves several practical disadvantages that must be carefully considered.

First, operating costs increase significantly. Landing at an additional airport entails paying landing fees, handling services, security charges, and possibly parking fees. Moreover, operations must be coordinated at a second airport, requiring more personnel, additional logistical support, and more complex planning. These factors raise the overall cost of the journey.

Another important aspect is the increase in total travel time. While each leg may be more fuel-efficient on its own, the time required for landing, refueling, and taking off again adds a delay that can affect the competitiveness of the route, as passengers often prefer quick connections or nonstop service.

From the passenger's perspective, the experience is also affected. Flights with stopovers are generally less appealing than direct flights, as they involve longer travel times and greater exposure to delays or operational issues. On long-haul routes, where rest is especially important, a stop halfway through can be inconvenient and tiring.

In addition, the environmental and social impact must be considered. The take-off and landing phases are the most fuel- and emission-intensive segments of a flight, per minute. Doubling these phases may increase the environmental footprint, as the damage is caused nearer to the surface. Furthermore, each take-off and landing

contributes significantly to aircraft noise and local emissions, which directly affects communities living near airports.

6.3. Regulatory Considerations

To operate an ISO it is necessary, as a minimum, to have the right to land at an intermediate airport for refueling. This stop does not involve boarding or disembarking passengers or cargo and is therefore considered a technical stop.

For this reason, the operation requires the use of the Second Freedom of the Air.

Second Freedom of the Air – the right or privilege, in respect of scheduled international air services, granted by one State to another State or States to land in its territory for non-traffic purposes (also known as a Second Freedom Right). [9]

Since ISO operations are intended for long-haul flights, it is also common to overfly multiple countries. As such, the First Freedom of the Air is also required.

First Freedom of the Air – the right or privilege, in respect of scheduled international air services, granted by one State to another State or States to fly across its territory without landing (also known as a First Freedom Right). [9]

Because the operation involves international flights, passengers must be boarded and disembarked in both the airline's home country and the foreign destination. Therefore, the Third and Fourth Freedoms of the Air are also necessary.

Third Freedom of the Air – the right or privilege, in respect of scheduled international air services, granted by one State to another State to put down, in the territory of the first State, traffic coming from the home State of the carrier (also known as a Third Freedom Right). [9]

Fourth Freedom of the Air – the right or privilege, in respect of scheduled international air services, granted by one State to another State to take on, in the territory of the first State, traffic destined for the home State of the carrier (also known as a Fourth Freedom Right). [9]

Additionally, since the airline's home country is on one end of the route and the technical stop occurs in a third country, it may be desirable to sell seats between the stopover and the final destination to maximize profitability. This would require the Fifth Freedom of the Air.

Fifth Freedom of the Air – the right or privilege, in respect of scheduled international air services, granted by one State to another State to put down and to take on, in the territory of the first State, traffic coming from or destined to a third State (also known as a Fifth Freedom Right). [9]

A total of 79 states signed the International Air Services Transit Agreement [10]. This agreement implies that all signatory countries grant each other the first two freedoms of the air automatically, meaning ISO would be possible between them if also the fourth and fifth freedoms are granted with a bilateral agreement.

This assumes that the airline conducting the ISO (Intermediate Stop Operation) is based at one end of the route. In such a scenario, the airline must navigate a more complex regulatory environment, requiring overflight rights

(first freedom), technical landing rights (second freedom), and traffic rights (third, fourth, and ideally fifth freedom) in at least three different states: the home country, the technical stop country, and the destination country. These requirements make coordination more difficult and reduce route flexibility, especially when bilateral air service agreements are limited or politically sensitive.

However, the operational and regulatory complexity is significantly reduced when the airline is based at or near the midpoint of the route. In such cases the airline's home base can serve both as a refueling stop and as a traffic-handling hub. This setup often allows for easier compliance with international agreements and more efficient route planning.

6.4. Evaluation of Trade-offs

The analysis of Intermediate Stop Operations (ISO) in the context of ultra-long-haul flights, specifically the Perth–London route, demonstrates that this operational model can provide significant improvements in fuel efficiency per passenger, but only under specific conditions. The case study shows that when a suitable aircraft is carefully selected for each leg, an ISO strategy may outperform a single-stage operation in terms of fuel consumption per passenger. In particular, the Boeing 777-200ER operating a two-leg journey with a technical stop in Dubai yielded a notably lower fuel consumption per passenger compared to both the direct operation with the same aircraft and the original Boeing 787-9 configuration.

However, this benefit comes with several trade-offs. Operational complexity increases due to the need for coordination at an additional airport, and economic costs rise from airport fees and ground handling services. Moreover, passenger experience may be negatively affected by longer travel times and reduced convenience compared to direct services.

In regulatory terms, ISO requires careful navigation of international airspace agreements. Access to the First and Second Freedoms of the Air is essential for technical stops, while broader operational and commercial opportunities – such as picking up or dropping off passengers at the stopover – require the granting of additional freedoms. These legal prerequisites may limit the applicability of ISO to specific routes and geopolitical contexts.

Environmental and social considerations also weigh heavily. Though ISO may reduce emissions per passenger in optimized scenarios, the additional noise impact on airport-adjacent communities, caused by duplicated take-off and landing cycles, cannot be overlooked.

In summary, while ISO represents a potentially viable strategy for improving efficiency on very long routes, its implementation is not universally advantageous. The decision to adopt such a model must be based on a detailed case-by-case analysis that incorporates fuel performance, aircraft capability, operational costs, passenger demand, regulatory feasibility, and environmental externalities.

7. SUMMARY AND CONCLUSIONS

This study examined the fuel consumption of passenger aircraft using the bathtub curve, with the aim of simplifying

fuel efficiency analysis across different aircraft and flight distances. The bathtub curve, which plots fuel consumption per passenger per 100 kilometers against range, was calculated for 50 of the most used commercial aircraft. Unlike traditional cruise-only methods, this approach included all flight phases, offering a more realistic assessment of fuel use.

To make the process more practical, a simplified analytical version of the bathtub curve was developed using five parameters. These were optimized in Excel and shown to closely match results from the full model. This analytical form allows for fast estimations and was implemented in Excel tools [8] designed to help users quickly evaluate fuel use and select appropriate aircraft for given flight distances.

The study also extended the bathtub curve application to estimate absolute fuel consumption and investigated Intermediate Stop Operations (ISO) through a case study on the Perth–London route. The findings showed that splitting the route into two legs with an aircraft optimized for the flight distance could reduce fuel consumption per passenger. However, this benefit is not guaranteed. ISO introduces extra complexity, including additional fees, longer travel times, and potential inconvenience for passengers, which may outweigh the fuel savings.

In conclusion, the bathtub curve offers a powerful and accessible way to analyze aircraft fuel efficiency. The simplified model and developed tools provide valuable support for planning and environmental assessment. ISO, while promising in some scenarios, requires careful evaluation of operational trade-offs before implementation.

This paper is based on a Bachelor Thesis [11]. Associated research data is published in Harvard Dataverse [8].

8. SYMBOLS AND ABBREVIATIONS

List of Abbreviations

ISO	Intermediate Stop Operations
LTO	Landing and Take-off
MFW	Maximum Fuel Weight
MPL	Maximum Payload
MSE	Mean Squared Error
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero-Fuel Weight
OEW	Operational Empty Weight
PL	Payload
PLF	Passenger Load Factor
SFC	Specific Fuel Consumption

List of Symbols

B	Breguet Factor
c	Thrust Specific Fuel Consumption
E	Glide Ratio
g	Gravitational Acceleration

m	Mass
m_{pax}	Passenger Mass
M_{cruise}	Cruise Mach Number
M_{ff}	Fuel Fraction
n_{pax}	Number of Passengers
n_{seat}	Number of Seats
R	Range
V	Cruise Speed (as true airspeed)

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