Fuel Consumption Analysis on Boeing 747-400 Based on Cargo Flight Operational Data

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Abstract. Aircraft cruising flight performance, namely fuel consumption can theoretically be calculated using the Breguet Range equation which is influenced by flight distance, aircraft weight, and aerodynamic efficiency. Operational estimation of fuel consumption (trip fuel) can be determined using the operations manual if the weight, flight distance and flight altitude of the aircraft are known. This study compares theoretical fuel consumption estimates and actual data from Boeing 747-400 aircraft from an international cargo airline. Actual fuel consumption data is obtained based on flight records in the flight maintenance log which contains flight routes, fuel onboard, and fuel burned but does not include aircraft weight and payload weight. The results of the analysis from 2 sample routes yield a strong effect between the amount of fuel onboard by fuel consumption and theoretical estimates, which results in a comparison fuel consumption 2.4% and 1.9% of actual data.

Keywords: Flight Cargo, Fuel, Breguet Range, Boeing 747-400

1 Introduction

Air cargo is goods sent or transported using an airplane that is equipped with goods delivery documents. Basically, this type of cargo really prioritizes speed so it doesn't take more than one week if the cargo is abroad. This cargo can be sent via two types of aircraft, namely joining a passenger aircraft or using a special cargo aircraft. Operations on cargo aircraft are generally not much different from operations on passenger aircraft. The difference is mainly in the payload where cargo planes do not carry passengers. However, both have similarities, namely that fuel consumption on aircraft is influenced by weight and flight distance. The heavier the aircraft, the more fuel it uses over the same distance. This paper compares fuel consumption on airline X's cargo flights between data according to the aircraft technical logbook and theoretical calculations with the condition that the payload weight is unknown.

2 Methods

2.1 Fuel Consumption according to ICAO

To obtain fuel consumption for a flight, the amount of fuel consumed at each stage of the flight

AVINER 2023, November 08-09, Jakarta, Indonesia

DOI 10.4108/eai.8-11-2023.2345976

is required. Therefore, ICAO determines the fuel quantities which are then iterated for each aircraft company. The types of fuel based on their function consist of **Taxi Fuel.** Where the fuel is used before take-off and **Trip Fuel.** Where the fuel is used from take-off to landing and the calculation used is :

$$W_{f_{trip}} = W_{f_{climb}} + W_{f_{cruise}} + W_{f_{descent}} \tag{1}$$

Where contains $W_{f_{trip}}$ as a fuel weight on trip phase (kg), $W_{f_{climb}}$ as a fuel weight on climb phase (kg), $W_{f_{cruise}}$ as a fuel weight on cruise phase (kg), and $W_{f_{descent}}$ as a fuel weight on descent phase (kg).

Contingency Fuel. Where the fuel is needed to compensate for unexpected factors and it is recommended to have 5% of the fuel trip so that the calculation used is :

$$W_{f_{cont}} = W_{f_{trip}} \times 5\% \tag{2}$$

Where contain $W_{f_{cont}}$ as a contingency fuel weight (kg).

Alternate Fuel. Where the fuel is used when another destination is needed on a flight and has the same calculation as the fuel trip but the time required is no more or equal to 1 hour.
Reserved Fuel. where the fuel used if given instructions to hold before landing and set at an altitude of 1500 ft for 30 minutes so the calculation used is [1] :

$$W_{f_{res}} = W_{f_{hold}} \tag{3}$$

Where contain $W_{f_{res}}$ as a reserve fuel weight (kg) and $W_{f_{hold}}$ as a fuel weight on holding phase.

2.2 Breguet Range Equation

This equation is used to explain how far an aircraft can fly with certain parameters, and this also influences the amount of fuel consumed [2]. Factors that influence this equation are the ratio of speed to thrust consumption, the ratio of lift coefficient to drag coefficient, and the natural logarithm of the ratio of aircraft weight before and after fuel is burned. The equation is [3] :

$$R = \frac{v\, C_L}{cT\, C_D} \ln \frac{W_1}{W_2} \tag{4}$$

Where contain R as a range (m), v as a cruise speed (m/s), C_L as a lift coefficient, cT as a thrust consumption (%), C_D as a drag coefficient, and W_1 and W_2 as an aircraft weight before and after certain range (kg).

This regression consists of one x regression associated with one y response and is in the form of a straight line. There are also β_0 and β_1 which are unknown constants and ε is a random error component. Parameters β_0 and β_1 are usually referred to as regression coefficients. These coefficients have an easy interpretation and are sometimes useful. The equation used is [3] :

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{5}$$

3 Results

3.1 Fuel Consumption based on Actual Data

To obtain actual fuel consumption data, aircraft technical logbook data is collected on one route. The following is a table of data on the Manas – Hong Kong and Manas – Liege routes:

Table 1. Flight time, Total Fuel Onboard, and Fuel Burned on Actual Data on the UCFM -VHHH Route.

No	Date	Flight Time	Total On Board	Burned
1	15-08-22	5:18	87265	67665
2	26-08-22	5:31	77949	58650
3	31-08-22	5:30	69300	53600
4	07-09-22	5:41	52313	42313
5	09-09-22	5:22	71764	57064
6	12-09-22	5:24	66961	54161
7	14-09-22	5:11	75996	57996
8	16-09-22	5:20	79118	62078
9	19-09-22	5:26	71497	55897
10	21-09-22	5:22	76900	49900
11	23-09-22	5:32	57200	47700
12	02-12-22	5:04	79170	59270
13	19-12-22	5:24	77680	58880

Table 2. Flight time, Total Fuel Onboard, and Fuel Burned on Actual Data on the UCFM - EBLG Route.

No	Date	Flight Time	Total On Board	Burned
1	16-08-22	6:57	108749	87449
2	24-08-22	6:50	104093	83293
3	27-08-22	7:06	102300	82500
4	08-09-22	7:34	106107	89707
5	20-10-22	7:31	107240	85540
6	27-10-22	7:27	107387	86087
7	19-11-22	7:31	107202	86802
8	22-11-22	7:32	105200	85500
9	24-11-22	7:13	104366	85066
10	29-11-22	7:16	104286	83286
11	13-12-22	7:30	102258	85358
12	15-12-22	7:31	106749	87349
13	20-12-22	7:31	96219	79919

After that, a graph is made according to each route with a comparison of total fuel on board with fuel burned. The following is a graph for the Manas – Hong Kong and Manas –Liege routes :

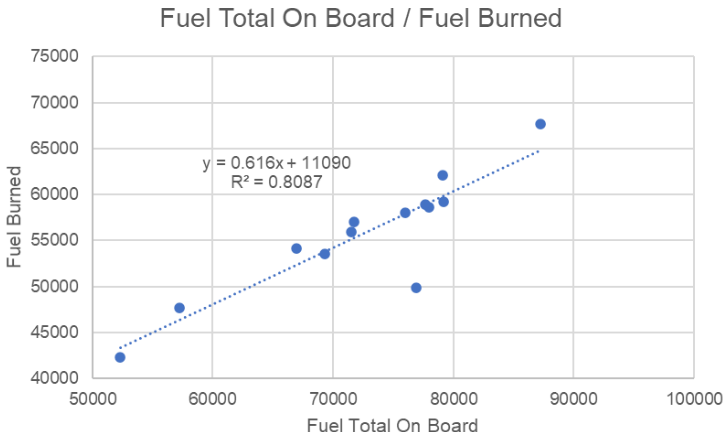

Fig. 1. Graph of Total Fuel Onboard / Fuel Burned on the UCFM – VHHH Route.

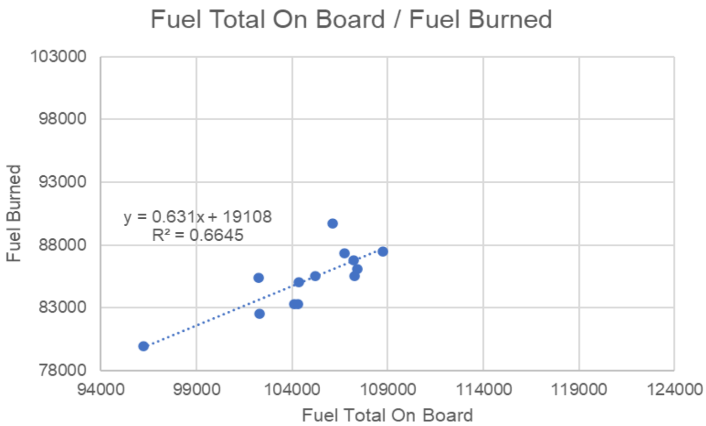

Fig. 2. Graph of Total Fuel Onboard / Fuel Burned on the UCFM – EBLG Route.

3.2 Fuel Consumption based on Theoretical Data

In calculating the amount of fuel consumption using theoretical data, fuel flow calculations were carried out using FPPM (Flight Planning and Performance Manual) data on the Boeing 747-400. By knowing the flight time data using the average of the actual data, adding the assumed altitude at cruise and the total mass of the aircraft is 35000 ft and 370 tons, added with the assumption that the altitude of the aircraft during cruise for the alternative airport route is 23000 ft, and assuming the taxi fuel is 500 kg, we get the following fuel amounts :

Table 3. Numbers of Variable Fuel according to Theoretical Calculations.

Route	$W_{f\ climb}$	$W_{f\ cruise}$	$W_{f\ descent}$	$W_{f\ cont}$	$W_{f\ alt}$	$W_{f\ res}$	Total Fuel Onboard	Fuel Burned

UCFM - VHHH	8600 kg	61308.8 kg	1050 kg	3547.9 kg	15608 kg	4720 kg	95334.7 kg	71458.8 kg
UCFM - EBLG	8600 kg	87298.4 kg	1050 kg	4847.4 kg	14616 kg	4420 kg	121331.8 kg	97448.4 kg

With the total fuel onboard calculation being :

$$TFO = W_{f_{climb}} + W_{f_{cruise}} + W_{f_{descent}} + W_{f_{taxi}} + W_{f_{cont}} + W_{f_{res}} + W_{f_{alt}} \quad (6)$$

Where contains TFO as a total fuel onboard (kg), $W_{f_{climb}}$ as a fuel weight on climb phase (kg), $W_{f_{cruise}}$ as a fuel weight on cruise phase (kg), $W_{f_{descent}}$ as a fuel weight on descent phase (kg), $W_{f_{taxi}}$ as a fuel weight on taxi phase (kg), $W_{f_{cont}}$ as a contingency fuel weight (kg), $W_{f_{res}}$ as a reserve fuel weight (kg), and $W_{f_{alt}}$ as an alternate fuel weight (kg), the fuel burned calculation being :

$$FB = W_{f_{climb}} + W_{f_{cruise}} + W_{f_{descent}} + W_{f_{taxi}} \quad (7)$$

Where contains FB as a fuel burned (kg), $W_{f_{climb}}$ as a fuel weight on climb phase (kg), $W_{f_{cruise}}$ as a fuel weight on cruise phase (kg), $W_{f_{descent}}$ as a fuel weight on descent phase (kg), and $W_{f_{taxi}}$ as a fuel weight on taxi phase (kg), the cruise time being the flight time minus the climb and descent time, and the fuel trip on the alternative airport route is as follows :

Table 4. Trip Fuel according to Alternative Airport Route.

Route	$W_{f\ climb}$	$W_{f\ cruise}$	$W_{f\ descent}$
ZGOW – VHHH	4100 kg	2647 kg	920 kg
EDGS - EBLG	3800 kg	2747 kg	920 kg

In calculating thrust consumption on theoretical data,

$$W1 = OEW + W_P + W_{f_{cruise}} + W_{f_{descent}} + W_{f_{cont}} + W_{f_{res}} + W_{f_{alt}} \quad (8)$$

Where contains $W1$ as an aircraft weight before certain range (kg), OEW as an aircraft operational empty weight (kg), W_P as an aircraft payload (kg), $W_{f_{cruise}}$ as a fuel weight on cruise phase (kg), $W_{f_{descent}}$ as a fuel weight on descent phase (kg), $W_{f_{cont}}$ as a contingency fuel weight (kg), $W_{f_{res}}$ as a reserve fuel weight (kg), and $W_{f_{alt}}$ as an alternate fuel weight (kg),

$$W2 = OEW + W_P + W_{f_{descent}} + W_{f_{cont}} + W_{f_{res}} + W_{f_{alt}} \quad (9)$$

Where contains $W2$ as an aircraft weight after certain range (kg), OEW as an aircraft operational empty weight (kg), W_P as an aircraft payload (kg), $W_{f_{descent}}$ as a fuel weight on descent phase (kg), $W_{f_{cont}}$ as a contingency fuel weight (kg), $W_{f_{res}}$ as a reserve fuel weight (kg), and $W_{f_{alt}}$ as an alternate fuel weight (kg), CL is

$$C_L = m \times g/\frac{1}{2}\rho v^2 s \tag{10}$$

Where contains C_L as a coefficient lift, m as an aircraft weight (kg), g as a gravity acceleration (m/s^2), ρ as a density (kg/m^3), v as a cruise speed (m/s), s as a wing area (m^2), CD is

$$C_D = C_{D0} + kC_L{}^2 \tag{11}$$

Where contains C_D as a coefficient drag, C_{D0} and k obtained in the polar drag coefficient table [6], and C_L as a lift coefficient, and with a cruise speed of 284 m/s, the Breguet Range equation becomes :

Table 5. Breguet Range Equation Variables.

Route	W_1	W_2	C_L	C_D	R	$c_{T\ cruise}$
UCFM - VHHH	374266.7 kg	312957.9 kg	0.451	0.049	4298306.8 m	0.0109%
UCFM - EBLG	388294 kg	300995.6 kg	0.451	0.049	5138003.6 m	0.0128%

3.3 Comparison of Fuel Burned based on Theoretical Calculations with Actual Data

In comparing the results of fuel consumption on the two routes, it is known that the total fuel onboard and fuel burned are theoretical data. Then the actual data is given and then entered into the graph. Then the results will be like the following :

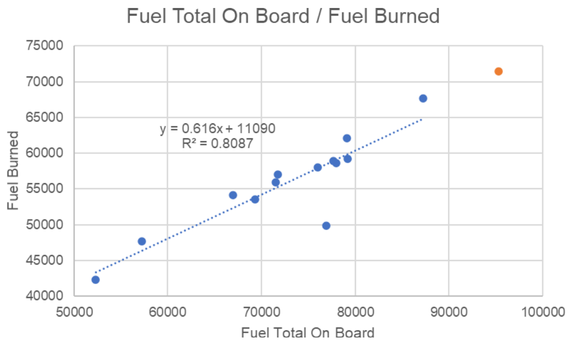

Fig. 5. Graph of Total Fuel Onboard / Fuel Burned on the UCFM – VHHH Route with Added Theoretical Calculation Numbers.

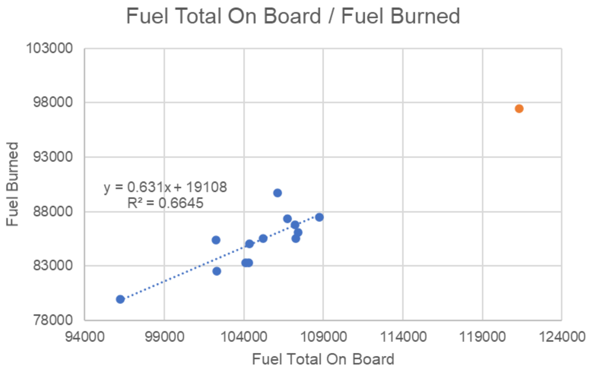

Fig. 6. Graph of Total Fuel Onboard / Fuel Burned on the UCFM – EBLG Route with Added Theoretical Calculation Numbers.

With the orange dots being theoretical data and the blue dots being actual data. If the total onboard fuel is determined in theoretical data as the x variable in the linear regres- sion equation, then we get fuel burned based on the linear regression equation. Then the difference between fuel burned in theoretical data and fuel burned in the linear re- gression equation is calculated, and the percentage of the resulting difference is divided by fuel burned in the linear regression equation.

Table 6. Fuel Consumption Comparison.

Route	Fuel Burned on Linear Regression	Fuel Burned on Theoretical Data	Differences	Percentage
UCFM - VHHH	69816.2 kg	71458.8 kg	1642.6 kg	2.4%
UCFM - EBLG	95668.4 kg	97448 kg	9767.6 kg	1.9%

4 Discussion

In the Manas – Hong Kong route and the Manas – Liege route, fuel consumption obtained through theoretical calculations which have been adjusted to the linear regression equation is 69816.2 kg and 95668.4 kg. This contradicts a study by Abdulaziz Azama- tov, which stated that for fuel consumption with a range of 6000 km, the amount obtained was 81 tons [6]. Meanwhile, the Manas – Liege route has a distance of 5138 km. So this study has limitations in calculating fuel consumption, namely cruise altitude and TOW which are not known by actual data from airline X.

5 Conclusion

Fuel consumption in theoretical calculations for the Manas – Hong Kong route is 71458.8 kg and for the Manas – Liege route is 97448.4 kg. The results of $c_{Tcruise}$ on the Manas – Hong Kong route is 0.0109% and $c_{Tcruise}$ on the Manas – Hong Kong route is 0.0128%, where the longer route has a more efficient amount of thrust consumption with a total aircraft mass of 370 tons at an altitude of 35000 ft during cruise.

Fuel consumption in actual data on the Manas – Hong Kong route varies from 42313 to 67665 kg by following the total onboard fuel which also varies according to the equation y = 0.616x + 11090 and on the Manas – Liege route from 79919 to 89707 by following the total onboard fuel which also varies according to the equation y = 0.631x + 19108. The graph on the Manas – Hong Kong route has a coefficient of determination, namely 0.8087 and the graph on Manas – Liege has a coefficient of determination, namely 0.6645, where the closer route has stronger variables to predict.

Comparison of fuel consumption based on theoretical calculations with actual data on the Manas - Hong Kong route has a fuel difference of 1642.6 kg with a percentage of 2.4%. Meanwhile, on the Manas – Liege route, the fuel difference is 1779.6 kg with a percentage of 1.9%. Where fuel consumption in actual data from longer routes has smaller differences with theoretical calculations.

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