

Project

Fuel Consumption of the 50 Most Used Passenger Aircraft

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Abstract

Purpose – Fuel consumption of passenger aircraft is certainly known, but towards the public it is considered an industry secret. This project defines fuel consumption for passenger aircraft, shows and evaluates methods and databases for its calculation, and lists the fuel consumption of the 50 most-used passenger aircraft. Input data is only from publicly available documents.

Methodology – 8 ways are considered to determine fuel consumption: Method 1: Specific Air Range (SAR), Method 2: Extended Payload-Range Diagram, Method 3: Bathtub Curve at Harmonic Range, Method 4: EEA Master Emission Calculator, Method 5: BADA, Method 6: Handbook Method, Method 7: Literature Review, Method 8: Metric Value (MV). Method 2 is the simplest method, calculating fuel consumption from the difference of maximum take-off mass (MTOM) and maximum zero-fuel mass (MZFM), which is divided by harmonic range and number of seats in the aircraft. Method 8 calculates fuel consumption from the CO₂ Metric Value (MV) defined in ICAO Annex 16, Vol. 3 and EASA CS-CO₂.

Findings – Fuel consumption should be defined as kilogram of fuel per kilometer flown, per seat. Each aircraft type has many variants. Different sources give different values for the parameters. This can lead to undetected errors and deviations among the results from different methods beyond their fundamental differences. Method 1 underpredicts, Method 2 overpredicts. Method 4 is a reliable source with apparently good results, but new aircraft types (like A320neo) are presently not in the database. For Method 8, EASA so far publishes only MVs from flight tests with the A330neo. More data will come with new aircraft being certified. With 7 input parameters, an average value can be calculated from Methods 1, 2, and 3. The results give a good first indication of aircraft's fuel consumption. Fuel consumption depends on range. For an economic range (range at maximum payload, harmonic range) modern aircraft consume between 0.02 kg/km/seat and 0.025 kg/km/seat of kerosine.

Research Limitations – The accuracy of the methods is limited. For this reason, the aircraft with the lowest fuel consumption cannot be named. CO₂ emissions can be calculated directly from fuel consumption (3.15 kg CO₂ / kg fuel). Otherwise, this project does not go further into emission calculations.

Practical Implications – Simple methods to determine the fuel consumption of passenger aircraft are presented.

Social Implications – Fuel consumption of passenger aircraft can be investigated and can be discussed openly independent of (missing) manufacturer's data.

Originality – So far, no report discusses so many ways to determine fuel consumption of passenger aircraft in such a simple and practical way.

Fuel Consumption of the 50 Most Used Passenger Aircraft

Task for a *Project*

Background

Fuel consumption of passenger aircraft is certainly known, but for the public it is considered an industry secret. Not for us. A closer look at aircraft performance fundamentals shows ways to determine the fuel consumption. It can be calculated from fundamental equations as well as from statistical equations for glide ratio and specific fuel consumption. Fuel consumption can also be calculated from the slope of the MTOM-line in the payload-range diagram. Fuel consumption can be calculated from an extended payload-range diagram, if MTOM, MZFM, and range at maximum payload (harmonic range) is known. [Burzlaff 2017](#) made an Excel table, from which fuel consumption versus range can be calculated. The consumption at harmonic range can be read from the graph as a representative value. Fuel consumption can also be obtained directly from the EEA Master Emission Calculator, from BADA (older public data), or from a conventional literature review. A new idea is to calculate fuel consumption (backwards) from the CO₂ Metric Value (although the MV was conceived in such a way to make this rather impossible). It is only necessary to estimate the cabin floor area of the aircraft in question. Take the 50 most used passenger aircraft from [Hurtecant 2021](#) to get going.

Task

This project defines fuel consumption for passenger aircraft, shows and evaluates methods and databases for its calculation, and lists the fuel consumption of the 50 most-used passenger aircraft. Input data is only from publicly available documents. The subtasks of your thesis are:

- Make a Systematic Literature Review (SLR) on the topic.
- Select one of the many definitions for fuel consumption and explain your choice.
- Explain the methods to calculate fuel consumption.
- Introduce the data sources to determine fuel consumption directly (EEA, BADA) or the data sources that obtain the parameters to calculate fuel consumption (Aircraft Characteristics for Airport Planning, EASA Aeroplane CO₂ Emissions Database)

- Analyze your fuel consumption data by looking at average values, the coefficient of variation, the coefficients of determination, the mean absolute percentage error, take your matrix of coefficients of determination as a Design Structure Matrix (DSM) and analyze the DSM.
- Analyze and interpret the fuel consumption data for all your aircraft in a systematic way.
- Describe your Excel tool.
- List the fuel consumption data in Excel and HTML on the WWW.

The report has to be written in English based on German or international standards on report writing.

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List of Symbols

A	Aspect Wing Ratio
a_0	Speed of sound at sea level
a_{11km}	Speed of sound in 11km
B	Breguet Range Factor
b_W	Wingspan
C	Fuel consumption
c	Specific fuel consumption, thrust specific (for jets)
c_P	Specific fuel consumption, thrust specific (for turboprop)
d_F	Fuselage diameter
E	Aerodynamic efficiency
E_{max}	Max. Aerodynamic efficiency
g	Gravitational acceleration
h	Altitude
k_e	Glide ratio factor
$l_{A/C}$	Aircraft length
l_{Cabin}	Cabin length
m	Mass
M_{cr}	Cruise Mach number
M_{ff}	Fuel fraction
m_F	Fuel weight
m_{MZF}	Maximum zero fuel mass
m_{OE}	Operating empty mass
m_{PL}	Payload mass
m_{TO}	Takeoff mass
n_{max}	max. number of seats
n_{OEM}	Number of seats from Original Equipment Manufacturer
OPR	Overall Pressure Ratio
$P_{ssl.eq}$	Take-off power (equivalent) at static sea level
R	Range
r	Radius
S_W	Wing Area
S_{wet}	Wetted Area
s	Chord
T_{ET}	Turbine entry temperature
T_0	Reference temperature at sea level
T_{11km}	Reference temperature in 11km
V	Velocity

Greek Symbols

Δ	Difference
η_P	Propeller Efficiency
λ	Bypass ratio

List of Abbreviations

AEED	Aircraft Engine Emissions Databank
AEM	Advanced Emission Model
ATM	Air Traffic Management
BADA	Base of Aircraft Data
BFFM2	Boeing Fuel Flow Method 2
CAS	Calibrated Air Speed
CCD	Climb, Cruise, Descent
EEA	European Environment Agency
EEC	EUROCONTROL Experimental Centre
EASA	European Union Aviation Safety Agency
FAR	Federal Aviation Regulations
FEIS	Fuel Burn and Emissions Inventory System
FL	Flight Level
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LCR	Long Range Cruise
LTO	Landing and Take-Off cycle
MCR	Maximum Range Cruise
MEW	Manufacturer Empty Weight
MTOW	Maximum Take-Off Weight
MZFW	Minimum Zero Fuel Weight
MV	Metric Value
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OML	Outer Mould Line
OPERA	Optimization in Preliminary Aircraft Design
RGF	Reference Geometric Factor
R&D	Research & Development
SAR	Specific Air Range
TOW	Take-Off Weight
UID	Unique Identification Number

List of Definitions

Breguet

Louis Charles Breguet was a 1880 born aircraft designer, who is falsely considered as the originator of the “Breguet Range Equation”. Originally, this equation was introduced in 1920 by J. G. Coffin in his NACA Report (NACA 1969). Since this equation is known as the Breguet Range Equation, it will be called in this project Breguet Range Equation as well (Burzlaff 2017)

Bathtub curve

The Bathtub Curve is a visualization of fuel consumption per passenger and 100 km flight distance over the flown distance. With this diagram, the range on which an aircraft can be operated most efficiently can be shown. The course of this curve conforms figurative to the profile of a bathtub, where the name originates. (Burzlaff 2017)

Cruise flight

Portion of a flight from the point where the aircraft has leveled off following a climb to its initial cruising altitude until the point where it commences its descent. (Young 2017)

Fuel consumption

Indicates the amount of fuel consumed per kilogram per kilometer per seat. All phases of the flight are considered.

Fuel reserves

The reserves are additional fuel carried on every flight to be prepared for unscheduled occurrences. The size of reserves depends on various factors, such as distance to alternate or weather conditions (Burzlaff 2017).

Specific air range

The still air distance traveled per unit of fuel mass consumed. (Young 2017)

1 Introduction

1.1 Motivation

Fuel consumption of cars is known for each model, and it is easily comparable because every car manufacturer is obliged to refer its fuel consumption to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) standard. But what about the fuel consumption of passenger aircraft? A standard is missing, the variety of configurations in different market segments are more difficult to compare (as for cars) and aircraft manufacturers do not entirely publish the fuel consumptions of their models. But there are ways to get more transparency on that.

This paper provides a variety of calculations for the 50 most used passenger aircraft in the world. The different methods will be explained, analysed and compared so that the most relevant data is then taken into account for the ranking the most efficient passenger aircraft. The evaluation will be discussed in detail, and it reveals transparency for older aircraft versus newer ones, turboprop and turbojet aircraft and single aisle as well as wide body aircraft. Have the aircraft manufacturers already reached a certain optimum? Some technological advances are indicated at the end.

The motivation of aircraft manufacturers to increase fuel efficiency is twofold – to increase the economy of operations and to reduce the environmental footprint.

1.2 Title Terminology

“Fuel Consumption of the 50 Most Used Passenger Aircraft”

Fuel

A substance that is used to provide heat or power, usually by being burned (Cambridge Dictionary).

Consumption

An amount of something that is used, or the process of using something, especially so that there is less of it (Cambridge Dictionary).

Passenger

A person who is travelling in a vehicle bus is not driving it, flying it, or working on it (Cambridge Dictionary).

Aircraft

Any machine that can derive support in the atmosphere from the reaction of the air (ICAO 2005).

Aircraft category

Classification of aircraft according to specified basic characteristics, e.g., airplane, glider, rotorcraft, free balloon (ICAO 2020b).

Each aircraft is divided into categories by certain certification rules, which are included in the type certificate. All aircraft mentioned in the project are certified according to FAR Part 25, Transport Category Airplanes (USA) or EASA CS-25, Large Airplanes (Europe). In order to clearly distinguish them from cargo aircraft, the word aircraft has been replaced by passenger aircraft in the title.

1.3 Objectives

The difficulty lies in the fact that fuel consumption for individual aircraft types is not sufficiently described in the literature. Therefore, the first step is to conduct a systematic literature review on the topic in order to reflect the current state of the art. In addition, the work is to inform about the different definitions of fuel consumption and show which calculation methods for fuel consumption are available. The main objective of the project is to create an Excel file that allows the user to view all the consumptions of the most commonly used aircraft models (World Airliner Census 2020), based on the different calculation methods. The selected methods will be compared and analyzed with each other and the aircraft will be sorted according to their consumptions.

1.4 Previous Research

This project is based on the master thesis of Daan Hurtecant (2021) and the project work of Marcus Burzlaff (2017).

In his master's thesis, Daan Hurtecant (2021) dealt with the most important environmental impacts of air traffic and how these can be evaluated from publicly accessible databases using an

Ecolabel. His considerations and calculations for the fuel consumption of certain aircraft types are meaningful. He also uses the World Airliner Census 2020 as a basis for this. In addition, he discusses three calculation methods, all of which are an integral part of this project work and are compared with each other. His Excel file for the Ecolabel is very helpful, as it also contains, among other things, many essential key figures for the calculation of fuel consumption.

The project work of Marcus Burzlaff (2017) deals with the calculation of fuel consumption and the implementation of an Excel file in order to be able to determine the fuel requirements of each aircraft from the publicly available documents "Aircraft characteristics for Airport planning". This so-called bathtub curve method is used as another possibility for calculating fuel consumption.

1.5 Structure of the Work

This project consists of 6 main chapters. The structure of this work is as follows:

- Chapter 2** The project starts with a systematic literature review on fuel consumption related to aircraft of general aviation. The current state of the art is summarized here.
- Chapter 3** This chapter explains the different methods of fuel consumption calculations with the underlying mathematical relations.
- Chapter 4** All necessary data sources and databases are listed and explained here.
- Chapter 5** This chapter explains the Excel file, compares all calculation methods, lists their variance and attempts to explain them.
- Chapter 6** This chapter provides the summary of the project.

2 Literature Review

2.1 Overview

In science, a Systematic Literature Review (SLR) is a procedure or method that involves identifying, collecting, analyzing, and critically evaluating relevant literature. In doing so, it is important to focus exclusively on articles that meet the specified inclusion criteria in an unbiased manner in order to approach a specific research question or hypothesis. If all relevant literature is available, a conclusion can be drawn that will influence further work and its results. Thus, the systematic literature review shows the state of the art for a specific topic. (Snyder 2019)

2.2 Bibliometric Analysis

In this chapter, a systematic literature search will show what expert literature already exists about fuel consumption of aircraft. Let's start with the master thesis of Daan Hurtecan (2021). Using the corresponding bibliography, further sources can be found to which this work refers. As a next step the search was extended to the data beacons of libraries. Elsevier's Scopus and Google Scholar, which were also used for the preparation of this project work, are particularly suitable for this purpose. Other catalogs can be found in the listing of Table 2.1. All entries in the library databases can be concretised or combined with Boolean operators. Their meaning is described below:

- AND means that both entered terms are included in the results. With each further "AND" the search is supplemented by the further search term. However, this limits the number of search hits.
- OR is used if at least one of the terms is to be contained in the search hits. Each additional "OR" extends the search radius by the described term and the number of hits.
- NOT excludes the following term.
- Parentheses are used to link several search terms by different Boolean operators.
- Truncations are a great help when a word family is searched for, an exact spelling is not known, or several spellings should be allowed. Often "*" or "?" are used for this purpose. (Kache 2005)

Table 2.1 now shows specifically which keywords and operators were used to try to specify the literature search.

Table 2.1 Boolean Operators and keywords for systematic literature review

Keyword 1	Operator	Keyword 2
((Fuel) OR (Fuel Consumption) OR (Fuel Burn))	AND	((Aircraft) OR (Aviation) OR (Airplane))

On Google Scholar, well over 100,000 hits were obtained using the above keywords. A detailed and differentiated analysis is not possible due to the high number of hits. Therefore, the search had to be narrowed down further. Thus, the focus was placed on sources that contain one or more of the keywords in the title.

Then the search was preceded by an "allintitle:" to narrow down the search. This reduced the number of relevant literatures to 44.

After a review of the documents, apparently only one document is really useful: The aforementioned project paper by Marcus Burzlaff (2017) entitled "Aircraft Fuel Consumption - Estimation and Visualization". The focus was more on emissions in flight rather than fuel consumption in general.

The same keywords were used to continue the search at Elsevier's Scopus. However, Elsevier's Scopus has an extended search mask. So it is possible to limit the search with the keywords to the abstract of a document, to the title, to the abstract or to keywords defined by the author. This reduces the number of hits. However, almost 50,000 entries were still found. Different restrictions reduced the entries, but very few were helpful. Rather, fuel consumption was described in general, some cited and explained Breguet's range formula, others mentioned payload-range diagrams besides.

In general, it can be stated that most sources only deal with different approaches to fuel calculation. In almost every source, Breguet's range equation is listed, but extended correlations are not mentioned.

Furthermore, there is no literature or work that explicitly lists the fuel consumption of individual aircraft.

Scholz's (2021) "Hints for Project and Thesis Writing" provides additional links to libraries and catalogs. Further search queries can be made in them. An overview of libraries used and the results can be seen in Table 2.2.

Table 2.2 Findings

Title	Author	Year
http://reports-at-aero.ProfScholz.de		
Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact	Caers, B.; Scholz, D.	2020
Fuel Costs due to Aircraft Systems	Scholz, D.	2007
Der spezifische Kraftstoffverbrauch von Flugtriebwerken (TSFC und PSFC)	Scholz, D.	2023
Kraftstoffverbräuche von Turbofan, Propfan und Turboprop im Vergleich	Koppe, M.	2012
Aircraft Preliminary Sizing with PreSTo - Re-Design of the Boeing B777-200LR	Seeckt, K.	2008
An Ecolabel for Aircraft	Scholz, D.	2017
http://library.ProfScholz.de		
Direct Operating Costs, Fuel Consumption, and Layout of the Airbus A321LR	Fonseca, D.	2021
Flugzeugentwurf am Beispiel eines Embraer ERJ 145	Lee, S.	2001
Flugzeugentwurf am Beispiel einer Fokker 100	Kohrt, M.	2001
Flugzeugentwurf am Beispiel einer Boeing B737-300	Wolgast, P.	2002
Flugzeugentwurf am Beispiel einer Boeing 757-200	Fricke, A.	2004
Aircraft Design Studies Based on the ATR 72	Niță, M.	2008
Assessment of Numerical Models for Thrust and Specific Fuel Consumption for Turbofan Engines	Schulz, O.	2007
Identifying CO2 Reducing Aircraft Technologies and Estimating their Impact on Global Emissions	Apffelstaedt, A.	2009
Background to the 3-Liter-Aircraft - How Clean is Aviation?	Tan, Y.L.	2011
Developing an Ecolabel for Aircraft	Haß, T.	2015
A General View on Fuel Efficiency in Commercial Aviation	MacDonald, A.	2012
Launch of an Ecolabel for Passenger Aircraft	Hurtecant, D.	2021
Definition of an Ecolabel for Aircraft	Van Endert, L.	2017
Aircraft Fuel Consumption- Estimation and Visualization	Burtzlaff, M.	2017
Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact	Brecht, C.	2019
http://paper.ProfScholz.de		
Fuel Consumption due to Shaft Power Off-Takes from the Engine	Scholz, D.; Seresinhe, R.; Staack, I.; Lawson, C.	2013
https://katalog.haw-hamburg.de		

Impacts of COVID-19 on aircraft usage and fuel consumption: A case study on four Chinese international airports	Dabin Xue, Zhizhao Liu, Bing Wang, Jian Yang	2021
Fuel consumption optimization in air transport: a review, classification, critique, simple meta-analysis, and future research implications	Singh, V.; Sharma, S.K.	2015
Future directions of fuel efficiency in aviation industry	Mrazova, M.	2013
Factors Affecting the Rate of Fuel Consumption in Aircraft	Hassan, T.H.; Sobaih, A.E.E; Salem, A.E.	2021
https://dnb.de		
Characteristics of the Specific Fuel Consumption for Jet Engines	Bensel, A.	2018
https://catalog.loc.gov		
General aviation statistics	[Washington] Dept. of Transportation, Federal Aviation Administration, Office of Management Systems, Information and Statistics Division.	
https://www.worldcat.org		
Minimization of aircraft fuel consumption subjected to arrival time constraint	Gilani, M.; Körpe, S.K.	2020
https://www.scopus.com/home.uri		
Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation	Seymour, K.; Held, M.; Georges, G.; Boulouchos, K.	2020
Improving aircraft approach operations taking into account noise and fuel consumption	A. Rodríguez-Díaz, A.; Adenso-Díaz, B.; González-Torre, P.L.	2019
Fuel efficiency of commercial aircraft An overview of historical and future trends	Peeters, P.M.; Middel, J.; Hoolhorst, A.	2005
Measurement of Aircraft Fuel Efficiency	Lim, D.; Kirby, M.; Nam, T.	2014
A Neural Network Model to Estimate Aircraft Fuel Consumption	Trani, A.A.; Wing-Ho, F.C.; Schilling, G.; H. Baik, H.; Seshadri A.	2004
Fuel Consumption Model of the Climbing Phase of Departure Aircraft Based on Flight Data Analysis	Zhang, M.; Huang, Q.; Liu, S.; Zhang, Y.	2019
Multipoint optimization on fuel efficiency in conceptual design of wide-body aircraft	Chai, X.; YU, X.; WANG, Y.	2017

2.3 Literature Review

In the course of the literature research, in addition to the different calculation methods, an explicit search was made for fuel consumption of aircraft.

In Wikipedia there is a listing of different airplanes and their consumptions referenced to a certain flight route. The task was to find out, view and analyze the original referenced sources. With the help of the Wayback Machine even deleted documents or web pages could be recovered.

Most of the documents are information brochures of the manufacturers or articles that compare some aircraft models and their consumption. In most cases, the consumption figures are referenced to actual routes flown. It should be noted that not every airline has the same seat configuration, especially not on long-haul routes. Therefore, the number of seats should be checked with the help of Seatguru and, if necessary, the typical seat configuration should be selected in case of missing information. It should be noted that consumption figures are usually given in different units. These need to be converted to a comparable unit. A detailed listing of the aircraft with the respective links can be found in the appendix. The consumptions can be found in the Excel file in the tab "Literature review".

3 Fuel Calculation

3.1 Overview

Before the individual calculation methods are presented, it is important to clarify which key figures describe the fuel consumption of an aircraft. Besides, the efficiency of an aircraft is determined by additional metrics that matters for airlines.

When measuring fuel consumption, a distinction must be made between:

- Full Mission Performance: The fuel consumption of the aircraft is considered during the entire mission. From leaving the gate at the departure airport until arrival at the destination gate.
- Instantaneous Performance: The fuel consumption of the aircraft is measured in steady-state cruise flight at an arbitrary point in time.

The full mission performance data, ideally being standardized and therefore comparable, is hardly published. Hence, in the following calculation of fuel consumption a selective performance indicator for steady-state cruise flight based on the Specific Air Range (SAR) is proposed for further considerations.

SAR describes the distance an aircraft will travel on the next incremental amount of fuel burned (Bonney 2010).

SAR is not a certified metric, but the key advantage is that only a few parameters such as altitude, speed, weight and atmospheric conditions are required for that. For traceability reasons it is necessary to include only publicly available parameters in the calculation.

Equation (3.1) defines the SAR and shows that the Breguet factor (B) depends on the aerodynamic efficiency (E), the velocity (V), the gravitational acceleration (g) and the specific fuel consumption (c). The exact determination of the parameters is complex, e.g., the aerodynamic efficiency can only be determined by (wind tunnel) measurements or Computational Fluid Dynamics calculations, a simplification is necessary here. (Chapter 3.2)

$$\text{SAR} = -\frac{dR}{dm} = \frac{V \cdot E}{c \cdot g} \cdot \frac{1}{m_{\text{average}}} = B \cdot \frac{1}{m_{\text{average}}} \quad (3.1)$$

Furthermore, the efficiency or "Air Transportation Output" includes the following parameters to the comparison (Bonney 2010).

- „Measure of distance travel“
 - Range (i.e. distance)
- “Measure of speed“
 - Maximum Range Cruise (MCR), Long Range Cruise (LCR)
- “Measure of time”
 - Time (e.g. Block time, Air time)
- “Measure of transportation”
 - Payload (Maximum Zero Fuel Weight (MZFV) - Operating Empty Weight (OEW) or Maximum Zero Fuel Weight (MZFV) – Manufacturer Empty Weight (MEW))
 - Useful load (Maximum Takeoff Weight (MTOW) – Operating Empty Weight (OEW))
 - Maximum Takeoff Weight (MTOW)
 - Floor Area
 - Number of Available Seats

In order to be able to give a practical value the number of available seats was chosen for the "Air Transportation Output". It is important that all the methods described below have the same unit so they can be compared with each other. A graphical summary of the parameters mentioned and the variant selected for the further course can be found in Figure 3.1.

Full Mission Metrics					
Single parameter metric	$\frac{\text{Block Fuel}}{\text{Range}}$				
Two-parameter metric	$\frac{\text{Block Fuel}}{\text{Payload} * \text{Range}}$	$\frac{\text{Block Fuel}}{\text{Useful Load} * R}$	$\frac{\text{Block Fuel}}{\text{MTOW} * \text{Range}}$	$\frac{\text{Block Fuel}}{\text{Floor Area} * R}$	$\frac{\text{Block Fuel}}{\text{Av. Seats} * R}$
Three-parameter metric	$\frac{\text{Block Fuel}}{\text{Payload} * R * \text{Speed}}$	$\frac{\text{Block Fuel}}{\text{Useful Load} * R * \text{Speed}}$	$\frac{\text{Block Fuel}}{\text{MTOW} * R * \text{Speed}}$	$\frac{\text{Block Fuel}}{\text{Floor Area} * R * \text{Speed}}$	$\frac{\text{Block Fuel}}{\text{Av. Seats} * R * \text{Speed}}$
	$\frac{\text{Block Fuel}}{\text{Payload} * R / \text{Time}}$	$\frac{\text{Block Fuel}}{\text{Useful Load} * R / \text{Time}}$	$\frac{\text{Block Fuel}}{\text{MTOW} * R / \text{Time}}$	$\frac{\text{Block Fuel}}{\text{Floor Area} * R / \text{Time}}$	$\frac{\text{Block Fuel}}{\text{Av. Seats} * R / \text{Time}}$
Instantaneous Performance Metrics					
Single parameter metric	$\frac{1}{\text{Specific Air Range}} = \frac{1}{\text{SAR}}$				
Two-parameter metric	$\frac{1}{\text{SAR} * \text{Payload}}$	$\frac{1}{\text{SAR} * \text{Useful Load}}$	$\frac{1}{\text{SAR} * \text{MTOW}}$	$\frac{1}{\text{SAR} * \text{Floor Area}}$	$\frac{1}{\text{SAR} * \text{Av. Seats}}$
Three-parameter metric	$\frac{1}{\text{SAR} * \text{Payload} * \text{Speed}}$	$\frac{1}{\text{SAR} * \text{Useful Load} * \text{Speed}}$	$\frac{1}{\text{SAR} * \text{MTOW} * \text{Speed}}$	$\frac{1}{\text{SAR} * \text{Floor Area} * \text{Speed}}$	$\frac{1}{\text{SAR} * \text{Av. Seats} * \text{Speed}}$

Note: R = Range

Figure 3.1 Summary of candidate metrics (Bonney 2010)

3.2 SAR Method

The specific flight range can be determined only with the help of the payload range diagram according to the definition and formula of SAR.

Already known is:

$$\text{SAR} = -\frac{dR}{dm} \quad (3.2)$$

Figure 3.2 shows a simplified payload-range diagram. Here, R_1 is the maximum range with the maximum payload m_1 (also called harmonic range). Reducing the payload and increasing the fuel leads to the longer range R_2 as the maximum range with maximum fuel carrying the associated reduced payload m_2 .

These payload-range diagrams can be found in the publicly available documents for airport planning. They are published by the respective aircraft manufacturer, who provides information about various characteristics, dimensions and key figures of the aircraft, which are indispensable for airport and maintenance planners.

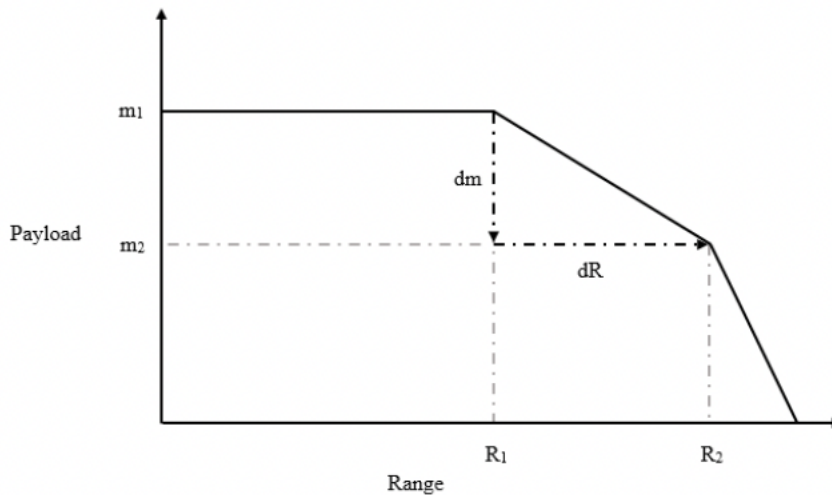


Figure 3.2 Simplified payload range-diagram (Van Endert 2017)

Therefore, considering the payload-range diagram SAR can alternatively be described as follows.

$$\text{SAR} = \frac{R_2 - R_1}{m_1 - m_2} \text{ [km/kg]} \quad (3.3)$$

However, SAR is expressed in kilometers per kilogram according to Equation (3.3). Since this is not a typical unit, the reciprocal of SAR results in an expression commonly used in the transport sector.

$$C = \frac{1}{SAR} = \frac{m_1 - m_2}{R_2 - R_1} \text{ [km/kg]} \quad (3.4)$$

This results in an absolute value for the average fuel consumption of an aircraft. However, this value cannot yet be compared with other aircraft consumption figures. Naturally smaller aircraft, which have a shorter range and therefore a lower mass, consume less fuel than larger aircraft.

Therefore, as already mentioned in Chapter 3.1, the capacity of the aircraft in the form of the number of available seats installed by the original equipment manufacturer (OEM) needs to be included in the calculation. This results in the inverse specific range being divided by the typical number (n) of seats on an aircraft.

$$C_{OEM} = \frac{1}{SAR \cdot n_{OEM}} \text{ [km/kg/seat]} \quad (3.5)$$

The typical seating is often found in the documents for airport planning. It may happen that this figure cannot be found and only the maximum seating capacity is given.

Using the maximum seating capacity to normalize fuel consumption would cause the rating scale to be overly strict because most airliners are fitted with a number of seats that is lower than the maximum number (Hurtecant 2021)

Therefore, Hurtecant (2021) plotted the typical seating of 75 reference aircraft against the maximum seating capacity to estimate the typical number of seats for aircraft using a linear regression. The accuracy of the straight-line equation is 97% and is part of Figure 3.3.

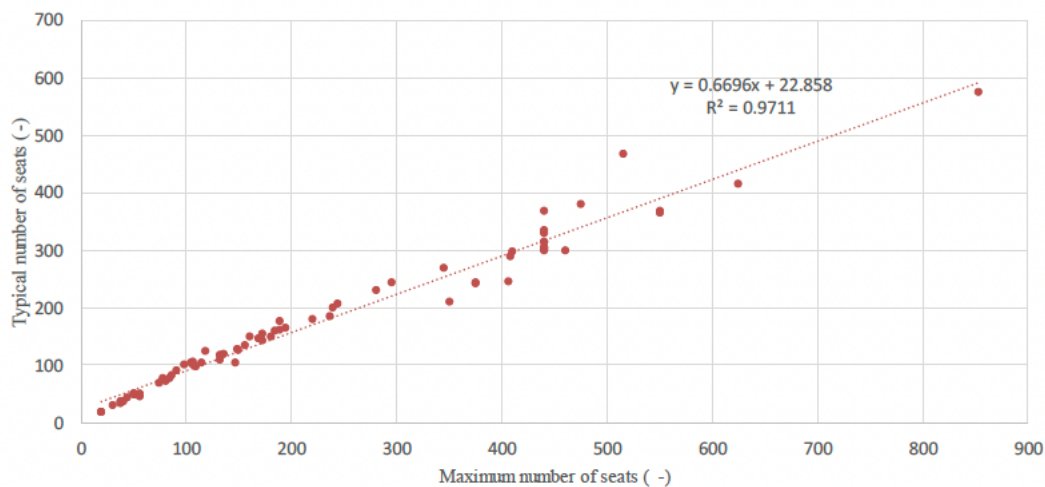


Figure 3.3 Statistic to predict the typical number of seats from the maximum seating capacity (Hurtecant, 2021)

Hurtecan (2021) concludes that the number of seats can be calculated as follows.

$$n_{OEM} = 0.6696 \cdot n_{max} + 22.858 \quad (3.6)$$

In a nutshell, the SAR method is a point-by-point consideration of fuel consumption in cruise flight. Therefore, SAR cannot be used if the amount of fuel consumed is to be considered over the entire flight.

However, the inherent simplicity of a point performance metric makes it attractive for this research (Bonney 2010).

As the fuel consumption for every aircraft is calculated similarly, it allows for easy comparison between aircraft. The proposed equation can thus be used as a reliable and standardized indicator for the average fuel performance (Hurtecan 2021).

3.3 Extended Payload Method

Chapter 3.2 describes a possible method for calculating aircraft fuel consumption from the payload-range diagram using only four known, publicly available parameters. Another method results from extending the payload-range diagram by the following relations (Young 2018).

$$m_{MZFW} = m_{OEW} + m_{PL} \quad (3.7)$$

$$m_{MTOW} = m_{MZFW} + m_F \quad (3.8)$$

This can be shown graphically using an alternative format (see Figure 3.4), which has the aircraft's weight as the ordinate and the payload-range envelope shown within the diagram (shaded). From point A to point B, the payload is constant, but the TOW increases as additional fuel is required for the increasing range. From point B to point C, payload is traded for fuel (here the TOW is equal to the MTOW). This progressive increase in range, resulting from the increase in fuel, is possible until the maximum fuel limit (i.e., fuel capacity limit) is reached. From point C to point D, the fuel is limited by the size of the fuel tanks, but the payload (and hence the TOW) reduces as the range increases (Young 2018).

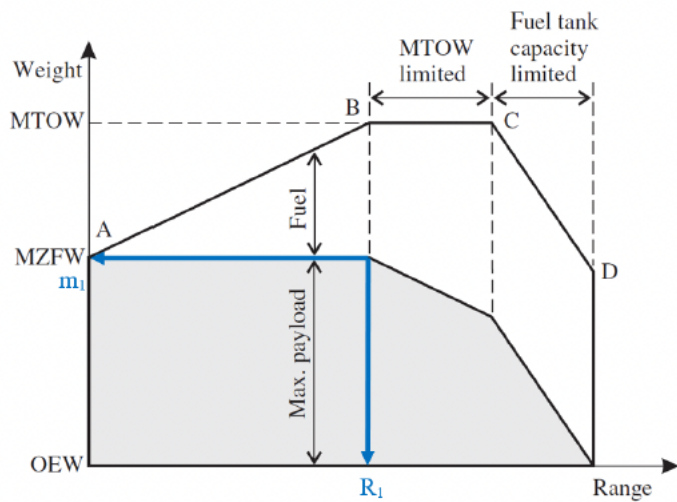


Figure 3.4 Extended payload-range diagram (Young 2017)

In addition, the two reference values R_1 and m_1 are shown in blue in Figure 3.4. Both values describe a point in the payload-range diagram, which is also called the design point of an aircraft. As already used in the SAR method, only the punctual fuel consumption in cruise flight is considered here.

Under this assumption and using Figure 3.4 in combination with Equation (3.7), the fuel consumption in kilograms per kilometer can now be calculated.

$$C = \frac{m_F}{R_1} = \frac{m_{MTOW} - m_{MZFW}}{R_1} \quad [\text{kg/km}] \quad (3.9)$$

The fuel mass m_F considered here contains an additional increment to the regular fuel: the mass of the reserve fuel. Therefore, the fuel consumption calculated with Equation (3.8) is higher than the actual value.

In order to be able to compare the consumption of the respective aircraft, the consumption is normalized with the typical seat configuration of the manufacturer.

$$C_{OEM} = \frac{m_F}{R_1 \cdot n_{OEM}} = \frac{m_{MTOW} - m_{MZFW}}{R_1 \cdot n_{OEM}} \quad [\text{kg/km/seat}] \quad (3.10)$$

The decisive advantage of this Extended Payload Method over the SAR method is that only the parameter R_1 has to be read from the payload-range diagram for the calculation. The other two parameters, MTOW and MZFW, are always known from the certification documents of the aircraft.

The extended payload-range diagram method eliminates the need to study every payload range diagram in depth, and therefore any inaccuracies in reading the diagram are also avoided. In conclusion, the proposed equation can be used as a reliable and standardized indicator for the average

fuel performance and as a simplified alternative to the SAR-based fuel consumption (Hurtecant, 2021).

3.4 Bathtub Method

In the previous chapters, two methods of calculating fuel consumption were explained which are only applicable to a flight at cruising altitude. In the following, a method will be presented in which the consumption is considered over the entire flight, including all flight phases.

In his project work, Burzlaff 2017 developed an Excel tool that calculates the fuel consumption of an aircraft for an exact range and generates a graph in form of a so-called bathtub curve. This curve describes the fuel consumption per 100 km and per seat and shows the area of least consumption. Figure 3.5 shows the bathtub curve using the A350-900 as an example:

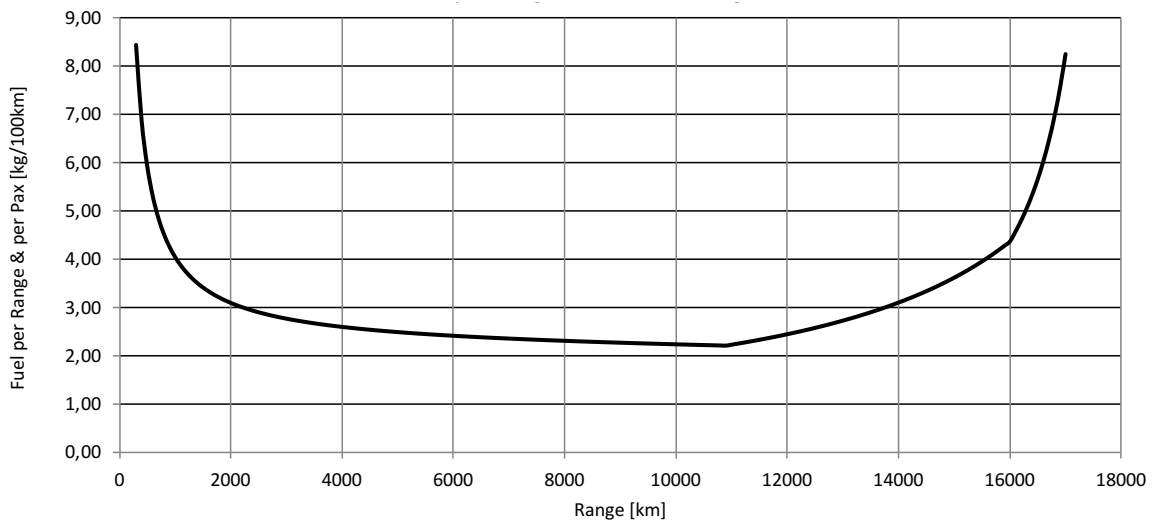


Figure 3.5 Example of an A350-900 bathtub curve (Burzlaff 2017)

It can be clearly seen that consumption jumps at the edges of the bathtub curve, but in the range from 2800 km to 11000 km it remains in a relatively narrow range of 2.8...2.1 kg/100km/pax.

To better understand the composition of the bathtub curve, some mathematical relationships are explained:

Already known is the Breguet factor B .

$$B = \frac{V \cdot E}{c \cdot g} \quad (3.11)$$

This forms the Breguet Range Equation.

$$R = B \cdot \ln \frac{m_1}{m_2} \quad (3.12)$$

Transforming Equation (3.11).

$$B = \frac{R}{\ln \frac{m_1}{m_2}} \quad (3.13)$$

Equation (3.12) only applies to the horizontal flight. However, since the bathtub method should take into account the entire mission of the flight (including takeoff, climb, cruise descent, loiter and landing), the individual fuel fractions must also be taken into account.

A Fuel Fraction is a relation between the mass m_2 at the end of a phase of flight and the mass m_1 at the beginning of this phase of flight (Scholz 2015)

$$M_{ff} = \frac{m_2}{m_1} \quad (3.14)$$

Considering the flight phases, the result for M_{ff} :

$$M_{ff} = \frac{m_{Shut\ Off}}{m_{Landing}} \cdot \frac{m_{Landing}}{m_{Loiter}} \cdot \frac{m_{Loiter}}{m_{Descent}} \cdot \frac{m_{Descent}}{m_{Reserve}} \cdot \frac{m_{Reserve}}{m_{Climb}} \cdot \frac{m_{Climb}}{m_{Descent}} \cdot \frac{m_{Descent}}{m_{Cruise}} \cdot \frac{m_{Cruise}}{m_{Climb}} \cdot \frac{m_{Climb}}{m_{Take\ Off}} \quad (3.15)$$

Simplified, it can be written:

$$M_{ff} = M_{ff,Ldg} \cdot M_{ff,Loi} \cdot M_{ff,Des} \cdot M_{ff,Res} \cdot M_{ff,Clb} \cdot M_{ff,Des} \cdot M_{ff,Crs} \cdot M_{ff,Clb} \cdot M_{ff,To} \quad (3.16)$$

Figure 3.6 shows an overview of the flight phases accompanying Equations (3.14) and (3.15):

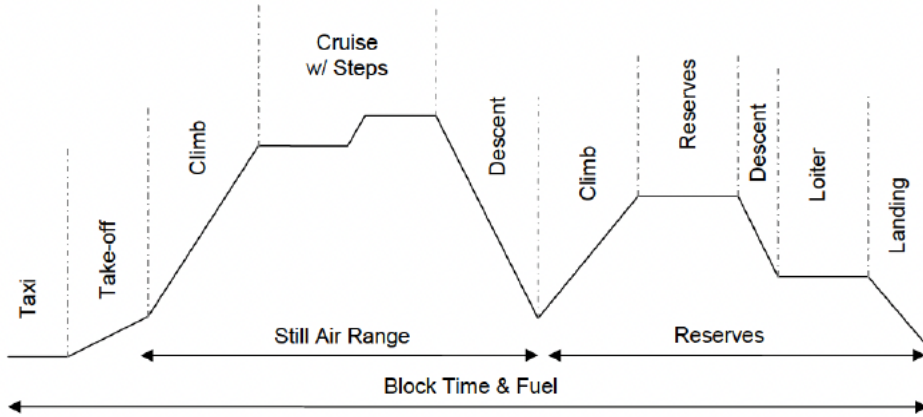


Figure 3.6 Different phases during flight operation (Mac Donald 2012)

The individual flight phases can be divided into two different groups. The Horizontal Flight and the Non-Horizontal Flight. Table 3.1 shows besides the two categories also the classification of the formula expressions according to Equation (3.14).

Table 3.1 Overview flight phases

Flight phase	Non-Horizontal flight	Horizontal flight
Fuel Fraction	$M_{ff,TO}; M_{ff,Cib}; M_{ff,Des}; M_{ff,Ldg}$	$M_{ff,Crs}; M_{ff,Res}; M_{ff,Loi}$

All fuel fractions describing the non-horizontal flight can be described simplified with $M_{ff,LTO}$. All other components are described simplified with $M_{ff,Cr-Res-Loi}$

The fuel mass fractions for each stage of the LTO cycle were calculated using an aircraft design optimization tool OPERA. While it is recognized that the fraction fuel burn for each stage of the LTO cycle are not equal, it was found during the analysis that the errors produced through estimating each stage fuel fraction as 0.994 was not significant and provided better results over estimating individual stage fractions (MacDonald 2012).

The fuel fraction for the LTO cycle is hence given as per Equation (3.16).

$$M_{ff,LTO} = 0.95929 \quad (3.17)$$

This value is used for the following calculation of the Breguet factor. Using Equation (3.12) and simplifying Table 3.1, the following relationship is obtained:

$$\frac{m_1}{m_2} = \frac{1}{M_{ff}} = \frac{1}{M_{ff,Cr-Res-Loi} \cdot M_{ff,LTO}} \quad (3.18)$$

In order to cover the entire flight, the mass ratio is adjusted to rely on the horizontal flight mass ratio.

$$M_{ff,LTO} \cdot \frac{m_1}{m_2} = \frac{1}{M_{ff,Cr-Res-Loi}} \quad (3.19)$$

Considering Equations (3.18) and (3.12):

$$B = \frac{R}{\ln \left(M_{ff,LTO} \cdot \frac{m_1}{m_2} \right)} \quad (3.20)$$

The Breguet factor is used in the calculation of fuel consumption (in kg).
It still applies:

$$m_F = m_1 - m_2 \quad (3.21)$$

Where m_1 is the mass before takeoff and m_2 is the mass after landing. The difference between the two parameters represents the actual amount (in kg) of fuel consumed.

Taking Equation (3.11) and (3.20) into account, the result is.

$$R = B \cdot \ln \left(\frac{m_1 + m_F}{m_2} \right) \quad (3.22)$$

The conversion to m_F results in:

$$m_F(R) = m_2 \cdot \left(e^{\frac{R}{B}} - 1 \right) \quad (3.23)$$

In summary:

$$C_{OEM} = \frac{m_F}{R_1 \cdot n_{OEM}} \text{ [kg/km/seat]} \quad (3.24)$$

A detailed description of Burzlaff's Excel tool is given in Chapter 4.3.

In conclusion, the Bathtub Method generates a more accurate value than the methods presented in Chapters 3.2 and 3.3. It takes into account all flight phases during a mission. But this can also be a disadvantage, because the result depends on the mission.

3.5 CO2 Method

So far, methods have been presented that require the payload-range diagrams are taken from Airport Planning Documents in order to calculate the fuel consumption.

In this chapter, another method will be presented, which includes the CO2 emissions evaluation metric value. How this is composed and on which data basis it is based is described in Chapter 4.6. In this chapter, which describes the mathematical basis, the value is taken as given.

It applies (ICAO Annex 16 2017).

$$CO2 \text{ emissions evaluation metric value } (MV) = \frac{1}{\overline{SAR} \cdot RGF^{0.24}} \quad (3.25)$$

Transforming the equation yields.

$$C = \frac{1}{SAR} = MV \cdot RGF^{0.24} \quad (3.26)$$

The reference geometric factor (RGF) is an adjustment factor based on the aircraft fuselage size derived from a two-dimensional projection of the fuselage. It is dimensionless and standardized with regard to 1 m². In addition, it is defined as follows (ICAO Annex 16 2017):

- *for aeroplanes with a single deck determine the area of a surface (expressed in m²) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor; and*
- *for aeroplanes with an upper deck determine the sum of the area of a surface (expressed in m²) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor, and the area of a surface bounded by the maximum width of the fuselage OML at or above the upper deck floor projected to a flat plane parallel with the upper deck floor is determined; and*
- *determine the non-dimensional RGF by dividing the areas defined in 1(a) or 1(b) by 1 m².*

Furthermore, note that the RGF includes all pressurized spaces including corridors, auxiliary spaces, stairwells, passageways, and areas that can accommodate cargo. The cockpit crew area or crew rest/work areas are excluded. The pressure bulkhead is assumed to be the aft boundary.

This results in four possibilities how RGF can be determined. All variants differ in their accuracy and are arranged in such a way that they start with the least accurate variant and end with the most accurate variant.

Option 1:

$$\text{RGF} = l_{A/C} \cdot d_F \quad (3.27)$$

Option 2:

$$\text{RGF} = l_{Cabin} \cdot d_F \quad (3.28)$$

Option 3:

$$\text{RGF} = l_{A/C} \cdot s \quad (3.29)$$

Option 4:

$$\text{RGF} = l_{Cabin} \cdot s \quad (3.30)$$

According to the Aircraft Design Chapter 6 (Scholz 2015):

$$l_{Cabin} = l_{A/C} - 1.6 \cdot d_F - 4\text{m} \quad (3.31)$$

And:

$$s = 2 \cdot \sqrt{2 \cdot r \cdot h - h^2} \quad (3.32)$$

Whereas:

$$h = r - 1\text{m} \quad (3.33)$$

And:

$$r = \frac{d_F}{2} \quad (3.34)$$

In order to compare the specific fuel consumption with the other methods, this still needs to be divided by the typical seat configuration. In summary, this method does not require many parameters, only the dimensions of the aircraft and the metric value.

3.6 Handbook Method

The handbook method goes back to the equation of Breguet's range formula and allows an estimation of the variables. Already known is:

$$B = \frac{V \cdot E_{max}}{c_{CR} \cdot g} \quad (3.35)$$

And further:

$$C = \frac{1}{SAR} = \frac{c \cdot g \cdot m}{V \cdot E_{max} \cdot n_{OEM}} \quad [\text{kg/km/seat}] \quad (3.36)$$

According to the International Standard Atmosphere (ISA) of the International Civil Aviation Organization (ICAO), the following conditions apply at mean sea level:

$$T_0 = 288.15 \text{ K} \quad (3.37)$$

$$a_0 = 340.294 \text{ m/s} \quad (3.38)$$

Moreover, in the troposphere (at an altitude of 11km) there is a constant temperature of

$$T_{11km} = 216.65 \text{ K} \quad (3.39)$$

From this, the speed of sound a at an altitude of 11 km can now be calculated:

$$a_{11km} = a_0 \cdot \sqrt{\frac{T_{11km}}{T_0}} = 295.07 \text{ m/s} \quad (3.40)$$

Using Equation (3.38) and the Mach number M_{cr} of an aircraft, V can now be calculated:

$$V = M_{CR} \cdot a_{11km} \quad (3.41)$$

In the following, an estimation for E will be considered. The following relationship applies here (Scholz 2017):

$$E_{max} = k_e \cdot \sqrt{\frac{A}{\frac{S_{wet}}{S_w}}} \quad [-] \quad (3.42)$$

Where A is the wing aspect ratio of the wingspan to the wing area (Schlüter 2006):

$$A = \frac{b_{wing}^2}{S_W} \quad (3.43)$$

k_e is composed as follows (Scholz 2023):

$$k_e = \left(3.229 \cdot 10^{-4} \frac{1}{km} \cdot R_1 \right) + 12.18 \quad (3.44)$$

The following factor is assumed for the ratio of $\frac{S_{wet}}{S_W}$.

$$\frac{S_{wet}}{S_W} \approx 6.1 \quad (3.45)$$

The following relationship for m holds:

$$m = \frac{m_{MTOW} + m_{MZFV}}{2} \quad [\text{kg}] \quad (3.46)$$

The following factor applies to g :

$$g = 9.81 \text{ m/s}^2 \quad (3.47)$$

Next c_{CR} should be estimated. For this purpose, an equation from Hammami (2021) is used:

$$c_{CR} = 3.735 \cdot 10^{-8} \cdot \lambda^{-2.12 \cdot 10^{-3}} \cdot V + 1.65 \cdot 10^{-5} \cdot \lambda^{-0.4} \quad [\text{kg/sN}] \quad (3.48)$$

Where λ is the bypass ratio of the respective aircraft and V is the cruise speed. However, Equation (3.48) only applies to turbofan aircraft.

To determine the fuel consumption of turboprop aircraft, another equation, based on the evaluations of Koppe (2012), should be added.

$$c_P = 3.25369 \cdot 10^{-7} \cdot \ln(P_{ssl,eq} \cdot OPR \cdot T_{ET}) \cdot 1.00060 \cdot 10^{-8} \quad [\text{kg/sW}] \quad (3.49)$$

Fuel consumption for turboprop can be calculated with an adjustment of Equation (3.36) as follows.

$$C = \frac{1}{SAR} = \frac{c_P \cdot g \cdot m}{\eta_P \cdot E_{max} \cdot n_{OEM}} \quad [\text{kg/km/seat}] \quad (3.50)$$

The following factor applies to η_P .

$$\eta_P = 0.82 \quad (3.51)$$

In conclusion, the fuel consumption of an aircraft can be determined using the handbook methods. For this, seven parameters of each aircraft must be known: MTOW, MZFW, V , R_I , wing-span b_{Wing} wing area S_W and the bypass ratio λ . Since the max. glide ratio drops at high Mach numbers (not considered here), this method is only applicable for "common" cruise Mach numbers (up to 0.89 or up to 263 m/s). In addition, as with the SAR method, the fuel reserve is assumed to be consumed.

4 Data Sources

4.1 Overview

Chapter 3 presented various methods that can be used to calculate fuel consumption for aircraft in general. The mathematical relationships were explained, a reference unit was defined that allows the consumption figures to be compared with each other.

In this chapter, it is explained how to obtain the input parameters to the methods given in Chapter 3. Furthermore, databases are presented that can be used to determine the fuel consumption of a specific aircraft.

4.2 Passenger Aircraft Census

First the Top 50 Most Used Passenger Aircraft need to be identified. This definition refers to all commercial aircraft in operation. The World Airliner Census of 2020 provides an excellent database for this purpose.

The World Airliner Census covers all commercial aircraft, both jet-powered and turboprop powered, with a capacity of more than 14 passengers, that were in service in August 2020 (Hurtecant 2017).

In April 2020, aviation came to an almost complete standstill due to the Corona pandemic and many aircraft were grounded at the time of the survey. However, since air traffic also rebounded significantly last year due to the lifting of Corona restrictions, the selection of aircraft assumes a full recovery. This means that the stored aircraft have rejoined the airline's fleet and are in service. However, the total number of aircraft considered in each case represent an inaccuracy. In the course of the Corona pandemic, some older aircraft models that were most unprofitable for the airlines, such as the Boeing 747-400, were flown out of service sooner than originally planned. This practice was seen at many of the world's airlines. The World Airliner Census does not take this into account, and it is difficult to conduct even a data collection of how many aircraft have actually left the fleets, as some decisions have not yet been finalized.

Therefore, the following procedure was chosen using World Airliner Census data:

- A full recovery and thus a full return of all aircraft was assumed.

- Due to increasing deliveries of certain aircraft types recently and increasing importance (i.e. growing deliveries) in aviation, the following aircraft were included: Airbus A220-300, Embraer E195-E2, Boeing 737 MAX9, Bombardier CRJ1000.
- Accordingly, some other aircraft types have been downgraded, either because of smaller deliveries or missing data: Fairchild Metro/Merlin, Beechcraft 1900C, Beechcraft B99, BAe Jetstream 31.

This now results in a listing that contains the 50 Most Used Passenger Aircraft based on the World Airliner Census figures. This represents 92.78 % of all aircraft as measured by the World Airliner Census.

Table 4.1 List of the 50 most used passenger aircraft (World Airliner Census 2020)

Aircraft Typ	Total passenger Aircraft	Ranking
Boeing 737-800	4788	1
Airbus A320	4132	2
Airbus A321	1637	3
Airbus A319	1243	4
Airbus A320neo	1009	5
Boeing 737-700	979	6
Boeing 777-300ER	805	7
ATR 72	795	8
Airbus A330-300	707	9
Embraer E175	624	10
Bombardier CRJ100	601	11
Bombardier CRJ200	601	12
Boeing 737-900	556	13
Boeing 787-9	540	14
Airbus A330-200	502	15
Embraer E190	501	16
Embraer ERJ-145	479	17
Bombardier CRJ900	471	18
De Havilland Canada Dash 8 Q400	462	19
Boeing 777-200	391	20
Boeing 777-200ER	391	21
Boeing 767-300	365	22
Boeing 787-8	363	23
Airbus A321neo	355	24
Boeing 737 Max 8	347	25
Airbus A350-900	321	26
De Havilland Canada Twin Otter	315	27
Boeing 757-200	302	28

Bombardier CRJ700	291	29
Airbus A380-800	237	30
Boeing MD-80	232	31
Beechcraft 1900D	220	32
Boeing 737-300	214	33
ATR 42	208	34
Airbus A220-300	200	35
Saab 340	188	36
Boeing 737-500	161	37
Embraer E195	161	38
De Havilland Canada Dash 8 Q300	157	39
Embraer E170	157	40
De Havilland Canada Dash 8 Q100	152	41
Boeing 717-200	145	42
Boeing 747-400	142	43
Boeing 737-400	141	44
Sukhoi Superjet 100	131	45
Embraer EMB-120 Brasilia	127	46
Fokker 100	109	47
Bombardier CRJ1000	67	48
Embraer E195-E2	40	49
Boeing 737 MAX 9	38	50
<hr/>		
TOTAL	27108	
TOTAL World Airliner Census	29217	
Average	92.78 %	

4.3 Student Data

As described at the beginning, the project work is based on the master thesis of Hurtecant (2021) and the project work of Burtlaff (2017).

Hurtecant created an Excel spreadsheet that already contains important information for the fuel calculation. All of the top 50 most used passenger aircraft can be found here. In addition to the typical seat distribution, the Maximum Take-Off Weight or Minimum Zero Fuel Weight, the important parameters of the payload-range diagram (R_1 , m_1 , R_2 , m_2) are also listed. This facilitated the work during the project. This table was taken over completely and can be found in the Excel file in the tab "Hurtecant".

In his project work, Burzlaff developed an Excel tool for precise calculation of fuel consumption over all flight phases. In addition to the already known parameters from the payload-range diagram (R_1, m_1, R_2, m_2), the number of seats, Maximum Take-Off Weight (MTOW) and Maximum Zero Fuel Weight (MZFW) for each of the 50 aircraft are also required. All parameters are part of the documents for airport planning. The weight per passenger is assumed to be 100 kg. The Mach number in flight is assumed to be 0.82 for widebody aircraft and 0.76 for short/medium aircraft. The range (for single calculation) corresponds to R_1 (harmonic range).

Figure 4.1 shows an excerpt from the Excel file, which illustrates the calculation using the A350-900 as an example:

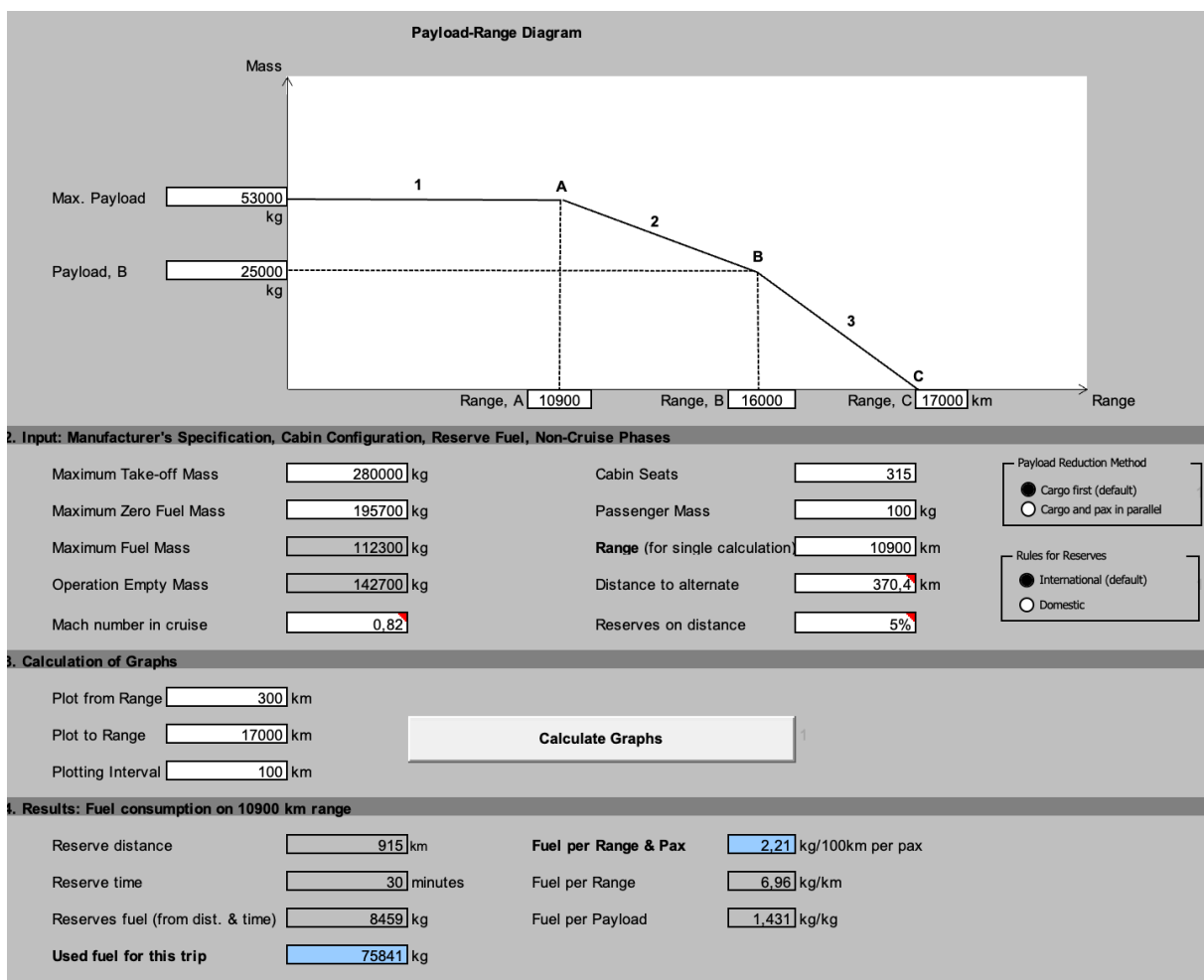


Figure 4.1 Extract from fuel calculator (Burzlaff 2017)

The blue fields show the fuel required for the specified route (including reserve fuel) and the consumption in kg/100km per pax. The output has to be converted to kg/km/seat accordingly.

4.4 BADA

The Base of Data (BADA) is a collection of ASCII files which specifies operation performance parameters, airline procedure parameters and performance summary tables for 438 aircraft types. This information is designed for use in trajectory simulation and prediction algorithms within the domain of Air Traffic Management (ATM). All files are maintained within a configuration management system at the EUROCONTROL Validation Infrastructure Centre of Expertise located at the EUROCONTROL Experimental Centre (EEC) in Brétigny-sur-Orge, France (EUROCONTROL 2014).

Although detailed data on aircraft performance are confidential and commercially sensitive, BADA transforms it such that aircraft models can be made available to a wide audience. The use of BADA is not limited to EUROCONTROL. The BADA family 3 model is provided to the ATM community worldwide and is used by R&D organizations, academic institutions, ANSP's and ATM support industry. Its use is free of charge, but regulated through a licence agreement that safeguards the interests of the aircraft manufacturers who are the principal aircraft performance reference data providers for BADA (Nuic 2010)

Unfortunately, it was not possible to obtain such access to view the data. Apart from that this database is a source that is not publicly accessible and therefore has been excluded from this survey.

However, a document could be found on BADA, which represents a set of performance summary tables for 67 aircraft types which are modelled by BADA Revision 3.0 (EUROCONTROL 1998).

This file contains a table of values which specifies the true air speed, rate of climb or descent and fuel flow for conditions of climb, cruise and descent at various flight levels. After the review of the document, it became apparent that only 19 of 67 aircraft types are relevant for this project, because only these are also in the list from Chapter 4.2. All other models mentioned are very outdated and do not belong to the 50 most used passenger aircraft.

Below there is an excerpt of the document depicting the Airbus A320:

BADA PERFORMANCE FILE												
98/03/12												
AC/Type: A320												
Last BADA Revision: 3.0												
Source OPF File: 3.0												
Source APF file: 3.0												
98/03/12												
98/03/12												
Speeds: CAS(LO/HI) Mach Mass Levels [kg] Temperature: ISA												
climb - 250/300 0.78 low - 50160												
cruise - 250/300 0.78 nominal - 62000 Max Alt. [ft]: 39000												
descent - 250/300 0.78 high - 73500												
=====												
FL	CRUISE				CLIMB				DESCENT			
	TAS [kts]	fuel [kg/min]			TAS [kts]	ROCD [fpm]			fuel [kg/min]	TAS [kts]	ROCD [fpm]	
	lo	nom	hi	lo	nom	hi	nom	nom	nom	nom	nom	nom
0					157	2180	2140	1890	129.4	142	1100	9.4
5					158	2160	2120	1870	128.1	143	1100	9.3
10					159	2150	2100	1850	126.8	149	1100	9.3
15					166	2250	2180	1910	125.5	160	1100	9.2
20					167	2230	2160	1890	124.2	192	1150	9.2
30	261	35.9	40.4	45.7	190	2620	2450	2140	121.6	230	1330	9.1
40	265	35.8	40.4	45.7	225	3100	2800	2440	119.1	233	1340	9.0
60	272	35.8	40.4	45.7	272	3690	3010	2520	114.1	240	1370	8.8
80	280	35.7	40.3	45.7	280	3540	2880	2400	109.1	280	1640	8.6
100	289	35.7	40.3	45.7	289	3390	2750	2270	104.1	289	1680	8.4
120	356	44.6	47.8	51.6	356	3260	2670	2230	99.4	356	2310	8.1
140	366	44.4	47.6	51.5	366	3060	2490	2070	94.6	366	2340	7.9
160	377	44.2	47.5	51.3	377	2860	2310	1900	89.8	377	2370	7.7
180	388	44.0	47.3	51.2	388	2650	2130	1740	85.1	388	2400	7.5
200	400	43.8	47.1	51.0	400	2430	1940	1560	80.5	400	2740	7.3
220	412	43.5	46.9	50.8	412	2220	1740	1390	76.0	412	2760	7.1
240	425	43.2	46.6	50.6	425	1990	1550	1210	71.6	425	2770	6.9
260	438	43.0	46.4	50.4	438	1770	1350	1030	67.2	438	2780	6.7
280	452	42.7	46.1	50.2	452	1540	1150	840	62.9	452	2790	6.5
300	459	41.5	45.1	49.3	459	1880	1360	950	58.6	459	3830	6.3
320	455	39.1	43.0	47.7	455	1690	1170	750	54.5	455	3620	6.1
340	451	37.0	41.3	46.4	451	1480	970	540	50.4	451	3430	5.8
360	447	35.2	40.0	45.6	447	1250	750	320	46.3	447	3270	5.6
380	447	33.8	39.0	44.1	447	940	470	70	42.4	447	2910	5.4
400	447	32.6	38.3	40.0	447	710	240	0	38.5	447	2840	5.2

Figure 4.2 Extract from BADA (EUROCONTROL 1998)

It shows a table of performance data with 13 columns. Each of these columns is explained below:

Column 1 Flight Level (FL)

Column 2 cruise True Air Speed (TAS) (nominal mass) in kg/min

Column 3 cruise fuel consumption (low mass) in kg/min

Column 4 cruise fuel consumption (nominal mass) in kg/min

Column 5 cruise fuel consumption (high mass) in kg/min

Column 6 climb True Air Speed (nominal mass) in knots

Column 7 rate of climb with reduced power (low mass) in fpm

Column 8 rate of climb with reduced power (nominal mass) in fpm

Column 9 rate of climb with reduced power (high mass) in fpm

Column 10 climb fuel consumption in kg/min

Column 11 descent True Air Speed (nominal mass) in knots

Column 12 rate of descent (nominal mass) in fpm

Column 13 descent fuel (nominal mass) consumption in fpm

Line 3 shows the type of aircraft.

Further explanatory notes on the data presented in the performance tables are given below (EUROCONTROL 1998):

- (a) Cruise data is only specified for flight levels greater than or equal to 30.
- (b) Performance data is specified up to a maximum flight level of 400 or to highest level for which a positive rate of climb can be achieved at the low mass. This maximum level is not necessarily the same as the maximum level specified in the OPF file and given in the PTF header.
- (c) True Air Speed for climb, cruise and descent is determined based on the speed schedules specified in Sections 4.1, 4.2 and 4.3 respectively of the BADA User Manual [RD1].
- (d) Rates of climb are calculated at each flight level assuming the energy share factors associated with constant CAS or constant Mach speed laws and using the reduced power corrections as given in Section 3.8 of RD1.
- (e) The fuel consumption in climb is independent of the aircraft mass and thus only one value is given. There are three different climb rates however corresponding to low, nominal and high mass conditions.
- (f) The rate of descent and fuel consumption in descent is calculated assuming the nominal mass. Values for other mass conditions are not given.
- (g) Discontinuities in climb rate can occur for the following reasons:
change in speed between flight levels (e.g. removal of 250 knot restriction above FL100)
transition from constant CAS to constant Mach (typically around FL300)
transition through the tropopause (FL360 for ISA)
- (h) Discontinuities in descent rate can occur for the following reasons:
transition through tropopause (FL360 for ISA)
transition from constant Mach to constant CAS
change in assumed descent thrust (specified by the BADA h_{des} parameter)
change in speed between flight levels (e.g. application of 250 knot limit below FL100)

For fuel consumption, FL360 is assumed for the A320 as an example. In addition, cruise fuel consumption (nominal mass) in kg/min (column 4) is considered. In Figure 4.2, this selection is marked with a red box.

Subsequently, this value must also be converted to the unit kg/km/seat as follows in order to be able to compare the results. The values from BADA only take into account the fuel consumed in flight.

$$C = \frac{CRUISE_{nom} \cdot 50}{V \cdot 3 \cdot n_{OEM}} \text{ [kg/km/seat]} \quad (3.34)$$

4.5 EEA

The European Environment Agency (EEA) provides and manages another database that illustrates the fuel consumption of aircraft. This is known as the Master Emission Calculator. All the information it contains is based on Eurocontrol's Fuel Burn and Emissions Inventory System (FEIS). This system estimates the total mass of fuel from all aircraft from the previous year that departed from or arrived at an airport in a relevant part of the territory of one of the 28 EU

Member States, or both (see EEA 2019). The FEIS uses Eurocontrol's Advanced Emission Model (AEM), which estimates fuel based on aircraft movements and, associated with that, the emissions that result from the combustion of the fuel (EEA 2019).

The aim of this database is to allow the user to display the fuel consumed and the resulting pollutants emitted by entering a specific aircraft type and a specified route length.

It has to be discussed which route length should be selected for the respective aircraft. For this it is important to understand that the stage length described by the EEA Master Calculator corresponds to the length of the cruise phase. In order to be able to determine a suitable reference stage length for the respective aircraft, it is worth taking a look at the payload-range diagram of the aircraft. However, airlines operate their aircraft on routes that are sometimes well below the maximum mission range. This is also illustrated in Figures 4.3 and 4.4.

Figure 4.3 presents a payload-range diagram for an Airbus A320-200 and a Boeing 737-800 combined with the number of flights the airplanes executed with a specific payload-range combination (Hurtecant 2021).

Figure 4.4 presents a payload range diagram of a Boeing 787-8 combined with the number of flights the airplanes executed with a specific payload-range combination.

It can be observed that almost no flight was operated with maximum payload or rather the maximum number of passengers. In addition, most of the time, the aircraft are used for relatively short routes of about 1000 NM, which deviates massively from the design range (Husemann 2018).

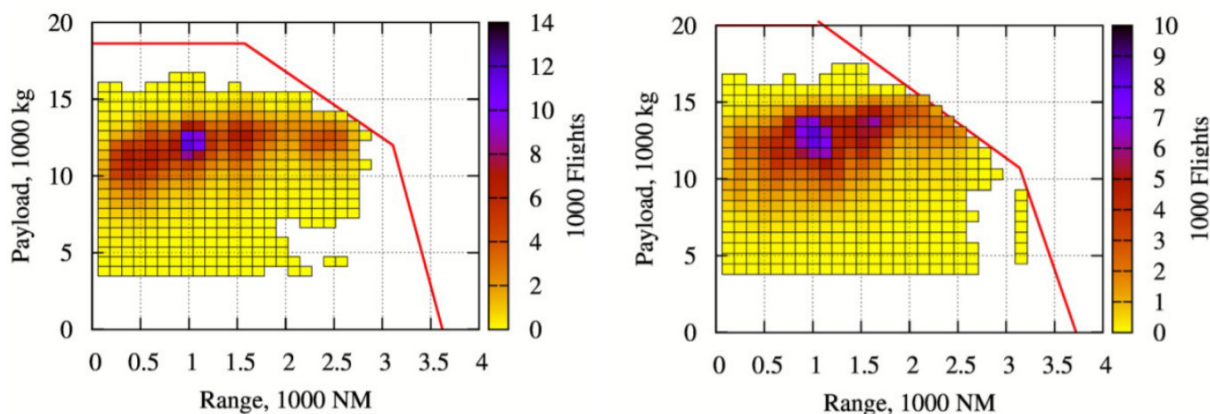


Figure 4.3 Annual number of flights and payload-range diagram of an Airbus A320-200 (left) and a Boeing 737-800 (right) (Linke 2020)

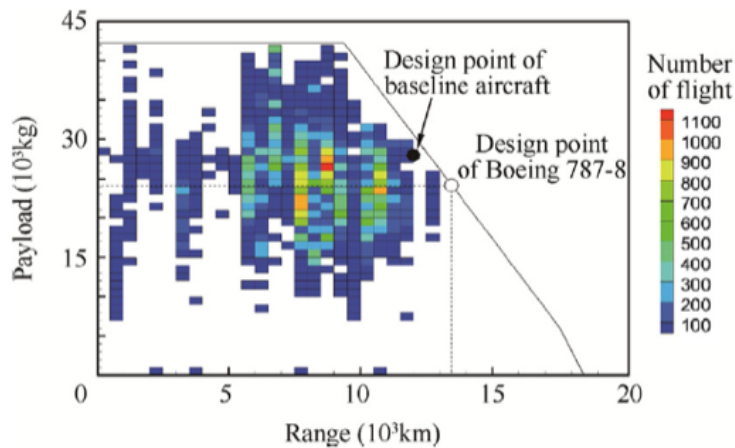


Figure 4.4 Annual number of flights and payload range diagram of a Boeing 787-8 (Chai 2018)

Hurteant (2017) concludes that the selected reference route length is half of Harmonic Range (R_I). He then compared the fuel consumption with that of the extended payload method. For him it was found that the fuel consumption for an entire flight is equal to the fuel consumption calculated with the extended payload-range diagram method multiplied by a factor of 0.84 with a standard deviation of 0.09. The factor 0.84 means in this case that the fuel consumption is smaller than the consumption calculated with Equation (3.9). This is due to the fact that Equation (3.9) assumes the reserve fuel to be consumed, and also because within the range R_I the aircraft is not operated with maximum payload.

In the table below, the values of Hurteant are now to be verified, taking into account the 50 most used passenger aircraft. Since some aircraft types are unfortunately not included in the Master Emission Calculator, the number of aircraft considered is reduced to 36.

Table 4.2 Extended Payload Range Diagram vs. EEA Master Emission Calculator

Aircraft Type	Fuel Consumption, Extended Payload-Range Diagram (kg/km/seat)	Fuel Consumption, EEA Master Emission Calculator (kg/km/seat)	Ratio of fuel consumption EEA/fuel consumption Payload-Range Diagram
Airbus A319	0.02740	0.02160	0.78815
Airbus A320	0.02662	0.02174	0.81666
Airbus A321	0.02013	0.02177	1.08121
Airbus A330-200	0.03410	0.02749	0.80620
Airbus A330-300	0.02892	0.02172	0.75115
Airbus A350-900	0.02479	0.01880	0.75836
Airbus A380-800	0.02953	0.02595	0.87872
ATR 42	0.04085	0.03387	0.82916
ATR 72	0.03176	0.02778	0.87460
Boeing 717-200	0.04015	0.03103	0.77294
Boeing 737 Max 8	0.02128	0.02048	0.96239
Boeing 737 MAX 9	0.02079	0.01940	0.93319
Boeing 737-300	0.02983	0.02791	0.93539
Boeing 737-400	0.03126	0.02601	0.83228
Boeing 737-500	0.04393	0.03106	0.70693
Boeing 737-700	0.02946	0.02482	0.84230
Boeing 737-800	0.02714	0.02163	0.79705
Boeing 737-900	0.01778	0.02047	1.15127
Boeing 747-400	0.03430	0.02676	0.78018
Boeing 757-200	0.02939	0.02428	0.82598
Boeing 767-300	0.02937	0.02425	0.82555
Boeing 777-200	0.02798	0.02491	0.89013
Boeing 777-200ER	0.02416	0.02503	1.03589
Boeing 777-300ER	0.02961	0.02636	0.89025
Boeing 787-8	0.02714	0.02291	0.84402
Boeing 787-9	0.02576	0.02056	0.79789
Boeing MD-80	0.03389	0.03067	0.90512
Bombardier CRJ900	0.03794	0.02859	0.75350
Embraer E170	0.04440	0.03264	0.73521
Embraer E175	0.04097	0.03166	0.77279
Embraer E190	0.03881	0.03225	0.83099
Embraer E195	0.03423	0.02790	0.81514
Embraer E195-E2	0.02637	0.02563	0.97190
Embraer EMB-120 Brasilia	0.06207	0.05823	0.93802
Embraer ERJ-145	0.03980	0.03660	0.91983
Fokker 100	0.03902	0.03393	0.86943
		Average	0.86

The calculation yields a factor of 0.86 with a standard deviation of 0.1. This proves Hurtecan's reasoning.

Figure 4.5 shows a section of the Master Emission Calculator using the A320 as an example at a route length of 1048 NM (1941km) which corresponds to half of R_l (harmonic range) of the A320.

Aircraft code - designators provided in separate worksheet		Manufacturer	AIRBUS INDUSTRIE				Engine type	Jet		
A320		One of the models associated with this aircraft type	A320 233				The most common engine ID in 2015 used for modelling this aircraft type	3CM026		
		Category	Landplane				Number of engines	2		
Aircraft type		Estimated parameters (based on year 2015)								
A320		Most frequently observed cruise flight level (100 ft)	Duration (h:m:ss)	Fuel burn (kg)	CO ₂ (kg)	NO _x (kg)	SO _x (kg)	H ₂ O (kg)	CO (kg)	
Default LTO (1) cycle	Default for a busy European airport, year 2015		00:27:00	742,54	2 338,99	10,97	0,62	913,32	6,52	
	ICAO default		00:32:54	816,17	2 570,93	11,28	0,69	1 003,89	8,25	
Enter a CCD (2) stage length (NM)	1 048	380	02:25:03	5 512,91	17 365,68	79,76	4,63	6 780,89	12,75	
TOTAL LTO + CCD 1048 nm.			02:57:57	6 329,08	19 936,61	91,04	5,32	7 784,78	21,00	
(1) LTO	Landing and Take-Off flight phases									
(2) CCD	Climb/Cruise/Descent flight phases									

Figure 4.5 Extract of EEA Master Emission Calculator by example of an A320

A distinction is made between two different flight phases. The first phase describes the landing and take-off phases and ends at 3000 feet.

Below that high, because information about flight profiles is not sufficiently accurate, the AEM calculates the amount of fuel burnt according to the ICAO LTO cycle methodology, which was defined by the ICAO Engine Certification specifications, and models flight movements (below 3 000 ft) as a series of defined thrust levels for defined lengths of time associated with each LTO cycle flight phase. The fuel burn is calculated thanks to the ICAO Aircraft Engine Emissions Data Bank (AEED), which provides EIs and fuel flow for a very large number of aircraft engines. As EUROCONTROL has developed a table that lists a large range of aircraft models and the engines with which they are generally equipped, the AEM can link each flight movement processed by the AEM to a specific engine as identified by its Unique Identification Number (UID), as listed in the ICAO Engine Exhaust Emissions Databank. (Eurocontrol 2019).

The second phase includes climb, cruise and descent (CCD) and is above 3000 feet.

Above that high, this profile is described in terms of a sequence of straight-line segments that are retrieved from the updated flight plan data managed by the EUROCONTROL Network Manager Operations Centre or partly or completely generated for flight movements outside of the EUROCONTROL zone of coverage. The fuel burn is calculated for each segment of a flight profile thanks to the aircraft performance information provided by EUROCONTROL's BADA (EUROCONTROL, 2016b). This database provides altitude- and attitude-dependent performance and fuel burn data for more than 200 aircraft types. Once the amount of fuel burnt is calculated for

each segment, the Boeing Fuel Flow Method 2 (BFFM2) is used to correct the amount of fuel that is burnt before multiplying by the EFs (Eurocontrol 2019).

Thus, looking at Figure 4.5, the fuel burn (6329.08 kg) can be determined (marked red).

In order to be able to compare the consumption figures with each other, this key figure should also be converted:

$$C_{OEM} = \frac{m_{Fuel\ burn}}{R_1 \cdot n_{OEM}} \text{ [km/kg/seat]} \quad (3.9)$$

In summary, the EEA Master Emission Calculator offers a very good possibility to display the consumption and also the emissions clearly and easily. The consumption calculated based on EEA data includes the LTO cycle and the cruise flight and can therefore be considered as realistic.

4.6 EASA

Finally, and for the sake of completeness, the EASA Aeroplane CO₂ Emissions Database is presented. Here, all CO₂ emissions of aircraft certified by EASA are collected. For this purpose, a so-called CO₂ metric value is determined.

It is a specific air range (SAR)-based metric adjusted to take into account fuselage size. The CO₂ metric value aims at measuring the technology performance of an aircraft type with respect to its fuel efficiency. During certification, it is compared to the applicable CO₂ limit as defined in ICAO Annex 16 Volume III (EASA 2023).

This database is to be expanded step by step over the next few years and provide a transparent insight into the CO₂ emissions of aviation, in particular for specific aircraft. Therefore, all jet aircraft with a maximum take-off mass of more than 5.7 t and propeller aircraft with a take-off mass of more than 8.6 t must be certified according to the ICAO CO₂ standard. From 2028, this is to apply to all aircraft in production.

So far, data availability is still scarce. EASA data only show the A330-800 and A330-900 certified to the new standard.

In the attached Excel file a fuel calculation was performed using these two aircraft types, taking into account the metric value and Equations (3.25), (3.26) and Equations (3.30) through (3.34). Since the metric value has only been specified for two aircraft models to date, this method is calculated as an example but not compared with the other methods. In the coming years and

with the increasing number of ICAO-certified aircraft, this calculation may become more important.

5 Data Analysis

In order to apply the presented methods with information from the different databases for the calculation of fuel consumption to the 50 most used passenger aircraft, an Excel file has been generated. With a normalised unit each consumption can be compared.

After a short introduction, the structure of the Excel file will be explained, and the different interpretation methods will be compared.

5.1 Overview

The Excel file contains 8 Methods that can be used to determine the fuel consumption for each of the 50 aircraft:

- Method 1 Fuel Consumption, SAR
- Method 2 Fuel Consumption, Extended Payload-Range Diagram
- Method 3 Fuel Consumption Bathtub Curve (Harmonic Range)
- Method 4 Fuel Consumption, EEA Master Emission Calculator
- Method 5 Fuel Consumption, BADA
- Method 6 Fuel Consumption, Handbook Methods
- Method 7 Fuel Consumption, Literature Review
- Method 8 Fuel Consumption, Metric Value

As data for the fuel consumption based on metric value is only available for 2 aircraft it's listed separately in tab "Fuel Consumption CO2 MV A330neo".

Furthermore, the Excel file can be divided into 13 tabs. All tabs are described in more detail in Table 5.1.

Table 5.1 Overview of Excel tabs with explanation

Tab	Explanation
Overview	At a glance, all 50 aircraft and their consumptions are listed using the above calculation methods. In addition, the average, standard deviation and the coefficient of variation for each calculation are given and shown graphically.
SAR Extended Payload Diagram Bathtub Curve EEA Master Emission Calculator BADA Handbook Method Literatur review	Each tab lists the fuel consumption and the respective input data. Values taken out of the databases are marked in green.
Fuel Consumption CO2 MV A330neo	Fuel consumptions for A330-800 and A330-900 calculated using the Metric Value with different RGF and Maximum Take-Off Weights.
Deviation	Differences of fuel consumption for each aircraft typ and method are listed. In addition, the coefficient of determination and the mean absolute percentage error (MAPE) are determined.
Matrix	The results from the tab "Deviation" are shown here in the form of a matrix.
Hurtecant	Most of the metrics relevant to the calculations are based on Hurtecant's Excel file. All necessary information was taken from this table and applied to the respective aircraft types.
TOP 50 Most Used Aircraft	In this table, you can find a ranking of which aircraft are most commonly used in aviation.

5.2 Comparison of Methods

The methods described in Section 5.1 differ in their approach to determining fuel consumption, this is why the determined fuel consumption also differs.

Method 1 The fuel consumption is obtained from the slope in the payload range diagram for a given distance in cruise flight. The additional fuel consumption caused by takeoff, climb, descent, landing is not considered. Hence, the consumption per km is lower than an average consumption of a flight.

- Method 2 In this method, the fuel reserves are included so that the consumption in kg/km/seat is higher than an average consumption of a flight.
- Method 3 The method considers the flight phases takeoff, climb, descent, landing with mission segment mass fractions, why realistic values can be expected. The selected range (Harmonic Range; R_I), i.e., the "range at maximum payload", is comparatively generous for consideration. In practice, the range is still below the Harmonic Range.
- Method 4 The consumption calculated via EEA includes the LTO cycle (landing, take-off phase) as well as the cruise flight. The consumption can be regarded as very realistic and practical.
- Method 5 The data from BADA only takes into account the cruise flight. The resulting consumption does not cover the LTO cycle.
- Method 6 Consumption was determined using Handbook methods, with the Breguet factor and SAR. Mission Segment Mass Fractions were not considered here. It is therefore a consumption per km in cruise flight.
- Method 7 The researched consumption figures are based on trade magazines or the author's own observations. Since in most cases a reference route is explicitly indicated or the consumption actually refers to flown routes, it can be concluded that the indicated consumption includes not the fuel reserves. It can also be assumed that all flight phases are included here.
- Method 8 The RGF and the Metric Value are needed to calculate the fuel consumption. It is not clear from the sources whether the consumption includes the LTO cycle or only refers to the cruise flight. It is also unclear whether the consumption includes fuel reserves. Nonetheless, this method may prove very useful in future years when multiple aircraft have been recorded.

Comparing the different methods there are at least 2 categories of methods: Method 1, 2, 5 and 6 determine the fuel consumption only for the cruise flight, whereas method 3, 4 and 7 refer to the full mission cycle incl. LTO providing basically more realistic data. Apart from that method 4,5 and 7 include real flight data.

The following subsections will now compare the different results of each calculation method.

5.2.1 Average Analysis

The mean values of the consumption data of all methods over all selected aircraft differ. This can be explained by the different assumptions listed in Chapter 5.2. Figure 5.1 now shows the average consumptions of each calculation method. Each figure corresponds to the procedure listed in Chapter 5.1.

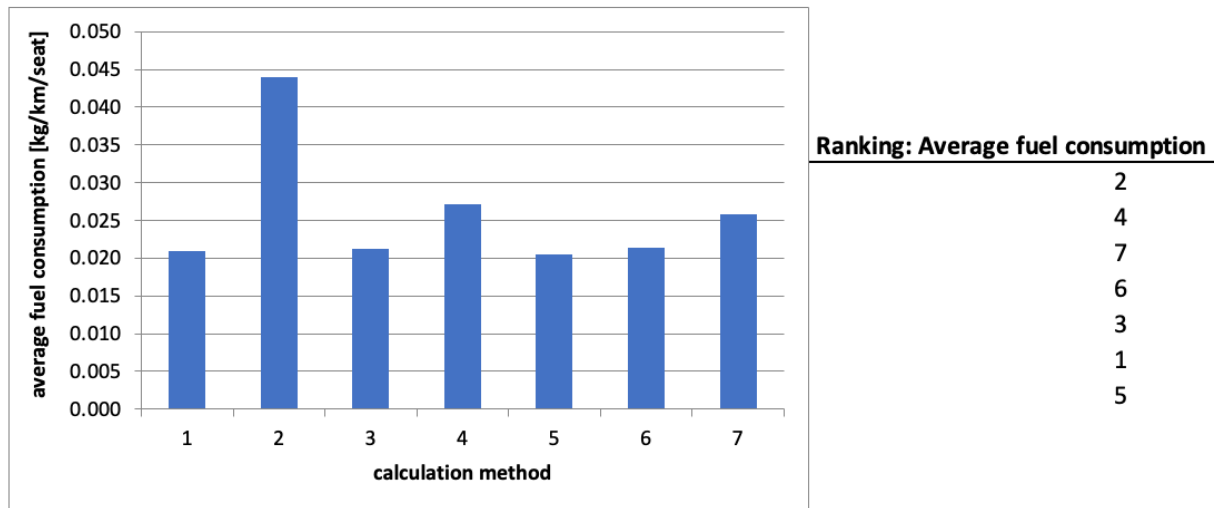


Figure 5.1 Results of the average fuel consumption of all methods (left) and the ranking (right)

It is particularly striking that the calculation according to Extended Payload-Range Diagram has the highest average fuel consumption. However, this can be explained by the complete consumption of the reserve fuel. The consumption in kg/km/seat is thus higher than an average consumption in flight. It is important to mention that the methods cannot be compared with each other, because the average refers to all recorded aircraft of a calculation. However, it is quite possible that in one method there is no information about a certain aircraft type, but in another there is. In the end, only aircraft types and thus their consumption can be compared if they occur in both types of calculation.

5.2.2 Coefficient of Variation Analysis

First, a standard deviation should be determined for all 7 variants. The standard deviation depends on the mean value. Large values (in absolute terms) have a larger standard deviation than smaller values. Therefore, a relative standard deviation must be used for a comparative evaluation. The so-called coefficient of variation.

The coefficient of variation depends on the selection of aircraft. The list of the top 50 most used passenger aircraft covers all sorts of aircraft types (e.g., short-haul, long-haul, fuel-efficient, inefficient aircraft). The coefficient of variation for each method refers to almost the same types of aircraft. Therefore, the coefficients are comparable. They should be similar among the variants. Large deviations are to be regarded as flaws.

Figure 5.2 first shows the distribution of the standard deviation for all methods. This is followed by the distribution of the coefficient of variation in Graph 5.3.

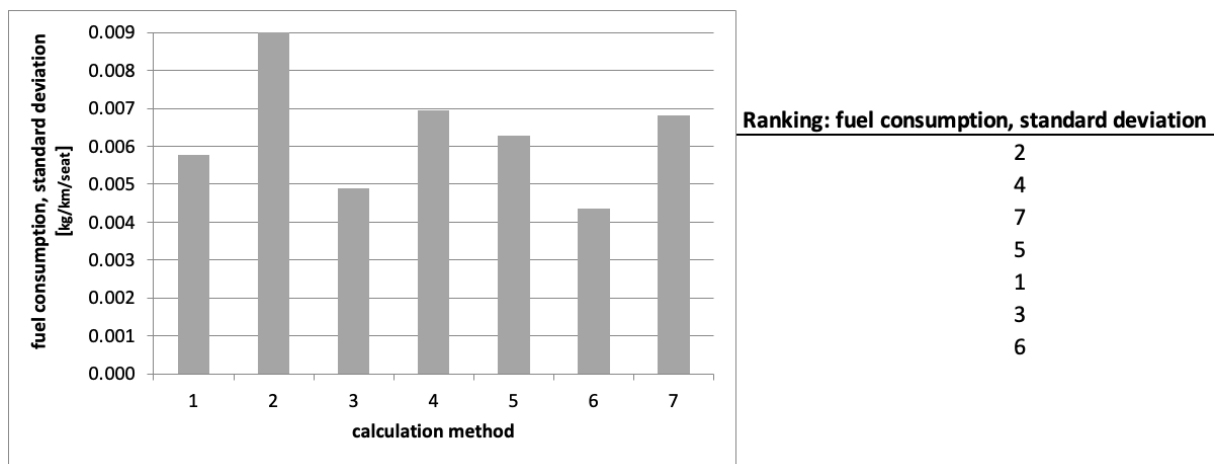


Figure 5.2 Results of the standard deviation of all methods (left) and the ranking (right)

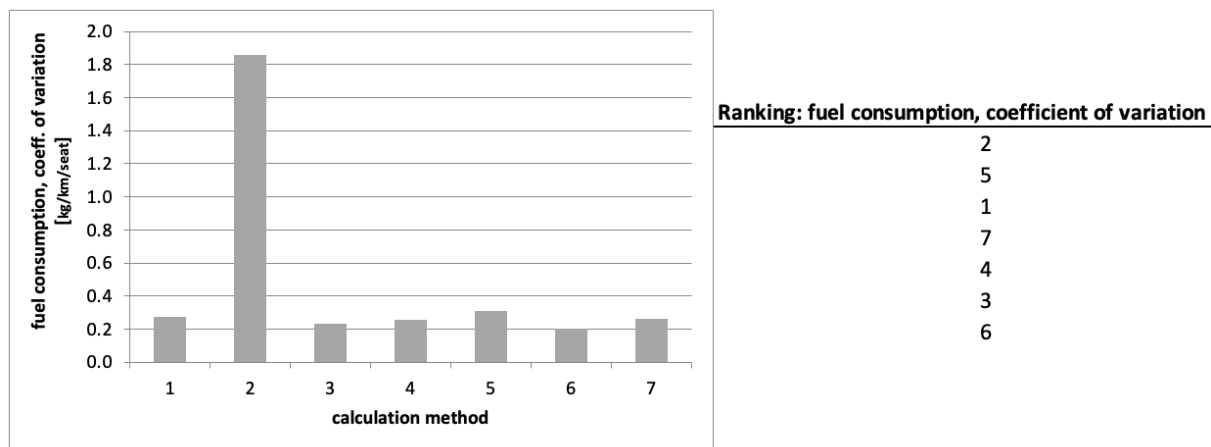


Figure 5.3 Results of the coefficient of variation of all methods (left) and the ranking (right)

It can be seen that all methods except Extended Payload-Range Diagram consumption have a very similar coefficient of variation between 0.204 and 0.307. On average, this is a value of 0.26 among these methods. Only Method 2 shows a much higher coefficient of variation of 1.86. Thus, the values of Method 2 scatter much more. As already mentioned, Method 2 has a higher average consumption. The standard deviation is also significantly higher for Method 2 than for the others (see Figure 5.3). While the standard deviation for the other 6 methods is in

the range of thousandths (0.0061 on average), the standard deviation for Method 2 is in the range of hundredths (0.082).

5.2.3 Coefficients of Determination Analysis

The coefficient of variation does not yet indicate in which direction the deviations from the average fuel consumption of the aircraft move. If in Method A an aircraft has a consumption value significantly above the mean value and this is also the case in Method B, then both methods show the same behavior.

Based on this, each method was compared to each other, and their coefficient of determination was determined. The results can be seen in a matrix of size 7x7. The diagonal of the matrix is by definition assigning the value 1, because the coefficient of a vector with itself is 1 (complete agreement). The matrix is symmetrical with respect to the diagonals.

The coefficient of determination should be as high as possible (ideally 1.0). Therefore, it is good if the mean of all coefficients (of a method with all other methods and with itself) is as high as possible.

Figure 5.4 shows the described 7x7 matrix and its mean values:

Coefficient of determination	Fuel Consumption SAR (kg/km/seat)	Fuel Consumption Extended Payload Range Diagram (kg/km/seat)	Fuel Consumption Bathtub Curve (Harmonic Range) (kg/km/seat)	Fuel Consumption EEA Master Emission Calculator (kg/km/seat)	Fuel Consumption BADA (kg/km/seat)	Fuel Consumption, Handbook Methods (kg/km/seat)	Fuel Consumption Literature review (kg/km/seat)	Average
Fuel Consumption SAR (kg/km/seat)	1	0.61879	0.04668	0.39468	0.02287	0.10377	0.52371	0.38721
Fuel Consumption Extended Payload Range Diagram (kg/km/seat)	0.61879	1	0.00754	0.85450	0.02415	0.04278	0.57103	0.44554
Fuel Consumption Bathtub Curve (Harmonic Range) (kg/km/seat)	0.04668	0.00754	1	0.00134	0.40219	0.27233	0.00004	0.24716
Fuel Consumption EEA Master Emission Calculator (kg/km/seat)	0.39468	0.85450	0.00134	1	0.05636	0.00440	0.35259	0.38055
Fuel Consumption BADA (kg/km/seat)	0.02287	0.02415	0.40219	0.05636	1	0.20456	0.03728	0.24963
Fuel Consumption, Handbook Methods (kg/km/seat)	0.10377	0.04278	0.27233	0.00440	0.20456	1	3.412E-02	0.23742
Fuel Consumption Literature review (kg/km/seat)	0.52371	0.57103	0.00004	0.35259	0.03728	0.03412	1	0.35982
Average	0.38721	0.44554	0.24716	0.38055	0.24963	0.23742	0.35982	
Average of Average:	0.32962							

Figure 5.4 7x7 Matrix of the coefficient of determination

The mean values of these coefficients vary between 0.237 (low) and 0.446 (acceptable). The mean value of these mean values is 0.33. The mean values of the determination coefficients are listed again in the following diagram:

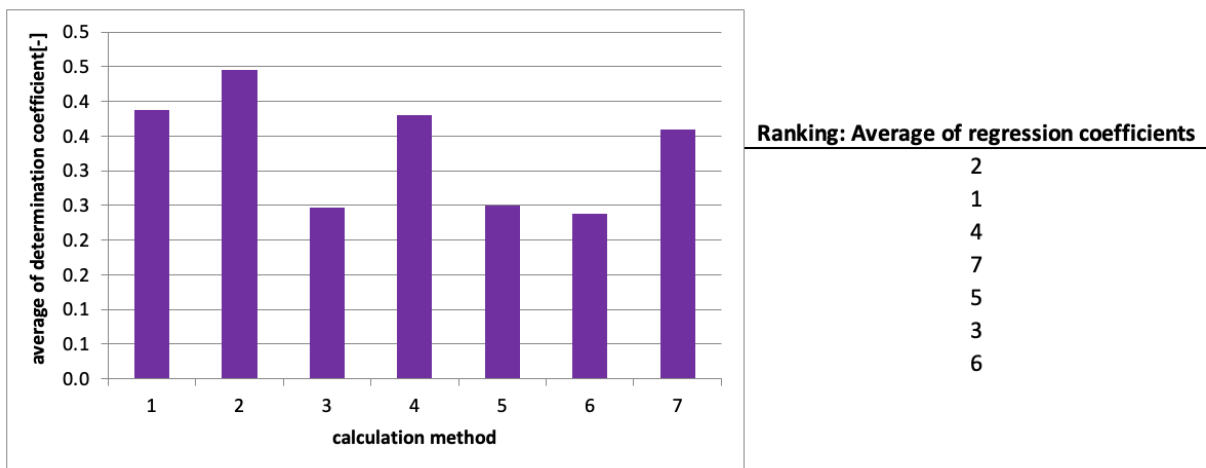


Figure 5.5 Results of the average coefficient of variation of all methods (left) and the ranking (right)

Method 2 thus has the highest and thus best value. This is in contradiction to the evaluation of the coefficient of variation.

5.2.4 Regression Coefficient Analysis as Design Matrix

The matrix of regression coefficients can also be understood as a Design Structure Matrix (DSM).

The design structure matrix (DSM) is useful in identifying where iteration is necessary (Smith 1995). The philosophy of the DSM method is that the design project is divided into individual tasks, and the relationships among these tasks can be analyzed to identify the underlying structure of the project. (Niță 2010)

One type of evaluation is the "Eigenstructure Analysis". The eigenvalues and eigenvectors determine the nature of the convergence of the design process in a similar way with the aircraft dynamics:

- *the eigenvalues give information about the rate of convergence,*
- *the eigenvectors give information about the shape of the natural motion (Niță 2010).*

Therefore, also here, with the help of the 7x7 matrix from Figure 5.4, we search for the highest eigenvalue and the corresponding eigenvector. The highest eigenvalue is 2.69 and the eigenvector has the values for the 7 methods:

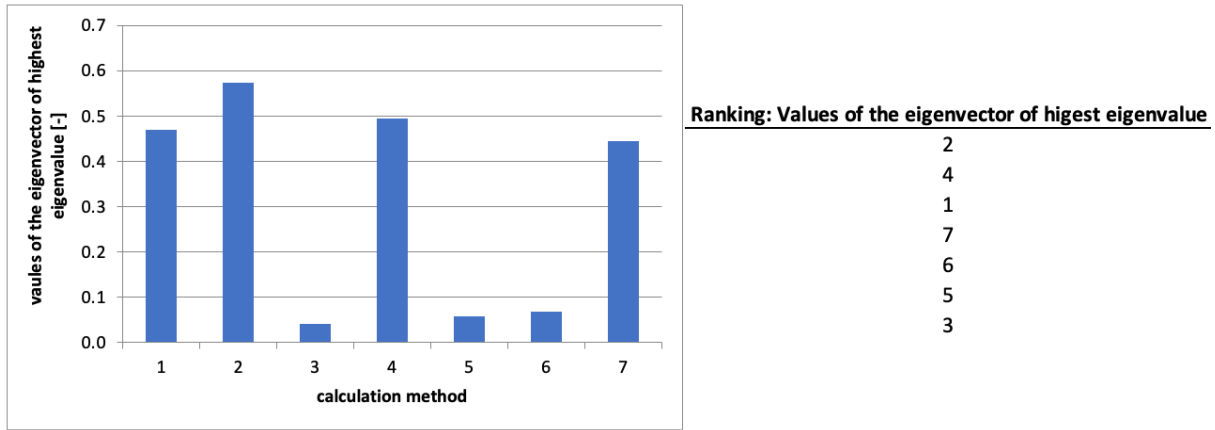


Figure 5.6 Results of the values of the highest eigenvector of all methods (left) and the ranking (right)

The figure shows that the ranking of the methods is different to the evaluation of the regression coefficients.

5.2.5 Mean Absolute Percentage Error (MAPE) Analysis

Even though MAPE is defined as "absolute", MAPE is actually a relative value because the amount of deviation is divided by the (correct) value. As with the regression coefficient, a matrix is generated. On the diagonal, the value is 0 because the deviation with itself is zero. The MAPE should be as small as possible (ideally zero). The aim is to use the mean value of all MAPE (one method compared to all other methods and to itself) as small as possible.

Figure 5.7 shows the 7x7 matrix for the mean absolute percentage error and its mean value.

MAPE	Fuel Consumption SAR (kg/km/seat)	Fuel Consumption Extended Payload Range Diagram (kg/km/seat)	Fuel Consumption Bathtub Curve (Harmonic Range) (kg/km/seat)	Fuel Consumption EEA Master Emission Calculator (kg/km/seat)	Fuel Consumption BADA (kg/km/seat)	Fuel Consumption, Handbook Methods (kg/km/seat)	Fuel Consumption Literature review (kg/km/seat)	Average
Fuel Consumption SAR (kg/km/seat)	0	0.82384	0.22078	0.32704	0.26581	0.18693	0.29879	0.35387
Fuel Consumption Extended Payload Range Diagram (kg/km/seat)	0.82384	0	0.30445	0.15603	0.39199	0.32374	0.20579	0.31512
Fuel Consumption Bathtub Curve (Harmonic Range) (kg/km/seat)	0.22078	0.30445	0	0.17058	0.28160	0.17034	0.21715	0.19499
Fuel Consumption EEA Master Emission Calculator (kg/km/seat)	0.32704	0.15603	0.17058	0	0.24604	0.22915	0.12927	0.17973
Fuel Consumption BADA (kg/km/seat)	0.26581	0.39199	0.28160	0.24604	0	0.24235	0.52979	0.27965
Fuel Consumption, Handbook Methods (kg/km/seat)	0.18693	0.32374	0.17034	0.22915	0.24235	0	0.33025	0.21182
Fuel Consumption Literature review (kg/km/seat)	0.29879	0.20579	0.21715	0.12927	0.52979	0.33025	0	0.24443
Average	0.35387	0.31512	0.19499	0.17973	0.27965	0.21182	0.24443	
Average of Average:	0.25423							

Figure 5.7 7x7 Matrix of MAPE

The mean values of MAPE vary between 0.18 and 0.354. The mean value of these averages is 0.254. The following figure shows the ranking of the mean values of the methods.

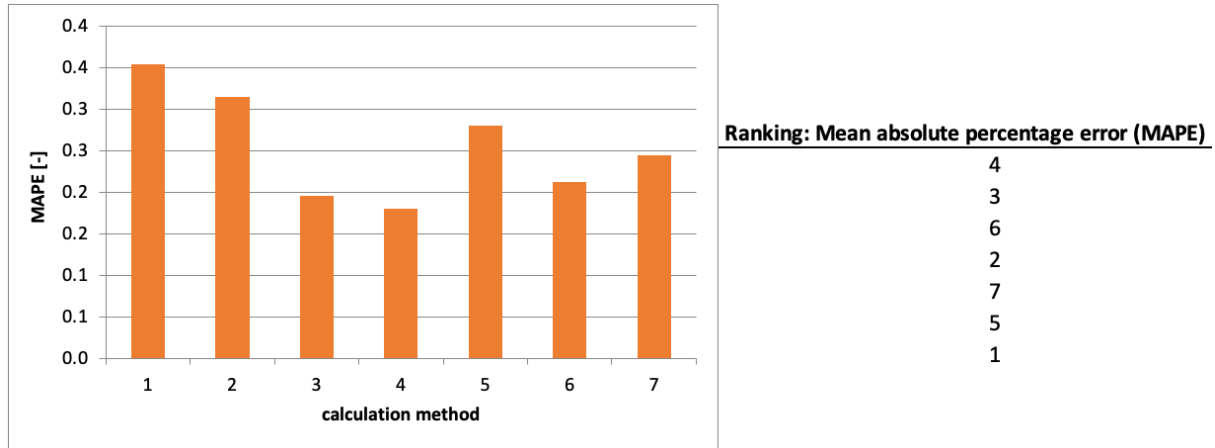


Figure 5.8 Results of MAPE of all methods (left) and the ranking (right)

It can be seen that the EEA Master Emission Calculator method performs best here.

5.3 Comparison of Data

In Chapter 5.2, the methods were compared with each other. What is missing is a comparison that includes the top 50 most used aircraft. First, the 50 aircraft are divided into three categories.

- Turboprop Aircraft
- Narrow Body Aircraft
- Wide Body Aircraft

In the following three graphs, consumption is plotted against the individual aircraft in the group. Each curve represents a method. Due to erroneous data, the De Havilland Canada Twin Otter was not included in any of the following evaluations.

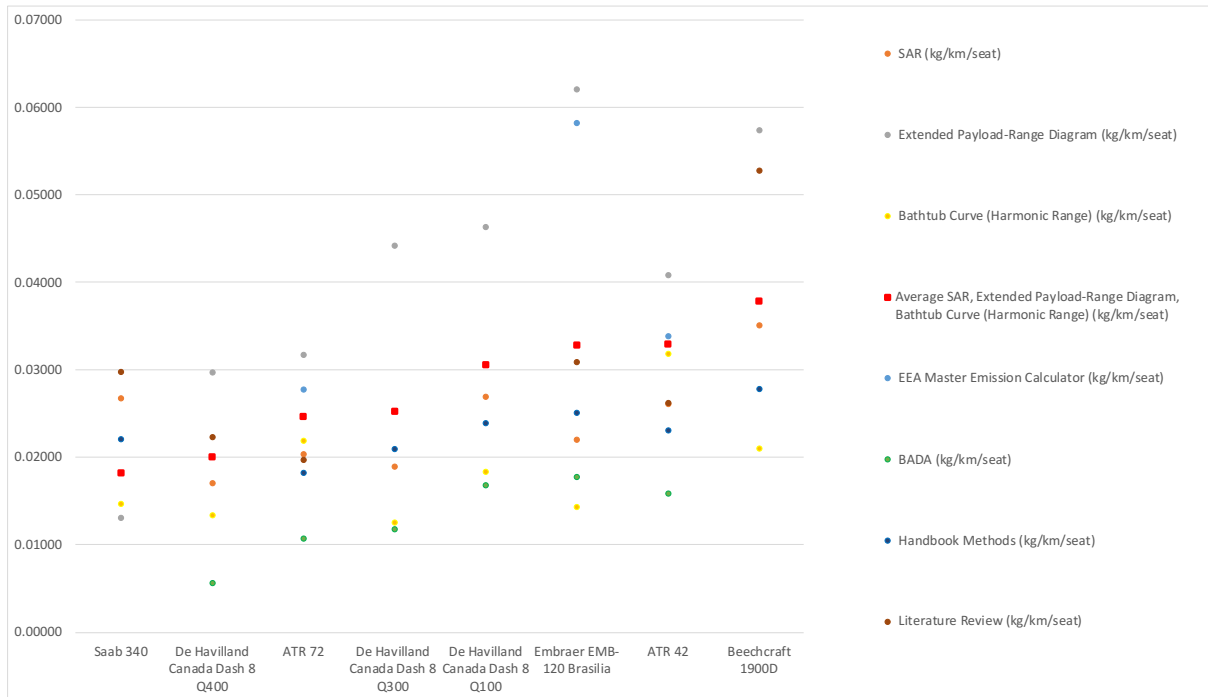


Figure 5.9 Comparison of fuel consumption of turboprop aircraft

The consumption figures for turboprop aircraft are widely scattered, see Figure 5.9. For the EMB-120 the max. value is roughly 400 % of the minimum value, for the De Havilland Canada Dash 8 Q400 it is 500%. This is probably due to an imprecise data basis. On the contrary data for the Saab 340 and ATR42 are closer to each other, an indication of more mature data. Given these scattered data it's difficult to determine the turboprop with the best fuel consumption. In order to better compare data an average fuel consumption out of SAR, Extended Payload Range Diagram and Bathtub Curve has been calculated for all aircraft. The aircraft types are ordered in Fig.5.9 starting with the lowest average fuel consumption first. Accordingly, the results are given for narrow and wide body aircraft as well.

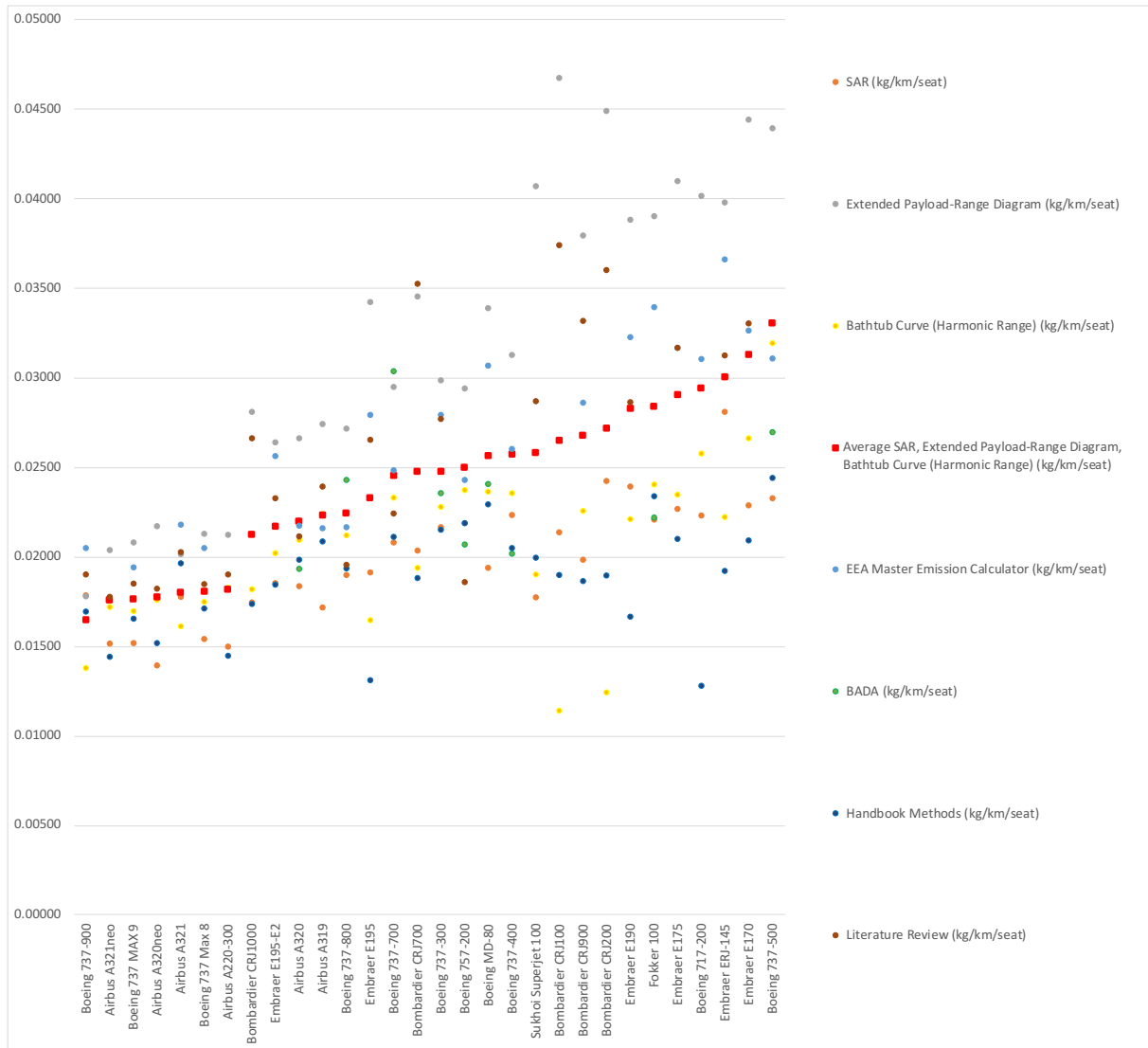


Figure 5.10 Comparison of fuel consumption of narrow body aircraft

First, the fuel consumption of different methods is less scattered compared to turboprop aircraft, see fig. 5.10. The extended payload range diagram method reveals substantial peaks for some aged aircraft (e.g., Boeing 717-200, Boeing 737-500, Bombardier CRJ100, Embraer E175/ERJ145) being conservative for all aircraft types. As MTOW and MZFW are precisely known from the certification documents the peaks could only originate from imprecise design point data (m_i , R_i).

Following the principle comparison in Chapter 5.2 Method 3 and 4 (i.e. Bathtub Curve, EEA) give the more realistic values. They are quite close to each other except for the Embraer aircraft. Unfortunately, some values are missing for Method 4. Apparently, the values for CRJ100/200 scatter widely and cannot be assessed here further.

The comparison of the most used passenger aircraft A320 and B737-800 shows an equal fuel consumption (difference is less than 0.5% according to EEA) although the B737-800 (1st flight 1997) was introduced ca. 10 years after the A320. Then, Airbus developed the A320neo (1st

flight 2014) with ca. 15% less fuel consumption compared to the A320 according to the bathtub figures (A320: 0.02093 kg/km/seat; A320neo: 0.01758 kg/km/seat). The better efficiency of the A320neo has been achieved by aerodynamic measures (e.g., winglets), engine improvements and an extension of the seat capacity from 150 to 165. Boeing answered the A320neo market success with the B737 MAX 8 (1st flight 2016) as the direct competitor. Both the bathtub method and the literature review show very similar fuel consumptions (EEA data is missing for the A320neo). But the B737 MAX 8 suffered then from the 2 accidents and a long-lasting process to regain certification. Further improvements are presently being achieved with configuration changes, i.e., with stretched versions, thus entering another market segment (B737-MAX9). The B737 MAX9 and the A321neo (with similar seat capacities) have similar average values, whereas the average value of the B737-900 is the lowest. As can be seen fuel efficiency is an important driver for the aircraft market that have been improved by configuration (e.g., aerodynamics, seats) and engine changes.

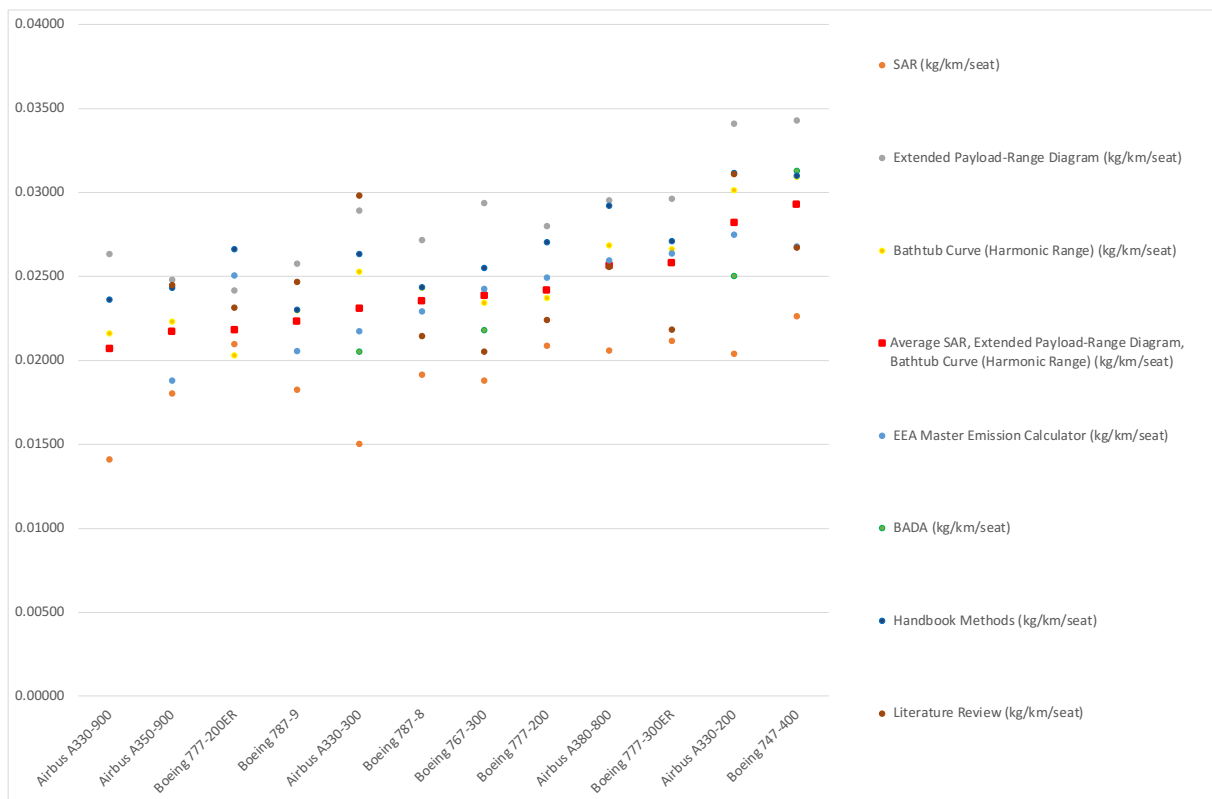


Figure 5.11 Comparison of fuel consumption of wide body aircraft

First, fuel consumption of wide body aircraft is also quite scattered for many aircraft types (e.g., A330-300: 100% increase from min. to max. fuel consumption), see Figure 5.11. Again, the Extended Payload-Range method shows very conservative, the SAR method very optimistic (i.e. low) fuel consumptions for the cruise flight. As only the Extended Payload-Range method includes the fuel reserve the consumption is significantly higher. The comparison of the A350-900 and B747-400 yields a higher fuel consumption of the Boeing aircraft. The reason is an

aged B747 with 4 engines is compared with the newer A350 with 2 engines. The direct competitors A350-900 and B787-8 show less fuel consumption for the Airbus aircraft. Overall, the Airbus A330-900(neo) together with A350-900 and B777-200ER offer the lowest fuel consumption. It has to be noted that the SAR value of the A330-900 is significantly lower than the others, thus lowering the average value.

Overall, a conclusion on absolute figures is difficult to make because of the scattered data. It would have been helpful to get access to OEM data.

It can be seen that the consumption figures for turboprop aircraft are more widely scattered than those for wide-body aircraft, for example. This is due to the data basis and the more difficult calculation methods (bypass ratio for propellers difficult to determine).

However, it can be stated for all three diagrams that the Extended Payload-Range Diagram method is probably the most conservative method.

The method according to EEA hardly represents the turboprop aircraft, but it lies in the middle of the other curves for narrow body aircraft as well as for wide body aircraft and has a good data coverage.

Figure 5.12 shows the consumption figures for the A330-900. Here, Method 8 (CO₂ MV A330neo) is to be compared with the other methods. As mentioned in Chapter 4.6, this calculation method is based on only one aircraft type (A330neo in two configurations).

It can be seen that the average value of method 1-3 is very close to the value of method 8 and thus has the lowest value of deviation. Method 2, on the other hand, has the largest deviation.

A330-900 Analysis	Method 1 (SAR)	Method 2 (Extended Payload- Range Diagram)	Method 3 (Bathtub Curve (Harmonic Range))	Average Method 1,2,3 (SAR, Extended Payload-Range Diagram, Bathtub Curve (Harmonic Range))	Method 4 (EEA Master Emission Calculator)	Method 5 (BADA)	Method 6 (Handbook Methods)	Method 7 (Literature Review)	Method 8 (CO ₂ MV A330neo)
Fuel Consumption (kg/km/seat)	0.01410	0.02633	0.02160	0.02068	no data available	no data available	0.02361	no data available	0.01897
Deviation to Method 8 (CO ₂ MV A330neo)	-0.25690	0.38764	0.13843	0.08972	no data available	no data available	0.24457	no data available	

Figure 5.12 Comparison of fuel consumption of A330-900

6 Summary

6.1 Summary Methods

A total of 8 calculation methods have been presented. For the Metric Value method 8 values are only available for one single aircraft type (Airbus A330neo in two configurations). For this reason, this method has not been considered further in the statistical evaluation.

For Method 1 (Fuel Consumption, SAR) four parameters (R_1 , m_1 , R_2 , m_2) are required. These are parameters that directly describe the consumption in cruise flight. Usually the parameters are determined by a payload range chart. A payload range chart is not publicly available for every aircraft.

Method 2 (Fuel Consumption Extended Payload-Range Diagram) shows consumption values that are clearly too high. A general correction of the values with a factor (of 0.86 as calculated here) should be avoided. However, Method 2 has the advantage that only three input parameters are required. Possibly, the method can be used to compare aircraft among each other.

Method 3 (Bathtub Curve) requires, like Method 1, the four parameters R_1 , m_1 , R_2 , m_2 as well as MTOW and MZFW. The method considers the flight phases takeoff, climb, descent, landing with mission segment mass fractions, therefore the values are to be considered realistic. In the comparisons under Chapter 5.2, Method 3 does not stand out particularly.

Overall, Method 4 (EEA) delivers very good values. However, data could only be provided for aircraft that are contained in the database.

For Method 5 (BADA) only a few (older) values were publicly available. BADA requires a license and is therefore not publicly available. It is not allowed to publish consumption values of individual aircraft.

Method 6 (Fuel Consumption, Handbook Methods) provides results in the correct size. The following input parameters are required: M_{CR} , R_1 , b_W , S_W , MTOW, MZFW, bypass ratio λ (BPR). The result is obtained only on the basis of aerodynamics and specific fuel consumption statistics.

In Method 7, fuel consumption was determined during a literature search. In most cases, routes actually flown by various airlines were considered and the fuel consumption determined. It is not clear from the documents what the utilization of the aircraft or the external circumstances (weather, wind, etc.) were. It is therefore difficult to evaluate the results.

Method 1, 2, 5 and 6 determine the fuel consumption only for the cruise flight, whereas method 3, 4 and 7 refer to the full mission cycle incl. LTO providing basically more realistic data.

6.2 Summary Fuel Consumption Aircraft

The fuel consumptions of different methods vary a lot. First, data has been compared in 3 categories, i.e., turboprop aircraft, narrow body and wide body aircraft. For turboprop data is too scattered for any specific conclusion.

The comparison of the most used passenger aircraft A320 and B737-800 shows an equal fuel consumption in the category narrow body. Newer aircraft types (e.g., A320neo) offer better fuel efficiency than former derivatives, i.e. A320. The more recent aircraft types on the market, i.e. A320neo and B737 MAX 8, have similar fuel consumption. The fuel efficiency is an important driver for the aircraft market that have been improved by configuration (e.g., aerodynamics, seats) and engine changes.

For wide body aircraft the calculation data varies a lot as well, still too much for an absolute comparison in that category. The direct competitors A350-900 and B78 show better values for the A350-900. Comparing an aged B747-400 with 4 engines with the newer A350-900 with 2 engines reveals of course a better efficiency for the A350.

6.3 Importance of Fuel Consumption in Civil Aviation

Fuel is one of the biggest expenses for airlines. Savings in fuel consumption will therefore directly lead to cost savings. Besides, also the greenhouse gas emissions are reduced accordingly.

The improvement of fuel consumption can then lead to an efficient use of resources. Also, fuel efficient aircraft can operate over longer distances. Hence, there is a potential for airlines to open up new destinations with less fuel consumption compared to bigger aircraft, e.g., operating the A321XLR. On the whole fuel consumption of modern aircraft drives the economic competitiveness of airlines. But nowadays technological improvements in aircraft/engine design have already reached a high degree of optimization. Now, further measures are being taken into consideration. Airbus has performed the first long-haul demonstration of formation flight in General Air Traffic (GAT) regulated transatlantic airspace with two A350 aircraft flying at three kilometers apart from Toulouse, France to Montreal, Canada (Airbus 2021). It confirmed a potential for more than a 5% fuel saving on long-haul flights, making use of a reduction of the

(induced) drag similar to the flight of migrant birds. Extending the number of aircraft operating in formation will increase the fuel savings furthermore. Disruptive new aircraft design like blended wing body design can offer up to 20% better efficiency compared to a traditional aircraft design (Airbus 2020). So, technological advances will further reduce the fuel consumption in civil aviation. The ecological footprint will of course also depend on the evolution of air traffic as a whole.

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