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A General View on Fuel Efficiency in Commercial Aviation

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Abstract

This focus of this thesis is to provide an insight into fuel consumption and efficiency of commercial aircraft. This is achieved by developing two methods to estimate the fuel consumption using a top down, then a bottom up approach respectively. The estimation methodologies allow comparisons to be made between the methods, enabling the most applicable method to be selected to suit user requirements. The factors which affect fuel consumption are discussed, with potential fuel saving techniques for existing aircraft presented.

The fuel consumption estimations are incorporated into an innovative flight booking tool, which allow users to select flight routes based on environmental impact and on their individual needs. This enables users to do their part towards fulfilment of an eco-conscience industry.

Fundamentally, the analysis finds that the industry growth predictions do not meet sustainability requirements. The paper discusses the unacceptability of the industry's complacency and overreliance on carbon compensation schemes, proposing the introduction of legislation to catalyse the shift towards a sustainable future.

The analysis concludes that sustainability is achievable within the industry, but that this will only be achieved through active input and efforts from all parties involved.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

A General View on Fuel Efficiency in Commercial Aviation

Background

New studies (e.g. **AGAPE 2010**) show that set goals for fuel efficiency and CO2 reduction in aviation may not be reached as originally (**ACARE 2001**) planed. This perhaps painful insight should lead to a fundamental rethinking. Instead of getting bogged down in details of technology it is time to step back and remind ourselves what is truly important and to look at the bigger picture. We need not only a metric for climate impact of aviation, but first of all a fuel metric. One that is meaningful, based on publicly available information and understandable also for the air traveller. Each offered flight needs a label that clearly states what it contains comparable with Quantitative Ingredient Declarations for food as demanded by Food Labelling Regulations. Only with this information the passenger can make an informed selection among the different products offered. This could boost the revolution in air transport as initiated by air transport liberalization and growth of low fare airlines. Again, as with low fare airlines, it will "ensure continued competition, consumer choice ... lower fares" and will "contribute to the development of ... environmentally efficient travel" (**ELFAA 2004**).

Task

The tasks of this thesis is to follow the ideas as expressed under background and to take this general view on fuel efficiency in commercial aviation by looking at facts maybe not addressed sufficiently in the past. Subtasks of this thesis are (given here as a general guidance):

- Review: Literature / state of the art review including current fuel metrics (3 litres), traffic forecasts, and strategic goals in the aviation sector and limits to growth (World3).
- Aerodynamics: Extending concepts of estimating drag polars from simple geometric parameters especially considering induced drag.
- Flight Mechanics: Taking an extended look at the payload range diagram and the Breguet range equation. Proposing a metric for fuel efficiency.

- Aircraft Design and Aircraft Operation: Discussing (i.e.) the influence of speed, altitude and range on fuel efficiency and climate change.
- Air Travel: Investigating offered flights, routings through Europe, fuel efficiency, graphical representations, forms and effectiveness of compensation schemes, proposals for their improvement or replacement, "flight labelling" and booking support followed by a discussion of (political) measures for its introduction.

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

References

ACARE 2001	ADVISORY COUNCIL FOR AERONAUTICS RESEARCH IN EUROPE: European Aeronautics : A Vision For 2020. Luxembourg : Office for Official Publications of the European Communities, 2001. – ISBN 92-894-0559-7, URL: http://www.acare4europe.org/docs/Vision%202020.pdf (2012-01-18)
AGAPE 2010	MULLER, R.: AGAPE Project Final Report : Publishable Summary. Brussels : AeroSpace and Defence Industries Association of Europe, 2010. – URL: http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/agape_final_report_summary.pdf (2012-04-16)
ELFAA 2004	EUROPEAN LOW FARES AIRLINE ASSOCIATION: Liberalisation of European Air Transport : The Benefits of Low Fares Airlines to Consumers, Airports, Regions and the Environment. Brussels : ELFAA, 2004. – http://www.elfaa.com/documents/ELFAABenefitsofLFAs2004.pdf (2012-04-21)

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Symbols

A	Aspect Ratio
B	Breguet factor
c	Specific Fuel Consumption
C_D	Drag Co-efficient
C_{Di}	Induced Drag Co-efficient
C_{Do}	Zero Lift Drag Co-efficient
C_L	Lift Co-efficient
D	Drag
E	Lift to Drag Ratio
e	Oswald Span Efficiency Factor
EI	Gas Species Index
$f(\ldots)$	Function
fc	Fuel Consumption
g	Gravity
H_0	Specific Humidity of Air
k_e	Oswald Correction Factor
L	Lift
M	Mach
m	Mass
P	Payload
p	Price
R	Range
S	Wing Area
s	Radiative Forcing Factor
V	Aircraft Speed
W	Weight
X	Relative Value (Indexed between 0 and 100)

Greek Symbols

ρ	Density
λ	Wing Taper Ratio
φ	Wing Sweep

Subscripts

$()_{ana}$	Analytical
$()_{CLB}$	Climb
$()_{CO2}$	Carbon Dioxide
$()_{comp}$	Compressor
$()_{CR}$	Cruise
$()_{DES}$	Descent
$()_{diffuser}$	Diffuser
$()_{eff}$	Effective
$()_{fc}$	Fuel Consumption
$()_{ff}$	Fuel Fraction
$()_{H2O}$	Water
$()_{L}$	Landing
$()_{LOI}$	Loiter
$()_{Max}$	Maximum
$()_{mF}$	Loiter
$()_{Min}$	Maximum
$()_{MTO}$	MTOW
$()_{MZF}$	MZFW
$()_{NOx}$	Nitrous Oxide
$()_{OEW}$	OEW
$()_{p}$	Price
$()_{PL}$	Payload
$()_{RES}$	Reserves
$()_{SO}$	Shut-Off

$()_{SO4}$	Sulphate
$()_{Stat}$	Statistical
$()_{t}$	Time
$()_{theo}$	Theoretical
$()_{TO}$	Take-Off
$()_{x}$	Specified Value

List of Abbreviations

A/C	Aircraft
ACARE	Advisory Council for Aeronautics Research and Innovation in Europe
ATC	Air Traffic Control
BPR	Bypass Ratio
EOW	Empty Operating Weight
GCR	Great Circle Route
GS	Gold Standard
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LRC	Long Range Cruise
LtG	Limits to Growth
LTO	Landing Take-off Cycle
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero Fuel Weight
PAX	Passenger
SFC	Specific Fuel Consumption
SGTP	Sustained Global Temperature Change Potential
VCS	Voluntary Carbon Standard
VGS	Voluntary Gold Standard

Terms & Definitions

Additionality

Reduction in emissions by sources, or enhancement of removals by sinks, that is additional to any of these activities that would occur in the absence of a Joint Implementation or a Clean Development Mechanism project activity, as defined in the Kyoto Protocol Articles on Joint Implementation and the Clean Development Mechanism **(Gösling 2007)**

Afforestation

Planting of new forests on lands that historically have not contained forests **(Gösling 2007)**

Carbon Lock-In

The condition which creates persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages **(Unruh 2000)**

CO2-e or CO2 equivalent

The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other GHGs **(Gösling 2007)**

Contraction and Convergence

A framework developed in the mid-1990s by the Global Commons Institute (GCI) as an antidote to the expanding, diverging and climate-changing nature of global economic development. The model now at the core of the UN Framework Convention on Climate Change has been approved by the European Parliament and many governments out with Europe **(Meyer 2004)**

Emissions Trading

A market-based approach to achieving environmental objectives that allows those reducing greenhouse gas emissions below what is required to use or trade the excess reductions, to offset emissions at another source inside or outside the country. In general, trading can occur at the intra-company, domestic and international levels. The IPCC Second Assessment Report adopted the convention of using ‘permits’ for domestic trading systems and ‘quotas’ for international trading systems. Emissions trading under Article 17 of the Kyoto Protocol is a tradable quota system based on the assigned amounts calculated from the emission reduction and limitation commitments listed in Annex B of the Protocol **(Gösling 2007)**

Multi-Staging

The process of separating long haul routes into a series of short stages. Implementation of Multi-staging allows a reduction in TOW, thereby achieving a significant reduction in fuel required for flight.

Optimum & Optimisation

Optimum within this thesis refers to the condition which provides the minimum fuel consumption, measured using mass fuel required for a predefined range. *Optimisation* refers to methods or processes performed to maximise this efficiency by providing a reduction in fuel burn or fuel consumption, for a defined or maximum range.

Radiative forcing

Radiative forcing is the change in the net vertical irradiance (expressed in watts per metre square) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as a change in the concentration of carbon dioxide or the output of the sun. Usually, radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values **(Gösling 2007)**

Reference Aircraft

Reference Aircraft are used throughout this thesis to assess and compare methods and parameters. Both Airbus and Boeing aircraft are used as reference aircraft and are referred to by manufacturer (Airbus 'A' or Boeing 'B') and model i.e. B737 or A320. All aircraft referred to within this thesis are jet aircraft. For simplicity, propeller driven aircraft have not been considered in this analysis, though many of the underlying theories would be universally applicable.

Reforestation

Planting of forests on lands that have previously contained forests but that have been converted to some other use **(Gösling 2007)**

Sustainable Development

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs **(WCED 1987)**

Sustained Global Temperature Change Potential

The global mean temperature change after *H* years of sustained emissions of 1 kg per year of a gas species (or 1 nautical mile per year for contrails and cirrus) **(Schwartz 2009)**

Three Litre Aircraft

Three Litre Aircraft refers to the application of the 'litres of fuel consumed per passenger and per 100 km' fuel metric in aviation. Three litres is taken as the benchmark or target value to allow direct fuel efficiency comparison, between modes of transport.

1 Introduction

1.1 Motivation

As the world economy continues to grow, the need to achieve sustainable development increases. CO_2 emissions and the requirement for sustainability are a global concern, across all sectors. Each sector must do whatever is within its power to ensure this is achieved. Closer analysis has identified clear gaps between current mobility trends and sustainable transport scenarios. This is especially the case with aviation, which is currently experiencing the fastest rates of growth among all transportation sectors.

There exists little transparency within the industry, despite the obvious benefits such transparency would provide. The unavailability of data has, in this regard, made estimating fuel consumption of commercial aircraft a complex task. The Airline Assessment Index summarises this frustration with;

> *"While it is well known that most air carriers have detailed information in regards to their fuel consumption and fuel efficiency, this information is not publicly available. At present, it was not possible to identify any suitable public alternative data source"* ***AAI 2012***.

This thesis presents techniques with which to arrive at estimates for fuel consumption, and discusses fuel consumption within aviation. Areas of concern are identified as are current practices which require closer scrutiny and re-appraisal in an effort to encourage transparency within the industry, and to bring about a change in thinking with regards to the current operating model in aviation.

1.2 Objectives

This paper intends to address some of the key issues within aviation that the author feels have been of recent, unduly overlooked or ignored. The thesis presents two methods for fuel consumption evaluation and discusses the operational factors which influence fuel consumption. Finally, the air transport model which is currently adopted is discussed. An innovative flight evaluator system is developed, along with a discussion on the legislation to encourage sustainability within the industry.

1.3 Structure of the Thesis

This structure of this thesis is as follow:

Chapter 2	Literature Review to provide context for the reader, as to the purpose and scope of the thesis complete
Chapter 3	Method presented to estimate Oswald Span Efficiency Factor
Chapter 4	Fuel mass estimation method presented and discussed, along with the proposal of an aviation applicable fuel efficiency metric. Further, the effects of range on total fuel consumption are analysed and discussed
Chapter 5	Environmental benefits of variation of flight parameters including flight speed, altitude and cruise Mach number are analysed and discussed
Chapter 6	Flight booking processes are analysed, along with carbon offset and trading schemes
Chapter 7	Thesis conclusion and final remarks

The reference of much literature has been employed, both within the literature review and within the main body of text. All sources have been referenced, with a complete reference list reproduced at the end of the thesis.

2 State of the Art

2.1 Environmental Targets & Goals

The UN estimates the global population by 2050 at around 9.3 billion **(UN 2011)**. As world population continues to expand, growth demands in all sectors will continue to escalate, gaining momentum as lower-income countries become increasingly industrialised **(IEA 1998)**.

Aviation is continuing to experience the fastest growth rates among all modes of transport **(IPCC 1999)**, and with as much as sixty to eighty percent of air traffic growth being attributable to economic growth **(Boeing 2012)**, greenhouse gas emissions from aviation are currently and will continue to grow at a rate far in excess of those of other sectors **(Bows 2005)**. Expansion on such a scale will bring with it high levels of pollution and will further increase the pressure on all sectors to reduce emission levels.

In response to these pressures, the governing bodies within aviation have outlined a set of goals which, if met, will go some way to ensuring the industry's sustainability. The commonly adopted goal is for carbon neutral growth from 2020, and a 50% reduction in net carbon emissions by 2050 compared to 2005 levels. These goals are championed by industries bodies, including **ATAG 2012**, **IATA 2011**, **ACARE 2011**, as well as by the aircraft manufacturers including Boeing, Airbus, Bombardier and Embraer.

It is becoming increasingly clear that the industry will not achieve these goals as predicted growth rates currently outpace efficiency improvements rates.

2.2 Forecasting Exponential Growth

The incumbent aircraft manufacturers produce annual forecasts which detail their expected growth within the aviation industry. These forecasts are used by many, including "airlines, suppliers and the financial community [to] make informed decisions" **(Airbus 2011)** in matters regarding aviation and air transport. These forecasts provide estimates for demand and traffic growth using market predictions and extrapolated historical data **(Boeing 2012)**.

These forecasts are rarely challenged and are generally accepted by the industry at large which is unsurprising given the vested interest the parties involved have in the predictions. Manufacturers wish for a stable, growing market, operators wish to ensure strength of demand, and passengers wish for aviation to remain competitive, cheap and available.

Analysis of growth predictions in conjunction with the set environmental targets reveals striking contradictions. Figure 2.1 illustrates relative industry growth, and emission levels, as a result of 5% annual growth and 3.5% annual efficiency improvement as the figure discussed by **Egelhofer 2008**, concurrent with the **IATA 2011**. It must be noted that this quoted level of efficiency improvement represents the best possible scenario for efficiency improvement within aviation. This is through the assumption of either instant integration of new technologies as they are developed across the existing fleet or, through technology improvements in new and modified aircraft of such magnitude that they positively affect global fleet average to this extent. Figure 2.1 therefore demonstrates that even if these assumptions are valid, i.e. that if the **ACARE 2001** goals are met, relative emission levels will still increase exponentially.

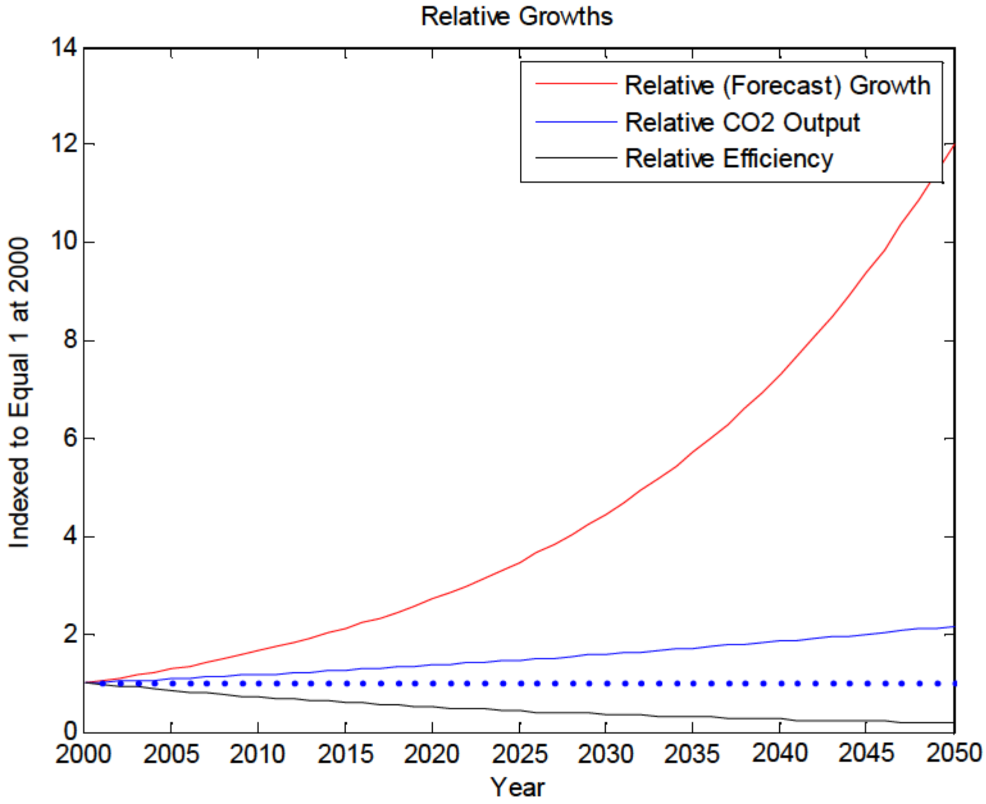

Figure 2.1 Relative growths of Industry, Emissions and Efficiency based upon predicted 5% growth and desired (maximum) 3.5% annual improvement of efficiency.

Put simply, aviation will only be sustainable if growth rates match efficiency improvement rates. That however assumes the current model of aviation is already sustainable, and that efficiency improvements of such scale are possible.

The **IATA 2011** publication has to some extent acknowledged this issue, by realising these goals cannot be met, instead indicating that technological shortfalls in efficiency will be compensated through carbon trading schemes. This is demonstrated in Figure 2.2. In stating this, IATA is failing to realise that the issue of sustainability is a universal problem across all sectors. If transport, or specifically aviation, is granted a higher degree of leniency than other sectors, then over-proportionally large reduction penalties will be imposed on every other sector **(Ceron 2007)**.

Deregulation of the aviation industry in Europe in 1997 brought with it massive changes in the way airlines were permitted to operate, which enabled the growth and development of the low cost carrier model. The EU currently has 20 low-cost carriers, representing 40.2% of the internal EU market. In 1990 there were none **(EUROPA 2011)**. Passengers are attracted to low cost carriers through low prices, yet they are ignorant of, or insouciant to, the increasing cost to the environment **(Uherek 2006)**.

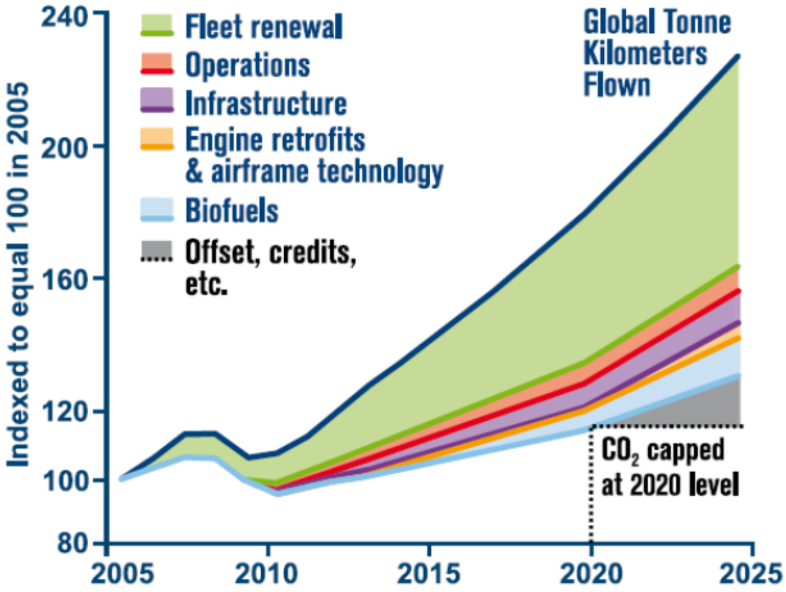

Figure 2.2 IATA industry predicted growth and anticipated efficiency improvements IATA 2009. Prior to 2009, IATA was adamant that carbon neutral growth would be possible without the need for offsets and credits.

The persisting upward trend in oil prices over the last several decades is set to continue. Realisation of 'Peak Oil'[1] is anticipated some time before the middle of the century **(Hirsch 2005)**, the consequences of which will further cause reserves to diminish, bringing with it accelerated inflation of oil prices.

The unavailability of oil this will bring with it will further cause prices to rise, with an ever increasing rate. The coupling effect of exponential growth, the increasing demand for, and

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[1] Peak Oil is the concept first explored by **Hubbard 1956**, which refers to the point at which maximum oil production is met, following which, production would enter terminal decline. The date of the reference bears additional significance, in identifying that this issue is not a new one, and the public have been aware this will occur for sometime, however the exact date Peak Oil will occur is the topic of much debate.

decreasing availability of oil will only cause the cost of air travel to further rise. As aviation begins to become more expensive, passenger numbers and demand will begin to decrease, placing great strain on the industry at large.

Despite predicting growth alone, these market forecasts have large implications for industry. The forecast's authors must recognise their implications, and realise that this exponential growth in unsustainable. Airlines welcome the security provided by these predictions, although it is the airlines that will ultimately bear the burden of decreasing demand and price inflation.

2.3 Emission Awareness and Fuel Metric

There exists a wide variation in public awareness of the magnitude of the environmental impact of aviation **(Gössling 2007)**. This is, in part, attributable to the difficulty the public have in assessing the real impact of aviation. This lack of clarity is by no means the fault of the passenger, but is due to the number of contradictory sources either unintentionally conspiring with or condemning the impact of aviation.

The airlines and manufacturers, who have the most accurate and detailed data on fuel consumption, are currently free to publish selectively the data they choose, and to a large extent control what is published by the media. Papers published by the scientific community rarely gain widespread media attention, and do not possess the lobbying power of the airline industry at large, inhibiting them from effectively communicating any message regarding the associated environmental damages.

The aviation industry currently contributes around £11 billion to UK GDP per annum and directly supports around 186,000 jobs **(Gill 2007)**. While the industry provides such economic positives, there is little (economic) reason for government to pursue legislation which promotes awareness of detrimental environmental impact.

While many passengers acknowledge the significant threat of aviation to the environment, a recent study by **Cohen 2011**, found there was little evidence that many consumers would forgo long-haul air travel because of climate concern. Instead passengers perceived that the extraordinary personal benefits of air travel outweigh associated emission impacts.

Further difficulty arises from the complexity of measuring and assessing the actual impact air travel is causing to our health and to the environment. The delay between the cause and effect of pollution means that the true impacts of pollutants are not experienced for some time following emission **Turner 2008**. Were this delay to not exist, it is possible that the population would pay more attention to the way resources are used.

The idea of substituting the cost to the environment against the cost of time also causes problems. A recent article for **Hamburger Abendblatt 2012**, for example, weighed up the environmental impact of flying versus driving, from Hamburg to the south of Spain. The article concluded that, while air travel was significantly more damaging to the environment, it is not possible to drive from Hamburg to the south of Spain in only two hours, which served to justify taking the flight over driving.

The introduction of a metric which provides an indication of an aircrafts' environmental performance could aid passengers in assessing flight options. This concept is explored in detail in sections 4 and 6 with the proposal of a metric system and the implementation of the system as part of a ticket booking scheme. This would assist the public in flight selection and provide awareness of environmental impact using an understandable rating system.

There currently does not exist, an industry standard fuel metric, which provides a simple and accurate reflection of aircraft efficiency. While the European standard transportation metric 'litres of fuel per passenger 100 km' is frequently used by the aviation industry, aircraft have such disparity in their operating efficiencies, that use of this metric is extremely misleading.

Lufthansa publish annual sustainability reports, detailing their fleet's 'specific fuel consumption', which is obtained by expressing absolute values in relation to transport performance, stating;

> *"The ratio 'litres per 100 passenger kilometres' (l/100 pax km) is calculated on the basis of actual load factors, distances actually flown [great circle distance] and the kerosene actually consumed", **Lufthansa 2011**.*

Airbus, for example, use the metric to compare the efficiencies of the A380, stating that it is 'more efficient than a small family car' **(Airbus 2011)**. While the A380 may potentially achieve an efficiency similar to a small family car, this figure is so highly dependent upon operational factors including crucially, seating arrangements, that its use across the board, is extremely misleading.

2.4 Carbon Trading

Several airlines, charities and independent companies offer the option of carbon offset schemes. These schemes estimate the emissions generated by a flight, and enable passengers to offset their carbon emissions by paying towards carbon offset schemes. These schemes generally have a ‘carbon calculator’, which estimates flight impact per passenger, enabling the passenger to pay directly for the emissions that they cause by taking that particular flight.

There is however a debate on carbon trading, in that the process by which a passenger is able to pay to offset the effect of their flights, may be further adding to public indifference on climate change. **Monbiot 2006** for example, claims that trading *carbon offsets* is an excuse to continue with business as usual, likening carbon trading to the selling of indulgences. **Gösling 2007** comments that voluntary compensation schemes have been criticised for creating and fostering the idea that there are simple, and financial, solutions to unsustainable lifestyles.

Credible compensation schemes will, theoretically, increase awareness among passengers, to create a more carbon conscious society by offering acceptable solutions to passengers, who may otherwise reject restrictions to air travel for economic, or similar, reasons (**Gösling 2007**).

Compensation schemes work by providing support to one of two categories. These may be biological ‘sinks’ where carbon is sequestered in biomass i.e. through afforestation or potentially through algae for biofuel growth. Alternatively the schemes are ‘emissions saving’, where energy-efficiency gains or replacement of fossil fuels by renewable energy sources reduces GHG emissions from a business-as-usual baseline **(Gösling 2007)**.

The *additionality* principle in carbon trading is one of the key issues of the carbon offsetting system **(Kollmus 2007)**. *Additionality* is the concept by which a scheme is able to verify the offsetting that it provides. A scheme is said to be *additional* if the project only occurs as a direct result of the finances made available from the offset scheme. *Additionality* is why many carbon offset projects take place in developing countries, given that this requirement is easier to demonstrate. The project must also ensure that an equal quantity of energy is being offset i.e. that electricity is no longer produced from non-renewable fossil fuels after construction of a wind farm.

An often ignored fact is that offset schemes too, are finite solutions. The area, for example, available for afforestation will be filled completely by aviation alone by 2050 if all aviation related climate impacts were to be compensated through afforestation **(Boon 2006)**.

Further, unless the trees planted through afforestation are not used for the production of biofuels, to substitute for fossil fuels, the area used for afforestation would have to be set aside infinitely to satisfy availability **(Read 2005)**, i.e. the replanted trees could never be cut down. Ironically, this might be even more problematic given that forests will increasingly be at risk from fire, and drought, and pestilence as a result of climate change **(Ceron 2007)**.

Under the *Contraction and Convergence* model, which is the widely supported model to harmonise global greenhouse gas emissions to a safe, sustainable levels **(Meyer 2004)**, show that aviation will soon fill its quota of complete allowable emissions. This indicated that even if all other sectors are zero-emitters, aviation will not be able to find enough compensation for its own growth.

Yet another difficulty arises due to the lack of certification standards common to all offset projects and vendors **(Gösling 2007)**. Several certification/verification schemes exist, including the Gold Standard (GS), Voluntary Gold Standard (VGS) and the Voluntary Carbon Standard (VCS), which go some way towards addressing this issue however the certification process generally causes the price per CO_2 tonne equivalent to increase, which further decreases the scheme's competitiveness. However with no certification standard, it is difficult for passengers to determine with confidence a scheme's viability.

2.5 The Limits to Growth

In 1972, a team lead by Dennis Meadows published "The Limits to Growth", (LtG) which detailed the method and results of modelling the consequence of exponential economic and population growth and finite resources. The LtG model, which was simulated using the dynamic non-linear feedback World3 modelling software, produced output scenarios for the future based upon world population, industrial output, pollution, food production and resource availability or depletion **(Meadows 1972)**.

The fundamental result of the LtG model was that continuous growth would eventually cause planetary limits to be exceeded, and cause the system to overshoot and collapse **(Turner 2008)**. Put simply, indefinite growth is impossible in a finite world **(Meadows 1972)**.

Thirty years following its publication, predictions from the LtG were compared with historical reality by **Turner 2008**. The report concludes that the predictions made were strikingly close to the reality, stating that;

> *"Unless the LtG is invalidated by other scientific research, the data comparison presented here lends support to the conclusion from the LtG that the global system is on an unsustainable trajectory unless there is substantial and rapid reduction in consumptive behaviour, in combination with technological progress."* ***Turner 2008***

The scenario titled 'standard run', most closely resonates with real, historical data, which results in global collapse before the middle of this century **(Turner 2008).**

The growth forecasts in aviation, discussed in section 2.2, are similar to those at the root of the cause of the LtG overshoot and collapse. If the LtG predictions are realised, and the world does experience overshoot and collapse, the first to suffer will be the non-essential, unsustainable, high cost, highly pollutant industries such as the current aviation model.

The LtG model however demonstrated that collapse was not inevitable, and that a sustainable society is both technically and economically possible. Such a society is likely to be much more desirable than a society that continually attempts to solve its problems of constant expansion **(Meadows 1992)**.

Hirsch 2005 discuss that, with adequate, timely mitigation, the economic costs to the world can be limited. If legislative action is taken two decades prior to the crash, the consequences could be limited. If action is only taken one decade prior, the legislation will help, but the system will still experience significant shortfalls in liquid fuels for roughly a decade following the peak. However, if legislation waits until following the crash to address the situation, the outcome will be severe.

Interventions which are not sanctioned in a timely fashion will result in the world supply/demand balance being achieved through massive shortages, which will create an intense period of significant economic hardship. Delaying action only serves to exacerbate the costs associated with world economic collapse. As the world locks itself into high-carbon trajectories while stabilization options progressively disappear **(World Bank 2011)**.

It is clear that decisive action must be taken now, and that all parties involved must realise the consequence of their actions and work together in a timely and appropriate manner to avoid economic collapse. New technologies will provide some relief, although these will inevitably fall short of sustainability requirements.

3 Aerodynamics

Much of the proposed ‘radical’ new aircraft configurations, including natural laminar flow or the blended wing body aircraft, focus predominantly on a reduction of zero lift drag C_{Do}. While much effort has been focused on studying such a task, it seems that less focus is being made on the evaluation and understanding of lift induced drag, C_{Di}.

The benefit of such understanding is significant and the effect of C_{Di} extends beyond the influence it exerts on aircraft performance in cruise. During take-off for example, induced drag can account for anything between 80-90% of aircraft drag. Given the influence of engine-out climb constraints on aircraft design, reduction in these areas can have a significant impact on cruise performance **Kroo 2005**.

A computational method for estimating C_{Di} developed in conjunction with **Niță 2012a** is analysed and modified to accurately represent the data extracted from two reference aircraft, the B737-800 and the MPC75[2]. These are then compared with the results of the A320 presented by **Niță 2012b**.

This method, in conjunction with an estimation method for C_{Do}, allows detailed analysis of a range of parameters and characteristics for each aircraft. Performed in this way, detailed examination may be performed on a range of aircraft parameters, and detailed study on parameter variation may be conducted.

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[2] MPC 75 was a project of the German company "Deutsche Airbus". The aircraft reached advanced stages of design however it was never produced, and the project was cancelled in 1993.

3.1 The Oswald Span Efficiency Factor

The Oswald (Span Efficiency) Factor, e, is a measure of the induced drag which arises from the non-elliptical lift distribution of a wing. This relationship may be presented in several ways, and is commonly given as per Eqn. 3.1.

$$C_{Di} = \frac{C_L{}^2}{\pi A e} \tag{3.1}$$

Oswald factor is generally estimated using statistical historic data, or using relationships such as those presented by **Raymer 1989** or by the **Finck 1978,** Datcom method. These methods are often static values which do not account for the dynamic dependency which exists between M and e, as shown in Eqn. 3.2. Without accounting for this relationship, computed values for $C_{Di,}$, and hence $C_{D,}$ are likely to contain significant errors.

$$e = f(M) \tag{3.2}$$

The Owsald factor is calculated analytically using the relationship as given in Eqn. 3.3 **(Niță 2012b)**. This equation estimates the theoretical e, given $e_{theo,}$ based on aircraft geometric properties A, φ_{25}, $\Delta\lambda$, given by Eqn. 3.4 and Eqn. 3.5 (**Hörner 1965**), and $f(\lambda)$ given by Eqn 3.6 (**DeYoung 1955**). e_{theo} is then multiplied by correction factors $k_{e,Stat}$ and $k_{e,M}$, to correct for flow compressibility effects and statistical hierarchical effects observed to exist as a result of aircraft configuration.

$$e_{ana} = e_{theo} k_{eM} k_{eStat} \tag{3.3}$$

$$e_{theo} = \frac{1}{1 + f(\lambda - \Delta\lambda) A} \tag{3.4}$$

$$f(\lambda) = 0.524\lambda^4 - 0.15\lambda^3 + 0.1659\lambda^2 - 0.0706\lambda + 0.119 \tag{3.5}$$

$$\Delta\lambda = -0.35659 + 0.45 e^{-0.0375\varphi_{25}} \tag{3.6}$$

The geometric parameters required for computation for each aircraft are given in Table 3.1, along with the values for e_{theo} which are calculated using Eqns. 3.3 – 3.6.

Table 3.1 Parametric values for A, φ_{25}, e_{theo} and λ

	λ	A	φ_{25}	e_{theo}
B737	0.219	9.4519	25.0235	0.98195921
MPC75	0.2609	9.6	23.5	0.98034658
A320	0.24	9.5	25	0.98106254

3.2 Correction Factors

The correction factors $k_{e,Stat}$ and $k_{e,M}$ are found by comparing analytical with empirical data for the three reference aircraft. This data is extracted from aircraft high speed drag polars, such as that presented in Appendix B. These drag polars graphically depict the relationship between C_L and C_D over a range of M during cruise flight. Data was extracted from these polars using a pixel counter tool built in *MATLAB*®, enabling data extraction to the accuracy of $C_L \pm 7.0$ E-04 and $C_D \pm 3.0$ E-05.

The linear approximation to C_D vs C_L^2, provides values for C_{D0} and G (given by Eqn. 3.7) for each value of M. The Oswald factor, e_{emp}, is then calculated over this range using Eqn. (3.8).

$$G = \frac{C_L^{\,2}}{C_{Di}} \tag{3.7}$$

$$e = \frac{1}{\pi A G} \tag{3.8}$$

The compressibility dependence factor, $k_{e,M,}$, calculated using Eqn. (3.9)**,** is dependent upon M, M_{comp} and arbitrary co-efficients a_e and b_e. This compressibility factor $k_{e,M,}$ provides increased flexibility over the Prandtl-Glauert compressibility correction factor, allowing closer correlation between e_{ana} and the values of e extracted from aircraft data, through minimisation of Eqn. 3.10.

$$k_{eM} = \begin{cases} a_e\left(\dfrac{M}{M_{comp}} - 1\right)^{b_e} + 1, & for\ M > M_{comp} \\ 1, & for\ M \le M_{comp} \end{cases} \tag{3.9}$$

$$\Delta e = (e \ - e_{ana})^2 \tag{3.10}$$

Values for the co-efficients a_e and b_e are given in Table 3.2, which are depicted graphically in Figure 3.1. The geometric mean of the plane drawn in Figure 3.1 is presented as the average values for commercial passenger jet aircraft.

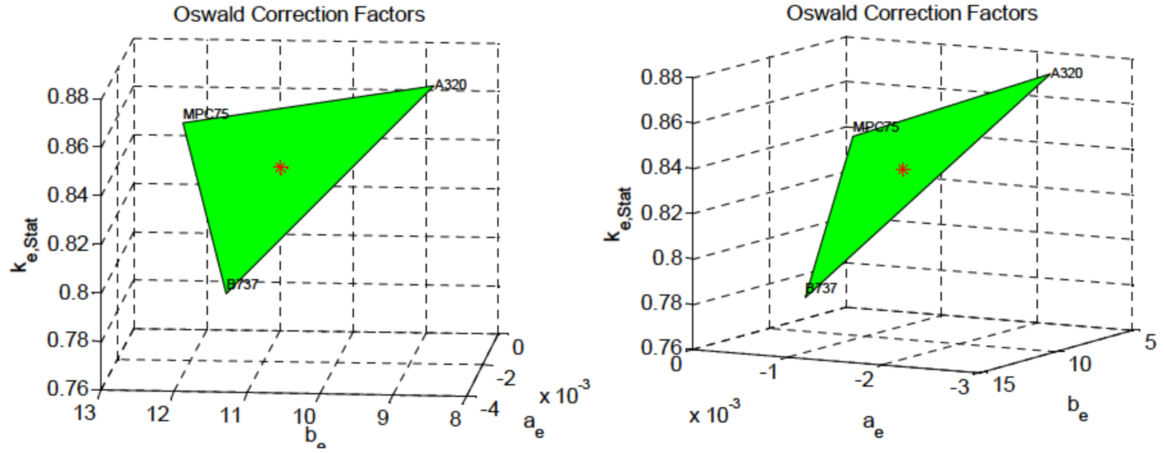

Figure 3.1 Graphical representation of a_e, b_e, and $k_{e,Stat}$ to locate geometric mean for the three points

Table 3.2 Parametric values for a_e, b_e, and $k_{e,Stat}$

	a_e	b_e	$k_{e,Stat}$
B737	-0.00063987	11.6625538	0.77854711
MPC75	-0.00122212	12.1985819	0.8526102
A320	-0.00270205	8.60171108	0.87859677
Geographic Mean	-0.00152135	10.8209489	0.83658469

The compressibility correction factor $k_{e,M}$ is calculated using Eqn. 3.9, and the values for the reference aircraft, presented in Table 3.2, and illustrated graphically in Figure 3.2. These are calculated for each of the three reference aircraft, for the mean values and for the Prandtl-Glauert method over a range of M typical of the high speed drag polars. It is observed that the compressibility factors of the three aircraft exhibit a close relationship over the range of M, a feature which the Prandtl-Glauert method does not accurately mimic.

The values presented for $k_{e,Stat}$ in Table 3.2 are applicable to each individual aircraft, and would produce reasonable accurate results were these to be used on similar category aircraft. **Niţă 2012b** however expands upon this, by presenting values for $k_{e,Stat}$ for other aircraft categories, as per Table 3.3. These have not been analysed in detail within the context of this thesis, and are hence presented for reference only. The rank applied to each aircraft category is concurrent with expectations for each category aircraft i.e. it is expected that fighter aircraft would have a lower C_{Di}, than a commercial airliner etc.

Table 3.3 Values for $k_{e,Stat}$ for a range of aircraft

Aircraft type	k_{eStat}	Rank
Jet Airliner	0.837	1
Business Jet	0.836	2
Propeller Aircraft	0.786	3
General Aviation Aircraft	0.779	4
Military Fast Jet	0.762	5

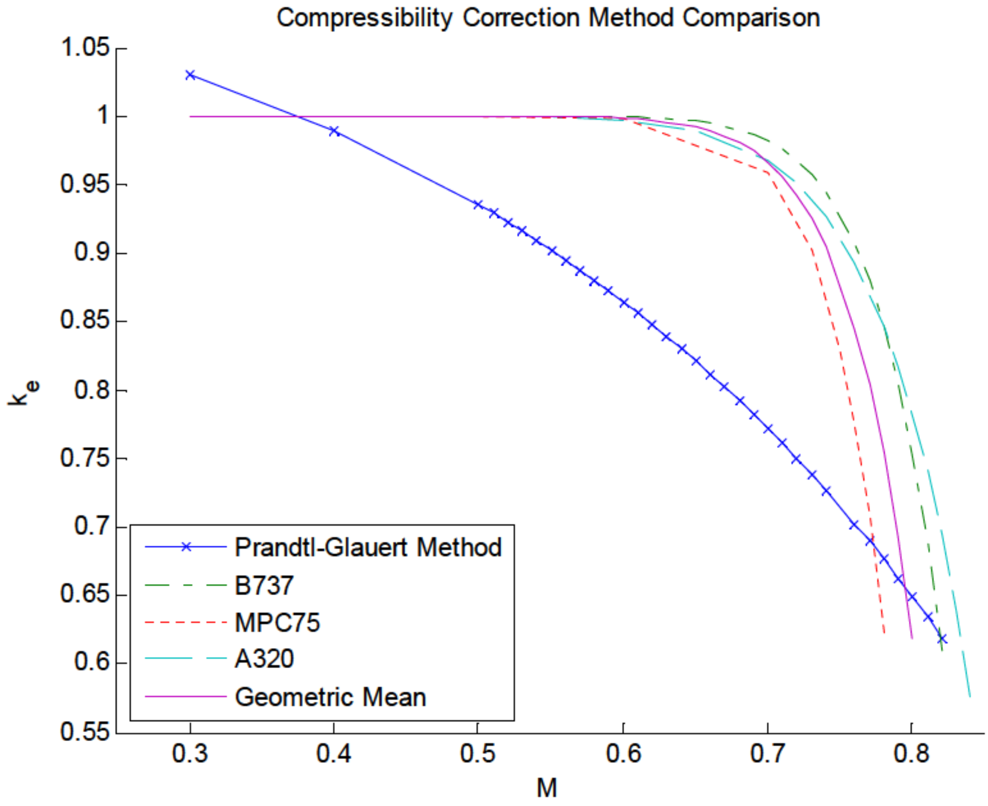

Figure 3.2 Comparison of compressibility factors $k_{e,M}$ observed from reference aircraft, Prandtl-Glauert correction and averaged method using the geometric mean of plane mapped using the reference aircraft data

3.3 Resulting Analysis

The applicability of the method extends beyond fuel mass estimation techniques, and along with several other parameter estimation methods, provides a powerful tool for aircraft analysis. To illustrate this, the results obtained using the method, e_{emp} and e_{ana} are plotted against M in Figure 3.3 for both the B737 and the MPC75. The results demonstrate close correlation between the empirical and analytical data, which serves to verify the accuracy of the method.

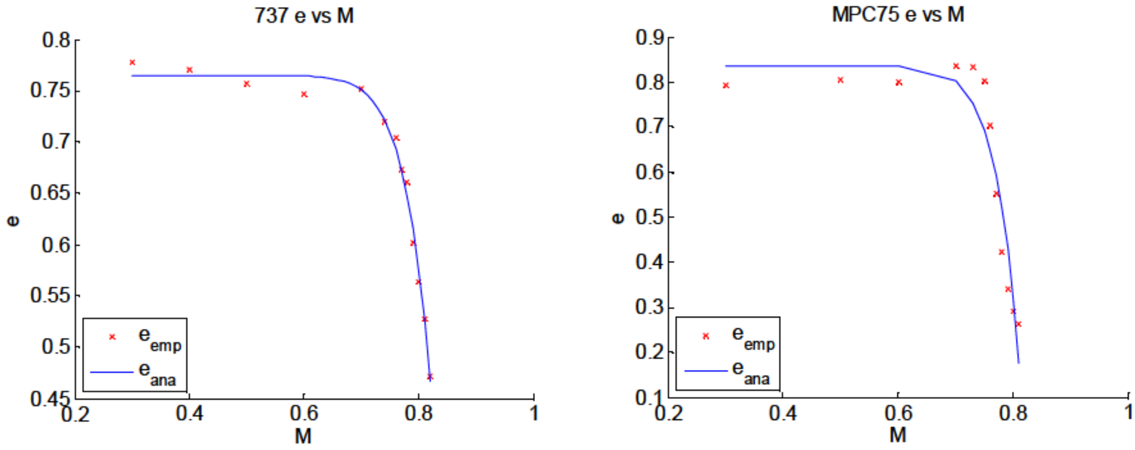

Figure 3.3 Measured e_{emp} and e_{ana} vs. M

Similarly, a range of parameters may be calculated to examine the relationship between M and C_{Di} on aircraft behaviour. This is illustrated in Figure 3.4, which depicts the relationship between the lift to drag ratio, E_{Max}, and M. The analytical model assumes constant C_{Do} and does not include any effects which may arise due to wave drag, which explains the deviation between empirical and analytical methods at lower M. E_{Max} is calculated using Eqn. 3.11.

$$E_{Max} = \frac{1}{2}\sqrt{\frac{\pi A e}{C_{D_o}}} \tag{3.11}$$

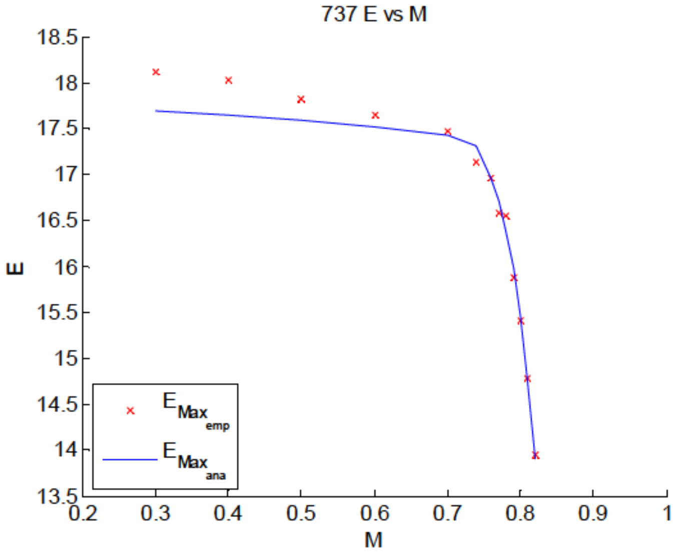

Figure 3.4 Empirical and analytical values for E_{Max} vs. M plotted for comparison

Finally, the drag polars, from which the original data was extracted, are reproduced analytically, as presented in Figure 3.5. These may be compared directly with the original drag polar, given in Appendix B.

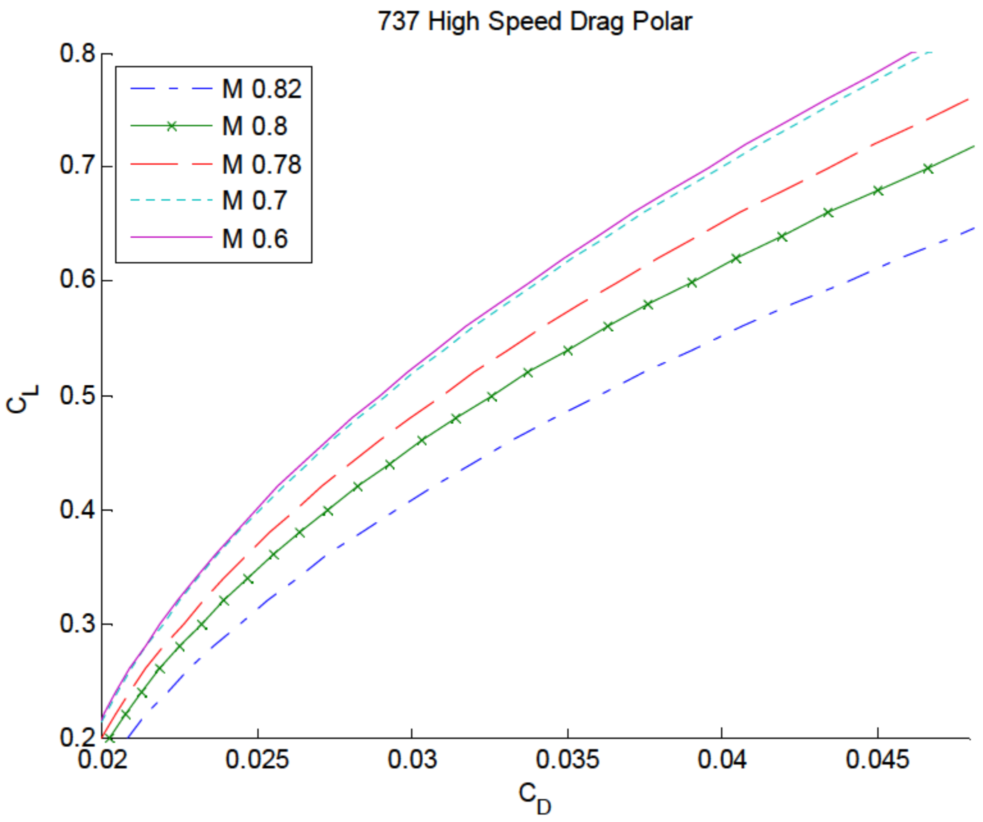

Figure 3.5 B737 high speed drag polar reproduced analytically, for comparison with real drag polar, given in Appendix (B)

The results of the analysis, notably the drag polar reproduction in Figure 3.5 demonstrate the accuracy and versatility of the method presented. The method may be applied to any aircraft, requiring only basic aircraft geometric parameters, and the correction factors given in Table 3.2 and Table 3.3 for computation. It was found during the analysis that the geometric mean of the points for the three reference aircraft provided a good approximation for these correction factors, and did not produce significant deviation from any of the reference aircraft individually.

Access to drag polars for a range of aircraft, including in different categories of aircraft, would enable further verification of these results enabling overall improvements in the accuracy of this method.

4 Flight Mechanics

4.1 Breguet Factor

The Breguet Range Equation, given by Eqn. 4.1 is a range estimation method, developed by French aviation engineer, Louis-Charles Breguet (1880-1955).

$$R = \frac{VE}{cg} \ln\left(\frac{m_1}{m_2}\right) \tag{4.1}$$

$$B = \frac{VE}{cg} \tag{4.2}$$

The Breguet factor given by Eqn. 4.2 may be calculated using several methods, two of which are presented here. The first uses a bottom up approach, by calculating aerodynamic and aircraft parameters empirically. Methods such as those presented in Section 3 along with Eqn. 4.3 provides computation of C_L, and C_D, hence these parameters, in conjunction with the fuel consumption estimation method developed by **Hermann 2010**, given in Eqn. 4.3, and method for flight speed estimation provide every parameters required to for B. The full derivation of the **Hermann 2010** method may be found in Appendix C for reference.

$$C_L = \frac{2W}{\rho V^2 S} \tag{4.3}$$

$$c = \frac{0.697\sqrt{\frac{t}{t_0}}(\phi - \vartheta - \frac{\chi}{\eta_{comp}})}{\sqrt{5 \times \eta_{diffuser} \times (1 + \eta_{BT} \times BPR)(G + 0.2 \times Ma^2 BPR \frac{\eta_{comp}}{\eta_{BT}}) - Ma \times (1 + BPR)}} \tag{4.4}$$

This method enables computation of B, and hence fuel consumption (as per Section 4.2), to be performed with relative ease, to a significant degree of accuracy. However much of the data required here is often difficult to find, accurately predict or compute. This can cause problems when using this method for analysis of commercial aircraft, and hence an alternative method is developed to be contrast with the method presented above.

The approximation that *B* remains constant during cruise flight allows manipulation of Eqns. 4.1 and 4.4, to arrive at a method to calculate *B,* given by Eqn. 4.5, using only mass and range data. This provides a straightforward method of calculating *B* given that the data required is readily available in airport planning and aircraft payload range diagrams.

$$B = \frac{R}{\ln\left(\frac{m_1}{m_2}\right)} \tag{4.5}$$

Airport planning documents, used for airport construction purposes, are generated by the aircraft manufacturers and are specific to individual aircraft or variants. These documents contain aircraft data including range and mass composition, presented in the form of a payload-range diagram. A typical payload-range diagram is presented in Figure 4.1. Many airport planning documents are available for free online, with both Boeing and Airbus, for example, publishing them via their respective websites **(Airbus 2011, Boeing 20121)**.

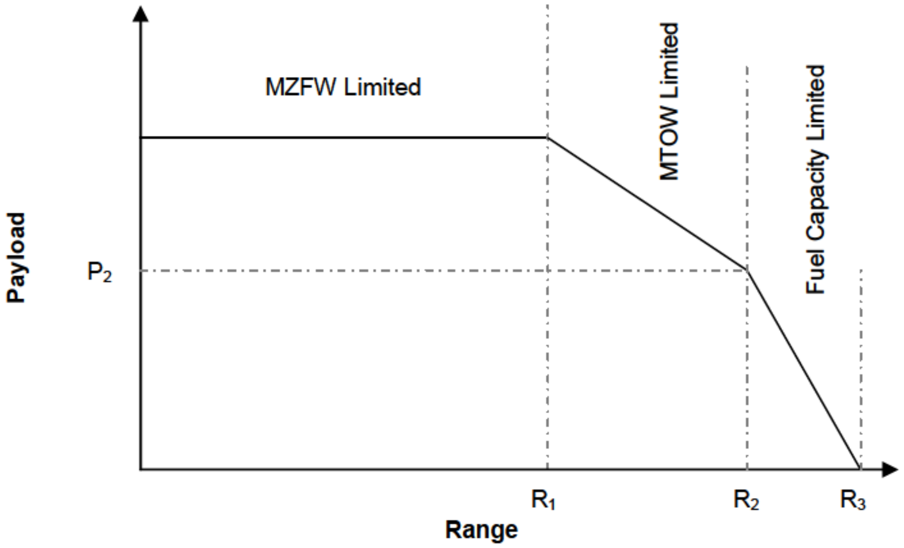

Figure 4.1 Schematic of typical payload range diagram

Referring to Figure 4.1, the points R_1, R_2 and R_3, are commonly referred to as 'range at maximum payload', 'maximum range', and 'ferry range' respectively. Flight section 1 is between 0 and R_1 flight section 2 is between R_1 and R_2, and flight section 3 is between R_2 and R_3. The flight sections are limited by payload (MZFW), MTOW and by maximum fuel capacity respectively. Flight section 2 require a trade-off between fuel and available payload, while flight section 3 is unique in that range is dependent on payload carried, and not on fuel available, since fuel is already at maximum.

Standard payload-range diagrams consist of three flight sections, defined by aircraft range. Each flight phase is limited by an inherent aircraft parameter/capacity, which is illustrated in Figure 4.1 and in Table 4.1. The parameters required to calculate *B* for each flight phase are also identified in Table 4.1.

Table 4.1 Flight Phase limiting parameters, including details on mass and range composition for use in Breguet factor estimation method discussed in section 4.1.

Flight Range	Limiting Parameter	m_1	m_2	R
1	MZFW	m_{MTO}	m_{MZF}	$R_1 + R_{RES} + V_{LOI}\, t_{LOI}$
2	MTOW	m_{MTO}	$m_{MTO} - m_{F,MAX}$	$R_2 + R_{RES} + V_{LOI}\, t_{LOI}$
3	Fuel Capacity	$m_{OE} + m_{F,MAX}$	m_{OE}	$R_3 + R_{RES} + V_{LOI}\, t_{LOI}$

This method provides three values for Breguet factor, at the extreme of each flight section. These however assume the aircraft is in cruise from point to point, and does not account for losses accrued during the flight stages of the LTO cycle. Fuel mass fractions, defined as the ratio of fuel mass between flight stages, in per Eqn. 4.7, are factors to account for the various losses or changes during each flight phase.

$$M_{ff} = \frac{m_2}{m_1} \tag{4.7}$$

The fuel mass fractions for the full mission are given by Eqn. 4.8. This defines the fuel fraction for each flight stage, working from left to right from shut-off through to take-off flight stage. Eqn. 4.8 is redefined using Eqn. 4.9. Figure 4.2 is used to illustrate the various flight stages as they occur during flight.

$$M_{ff} = \frac{m_{SO}}{m_L} \times \frac{m_L}{m_{LOI}} \times \frac{m_{LOI}}{m_{DES}} \times \frac{m_{DES}}{m_{RES}} \times \frac{m_{RES}}{m_{CLB}} \times \frac{m_{CLB}}{m_{DES}} \times \frac{m_{DES}}{m_{CR}} \times \frac{m_{CR}}{m_{CLB}} \times \frac{m_{CLB}}{m_{TO}} = \frac{m_{SO}}{m_{TO}} = \frac{m_2}{m_1} \tag{4.8}$$

$$M_{ff} = M_{ff,L} \times M_{ff,LOI} \times M_{ff,DES} \times M_{ff,RES} \times M_{ff,CLB} \times M_{ff,DES} \times M_{ff,CR} \times M_{ff,CLB} \times M_{ff,TO} \tag{4.9}$$

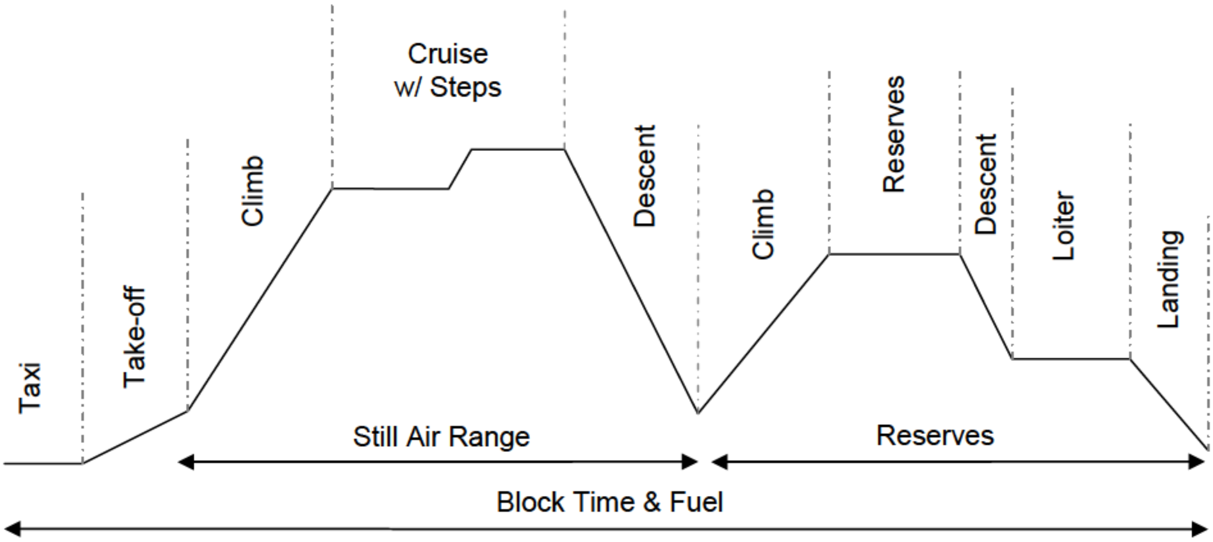

Figure 4.2 Mission fuel and reserve schematic, including reserve flight phases

Defining the separate mission stages as per Eqns. 4.10 and 4.11, we can shorten Eqn. 4.9, to arrive at 4.12.

$$M_{ff,LTO} = M_{ff,TO} \times M_{ff,CLB} \times M_{ff,DES} \times M_{ff,L} \times M_{ff,CLB} \times M_{ff,DES} \tag{4.10}$$

$$M_{ff,CR-RES-LOI} = M_{ff,CR} \times M_{ff,RES} \times M_{ff,LOI} \tag{4.11}$$

$$M_{ff} = M_{ff,LTO} \times M_{ff,CR-RES-LOI} \tag{4.12}$$

The fuel mass fractions for each stage of the LTO cycle were calculated using an aircraft design optimisation tool *OPERA*. While it is recognised 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. The fuel fraction for the LTO cycle is hence given as per Eqn. 4.13.

$$M_{ff,LTO} = 0.95929 \tag{4.13}$$

Eqns. 4.14 - 4.16 are therefore used to calculate the Breguet factor at the Max payload range, max range and ferry range or B_1, B_2 and B_3 respectively.

$$B_1 = \frac{R_1 + R_{RES} + V_{LOI} \times t_{LOI}}{\ln\left(\dfrac{M_{ff,LTO} \times m_{MTO}}{m_{MTO} - m_{MZF}}\right)} \tag{4.14}$$

$$B_2 = \frac{R_2 + R_{RES} + V_{LOI} \times t_{LOI}}{\ln\left(\dfrac{M_{ff,LTO} \times m_{MTO}}{m_{MTO} - m_{F,Max}}\right)} \tag{4.15}$$

$$B_3 = \frac{R_3 + R_{RES} + V_{LOI} \times t_{LOI}}{\ln\left(\dfrac{M_{ff,LTO} \times (m_{MTO} + m_{F,Max})}{m_{OE}}\right)} \tag{4.16}$$

B_1 is taken to represent the Breguet factor for the entire first flight range, and linear interpolation, calculated using Eqn. 4.17, which calculates B, for values between B_1 and B_2 and between B_2 and B_3.

$$B(r) = B_i + (r - r_i)\left(\frac{B_{i+1} - B_i}{r_{i+1} - r_i}\right) \tag{4.17}$$

$$i = 1, 2$$

4.2 Fuel Mass Calculation

Employing the method to calculate *B(r)*, as per Section 4.1, fuel mass may be then calculated by using Eqns. 4.18 - 4.20, which determine the fuel fraction for each stage of the flight regime.

$$M_{ff,CR} = \frac{m_{DES}}{m_{CR}} = e^{-\frac{R_{CR}}{B}} \tag{4.18}$$

$$M_{ff,RES} = \frac{m_{DES}}{m_{RES}} = e^{-\frac{R_{RES}}{B}} \tag{4.19}$$

$$M_{ff,LOI} = \frac{m_L}{m_{LOI}} = e^{-\frac{V_{LOI} \times t_{LOI}}{B}} \tag{4.20}$$

The fuel fractions for the standard flight, i.e. a flight which does not make use of the reserve fuel is defined as per Eqn. 4.21. The remaining, unused, fuel left on-board is then defined as per Eqn. 4.22.

$$M_{ff,STD} = M_{ff,L} \times M_{ff,DES} \times M_{ff,CR} \times M_{ff,CLB} \times M_{ff,TO} \tag{4.21}$$

$$M_{ff,REM} = M_{ff,LOI} \times M_{ff,DES} \times M_{ff,RES} \times M_{ff,CLB} \tag{4.22}$$

Fuel mass is calculated using Eqn. 4.23 for any range between r_1 and r_3.

$$m_{F,STD} = m_{TO}\left(1 - M_{ff,STD}\right) \tag{4.23}$$

Between point 1 and point 2: $m_{TO} = m_{MTO}$
Between point 2 and point 3: $m_{TO} = m_{OE} + m_{MF} + m_{PL}(R)$

For a flight range up to section R_1, the take-off mass m_{TO} is initially unknown. Using Eqn. 4.24, we arrive at Eqn. 4.25, which calculates the fuel remaining i.e. the unused reserve fuel for the flight.

$$m_F = m_1 - m_2 \tag{4.24}$$

$$m_{F,REM} = m_{MZF}\left(\frac{1}{M_{ff,REM}} - 1\right) \tag{4.25}$$

Total fuel mass is then calculated by Eqn 4.26, and standard fuel mass is using Eqn. 4.27.

$$m_{F,TOTAL} = m_{MZF}\left(\frac{1}{M_{ff,TOTAL}} - 1\right) \tag{4.26}$$

$$m_{F,STD} = m_{F,TOTAL} - m_{F,REM} \tag{4.27}$$

Eqn. 4.27 may then be manipulated into a full mission fuel metric, as given in Eqn. 4.28. This may also be expanded into the common l/ (100 km.Passenger) metric using cargo and passenger load factors, similar to that which is performed in the automotive industry, as per the analysis performed for Figures 4.6 and 4.7 in Section 4.3.

$$\frac{m_{F,STD}}{R} = \frac{m_{F,TOTAL} - m_{F,REM}}{R} \tag{4.28}$$

4.3 Fuel Consumption Analysis

To validate the results of the fuel mass estimation methods, fuel consumption calculated for the B737 reference flight is compared with the payload range method presented in Section 4.1, and with data on 737 fuel consumption taken from **ICAO 2010**, which estimates fuel consumption using the *CORINAIR* fuel database. The reference flight conditions are defined as per the payload range diagram, for a flight range of 3000km. For the B737 this equates to a flight between 31 kft and 35 kft (9.5 km and 10.7 km), at M of 0.76 (LRC) for standard atmospheric day + 10°C. For this flight, take-off weight is estimated using an approximate TOW resulting from the payload range analysis method, at approximately maximum payload.

The results of this comparison are presented in Figure 4.3, which demonstrates the close correlation between all four estimation methods. The ICAO estimates include default airline load factors i.e. reduced TOW, which have not been accounted for in the payload range or Breguet analysis. This serves to explain the differences which exist between the estimation methods. The Breguet method including fuel reserves is presented to illustrate the fuel reserves which would be required for the flight specified as opposed to the fuel actually consumed.

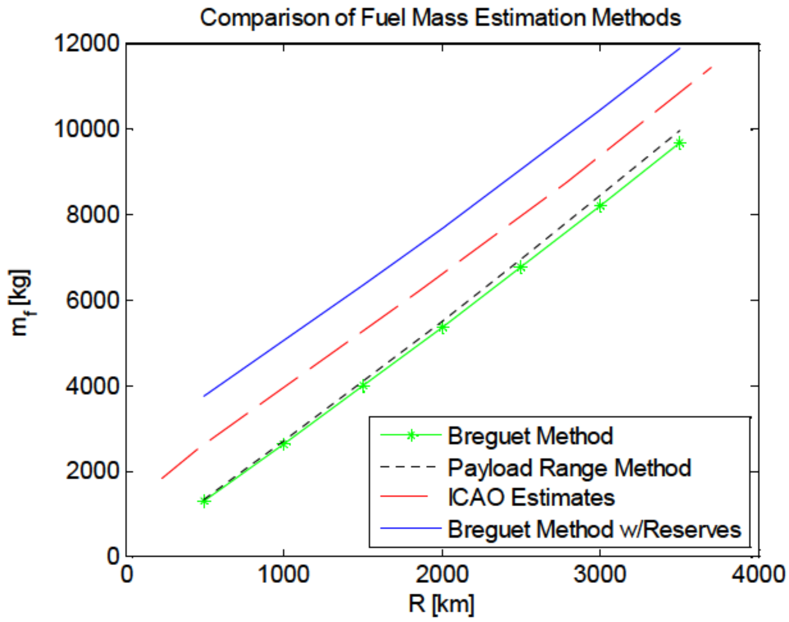

Figure 4.3 Comparison of fuel mass, m_F estimation methods for 3000km - B737

Following verification of the method(s), an analysis tool was developed using *MATLAB*®, which allowed analysis to be performed on a large number of aircraft simultaneously, requiring only weight and range data to be input for each aircraft. The resulting fuel masses required for the complete aircraft range are then analysed to examine changes in both consumption and efficiency over each flight section. The results for the B737-800 are illustrated graphically in Figure 4.2 - Figure 4.5.

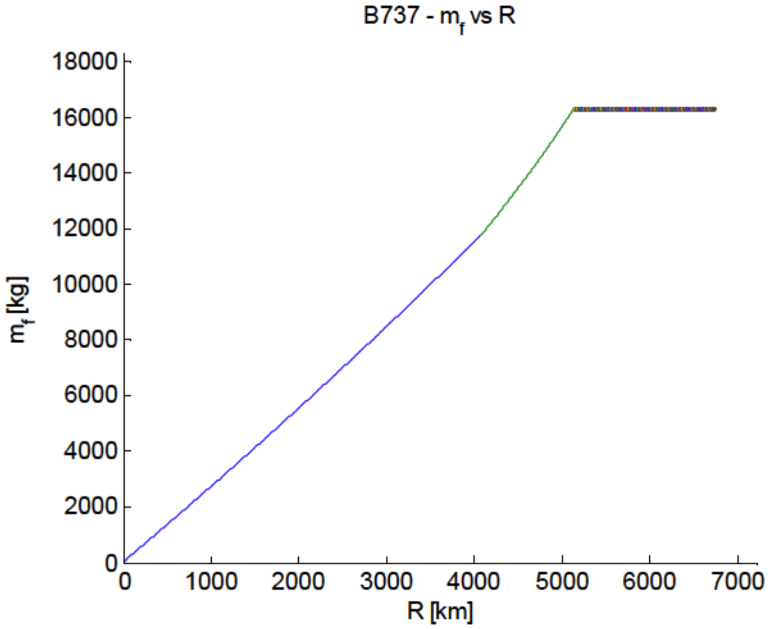

Figure 4.4 Fuel mass, $m_{F,}$ vs. range, *R* - B737-800

Figure 4.2, illustrates the exponential relationship between fuel mass and range over the first and second range conditions, demonstrating a quasi-linear relationship over these ranges, which becomes more apparent on aircraft with longer ranges.

Fuel mass required is constant, at maximum fuel capacity, for the third range condition. Flights in this region require a reduction in payload to allow additional range, which is approximated using the linear relationship given in the payload range diagrams.

Figure 4.2 and Figure 4.3 demonstrate the efficiency behaviour of the aircraft. For both flight ranges one and two, the efficiency of the aircraft worsens with range. It is interesting to note that flight range two is considerably more efficient than flight range one, since B_2 is greater than B_1. This efficiency improvement is however at the expense of additional payload, a phenomenon which is not easily observed when using the Breguet range equation alone. It is hence that this method of analysis presentation provides interesting insight into the real implications of aircraft range.

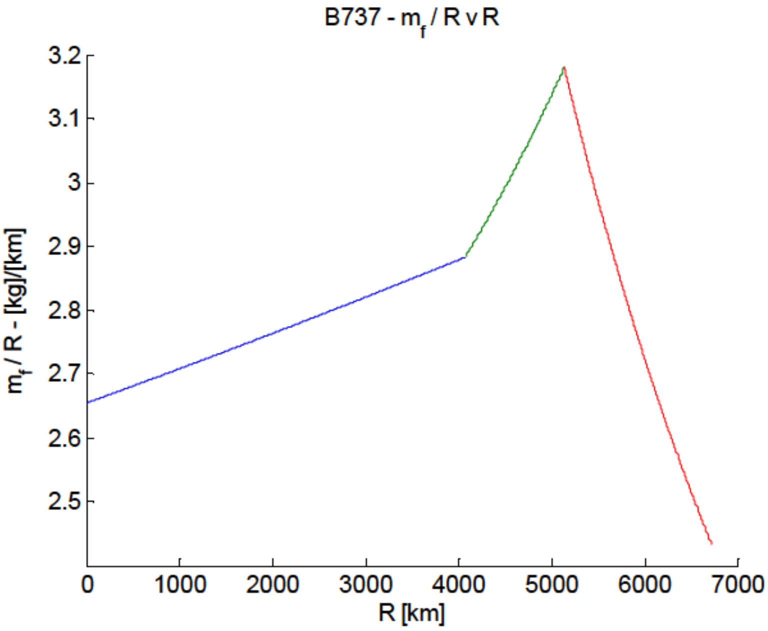

Figure 4.5 Fuel mass, m_F /Range, R vs. Range, R - B737-800

Figure 4.6 and Figure 4.7 illustrate demonstrate the discussed l/ (100 km.Passenger) for both the B737 and the B777. These have been calculated using the standard number of seats as specified by the manufacturer, using the **EASA 2008** recommended weight of 94 km per passenger, incorporating the load and cargo factors specified by **AAI 2012** to arrive at an approximate average value with which to compare aircraft to the much used l/ (100 km.Passenger) metric used for road transport.

Figure 4.7 is presented to further illustrate the changes which occur over longer ranges, where the exponential relationship between range and fuel consumption is more apparent.

It is observed that the aircraft efficiencies are almost linear for the first and second flight section and that in all instances, efficiency decreases with range. The efficiency change in the third flight section diverges towards infinity at R_3, hence both figures only depict the change in efficiency up to the point mid-way between R_2 and R_3, to illustrate the concept.

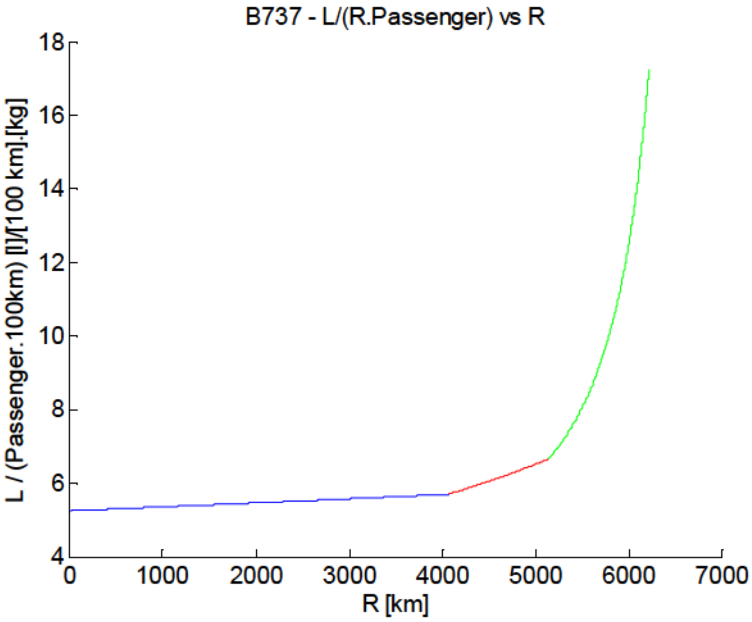

Figure 4.6 Litres per passenger 100 km vs Range *R* - B737-800

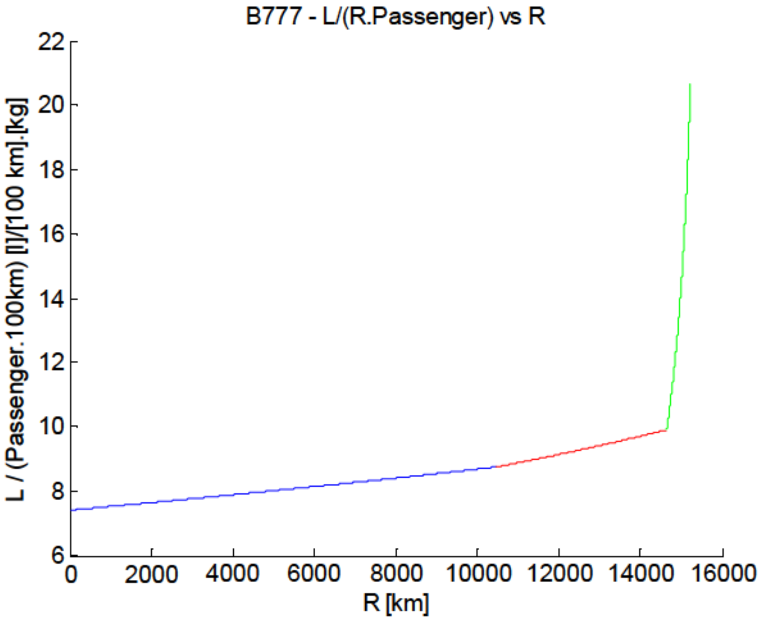

Figure 4.7 Litres per passenger 100 km vs. Range *R* - B777-ER

4.4 Fuel Consumption Summary

The payload range method presented is differentiated from other fuel consumption estimation methods in that it uses a top down approach using real flight data, as opposed to approaches which calculate fuel consumption based upon aircraft build up and composition, such as the method of calculating *B* using aerodynamic data. The comparative analysis performed, indicate that the method produces accurate results, despite requiring significantly less input data and computation than alternate methods.

The method is, however, limited to aircraft with specific payload range diagrams, Boeing for example produce only one payload range diagram for both the B737-800 and the B737-800 winglets. While both aircraft are fundamentally similar, they possess small, but significantly different performance characteristics. In such circumstances however, correction factors could be employed to reflect these performance differences. This may also be said for performance upgrades or deteriorations over time, which would similarly, not be reflected in the method.

Furthermore, the method requires little assumptions be made regarding actual aircraft operation, using only data which is provided directly from the manufacturer in the computation process. Despite this however, these assumptions may possess the potential to create non-negligible errors in absolute fuel mass calculations. If the user of the method is aware of these issues, and the methods limitations, then it may be used in relative fuel consumption estimation purposes, such as that presented in Section 6.

5 Operation & Aircraft Design

5.1 Introduction

When assessing operating costs, an airline must consider both the time and monetary implications of each flight. Factors including, aircraft lease agreements, staff salaries and desire to maximise productivity, for example, all carry financial implications, which must be accounted for during flight planning. If the price of oil however, continues to rise as is predicted, or if taxes were imposed upon aviation fuel, minimising fuel consumption would become the primary factor which influences airline operations.

To combat fuel price rises, several airlines have taken measures such as reducing flight speed in an effort to reduce fuel consumption. Northwest Airlines have, for example, adopted lower flight speeds which they project will, on one long haul (Minneapolis to Paris) route, save them approximately 162 gallons (481.5 kg) of fuel, while only increasing total trip time by around 1.5% **(New York Times 2008)**.

The effects of similar parameter variation is analysed in detail, to investigate the fuel saving potential through operation and flight regime optimisation. The analysis is achieved through application of the method to calculate e, as discussed in Section 3.

The analysis is performed using both the B737 and A320 reference aircraft, using the aircraft specific values for the co-efficients a_e and b_e, to ensure greatest accuracy in the method. The Breguet factor, is then calculated using the aerodynamic equations and the method of calculating c, presented in **Hermann 2010**, as per Section 4.

The reference flight is taken as a flight with a range of 3000km, which for the B737 this is a flight between 31 kft and 35 kft (9.5 km and 10.7 km), at a cruise Mach of 0.76 (LRC) for standard day + 10°C.

5.2 The Effect of Independent Variation of Cruise Speed and Altitude on Fuel Consumption

Fuel consumption is affected by flight altitude due to the effects of both temperature and density changes on E, M, V and c. The relationship between m_F and h is depicted graphically in Figure 5.1(a), from this, it is clear that the optimum flight altitude lies at approximately 9700m. This represents the optimum altitude at an instantaneous point in time for the cruise flight. Over the course of the flight this optimum would increase as fuel is burned i.e. for the cruise climb condition, which in reality would be approximated using a stepped approximation to cruise climb, dictated by ATC.

These findings are concurrent with the optimum *h* suggested by the manufacturer in the payload range diagram, and it is clear that deviation from this optimum would result in a non-insignificant reduction in fuel burn.

Similar analysis is repeated to study the possibilities for fuel burn reduction through a decrease in cruise speed. The analysis performed returns a similar outcome, depicted in Figure 5.1(b), arriving at an optimum cruise speed of around 220m/s, which at 9700m translates to a cruise *M* of 0.76 (LRC), as given in the payload-range diagram. This speed would allow significant reduction in fuel consumption over higher flight speeds typical of standard aircraft cruise speed, which for the 737-800 is approximately *M* of 0.79.

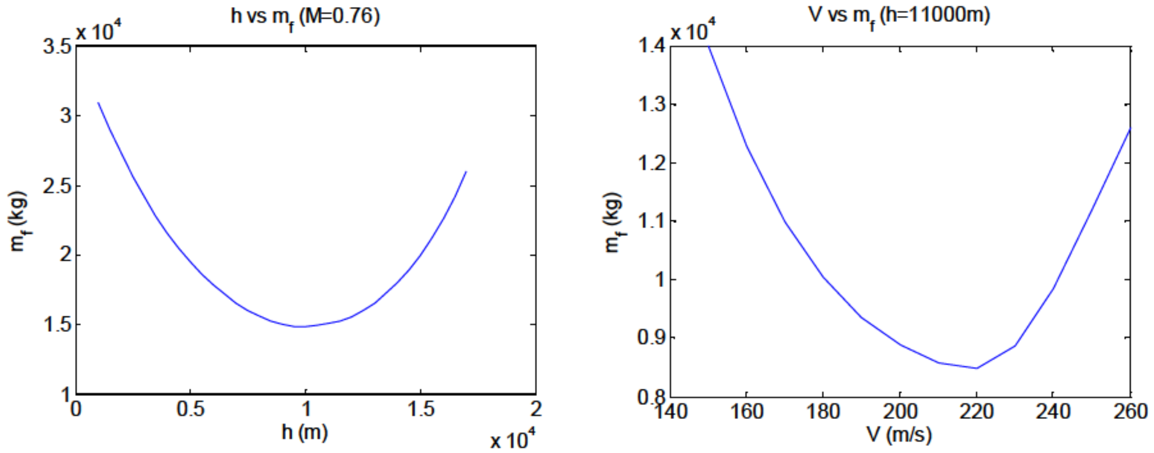

Figure 5.1 (a) (left) Altitude, *h*, vs. fuel mass required, m_F, (b) (right) True Airspeed, *V*, vs. fuel mass required, m_F

5.3 The Effect of a Parallel Variation of Mach and Altitude on Fuel Consumption

The analysis performed in Section 5.2 did not yield a significant fuel reduction through variation of either cruise speed or altitude independently over the reference case. The effect of a parallel variation of both M and h is performed on the aircraft.

The analysis is performed using an iterative process, which is required due to the inherent dependency which exists between the flight condition parameters. Figure 5.2 illustrates this process, which is repeated for each value of M between 0.3 and 0.82 in 0.01 step intervals, for an altitude range of 1000m to 11000m in 500m intervals. Eqns. 3.3, to find e, and 4.4 to find B are required to calculate each block in the diagram. Speed of sound a, and flight speed, V are calculated using Eqns. 5.1, and Eqns. 5.2, respectively, using standard atmospheric data for ρ and T, and standard value for the ideal gas constant R.

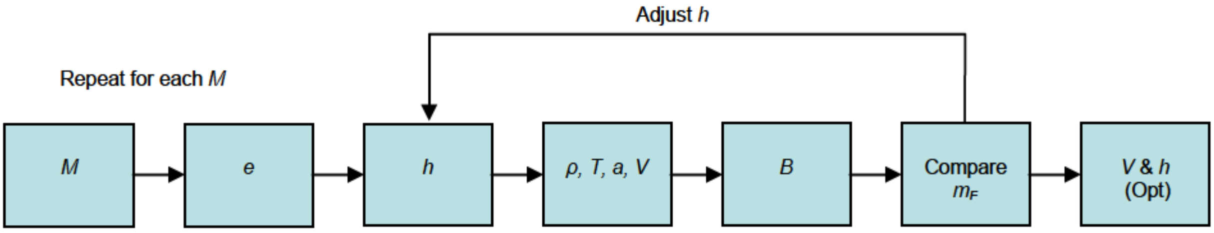

Figure 5.2 Simplified process schematic for evaluating optimum V and h for each M

$$a = \sqrt{\gamma RT} \tag{5.1}$$

$$V = aM \tag{5.2}$$

It is observed that h_{OPT} decreases as M decreases until a point at which the increasing atmospheric density causes an increase in C_D, and reduction of E, which in turn causes an increase in m_F.

The resulting parallel variation in both cruise Mach and altitude is plotted in Figure 5.3 for M 0.76 (LRC) and M 0.7. Figure 5.3 clearly demonstrates that the optimum h decreases as M decreasing.

The optimum flight speed and altitude for the 737-800 is found to be M of 0.7, at an altitude of approximately 8300m. Flight at this regime yields a 3.75% saving in fuel, which equates to 323.67kg fuel saved over the 3000km range when compared with the reference case. This corresponding decrease in M and h would only result a flight time increase of just over 17 minutes, assuming only cruise flight.

Interestingly, the optimum flight attitude for the A320 occurs at M of 0.66, which is significantly lower than the quoted M for long range cruise of 0.76, and significantly lower than that of the B737-800.

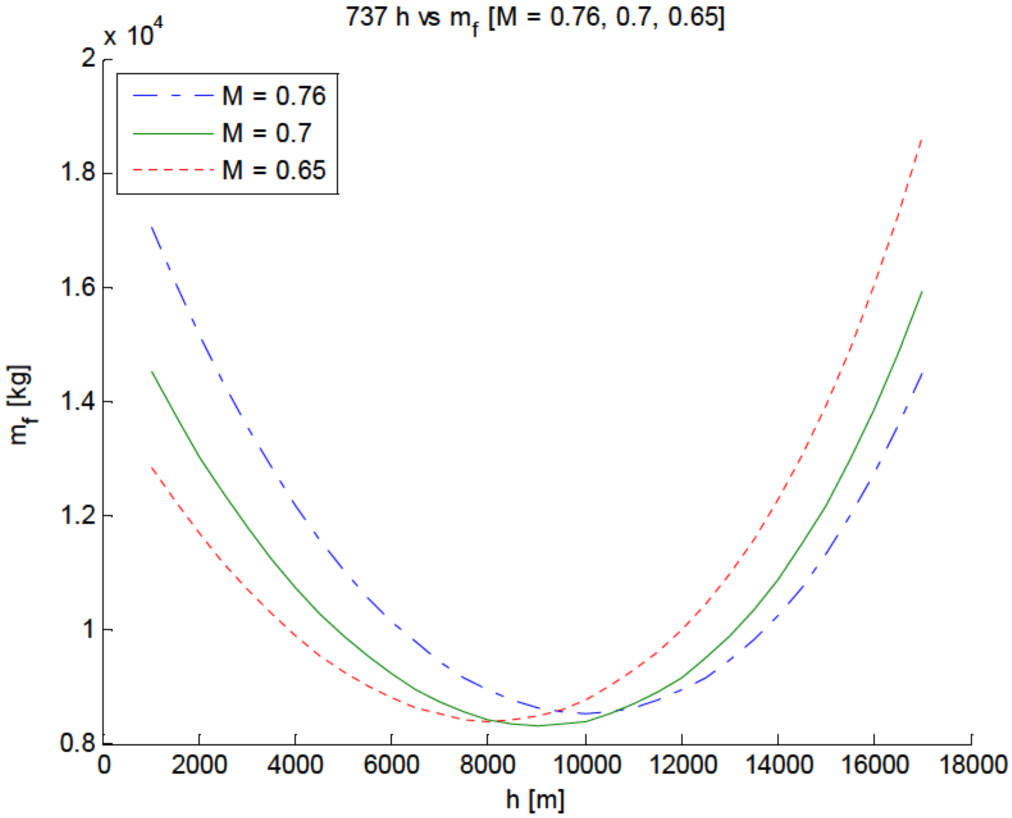

Figure 5.3 Altitude, *h*, vs. fuel mass required m_F for 3000km trip. Illustrates the decreasing optimum *h* with decreasing *M*. *M* of 0.76 (LRC), *M* of 0.7 (optimum) and *M* of 0.65 plotted here to illustrate example - B737

The saving potential for one flight does not seem significant, but such optimisation would allow significant savings were they to be adopted across an entire fleet. The trade-off which would have to be performed between the additional flight time and the fuel saved would however need to be addressed, and it may only become the case that this be viable in the event of a fuel price shock.

5.4 Emission at Altitude

The relationship between radiative forcing due to emission release and flight altitude as discussed by, **Kohler 2008** and **Radel 2008** is analysed to assess the full environmental implication of flight regime variation. **Schwartz 2009** method of calculating the total global temperature change, $\Delta T_{s,100}$, as a result of one flight**,** given by Eqn. (5.3), is hence used to assess the impact relative to the reference flight case.

$$\Delta T_{s,100} = \sum_{i=1}^{Ni} SGTP_{i100} E_i s_i + \sum_{j=1}^{Nj} SGTP_{j100} L s_j \tag{5.3}$$

$$i = CO_2, H_2O, CH_4, O_3\ Short, O_3\ Long, soot, SO_4$$

$$j = contrails, cirrus$$

This method assesses the impact of CO_2, H_2O, O_3 *Short*, O_3 *Long*, CH_4, *soot*, SO_4 and Aircraft Induced Clouds (*AIC)*, by taking the sustained global temperature change potentials $SGTP_{i,100}$ of each species, as a fraction of the species emission index E_i, and the aforementioned radiative forcing factor $s_{i,j}$ which occurs due to flight altitude implications. The $SGTP_{i,100}$ of each species are presented in Table 5.1.

The emission index, E_i, defined by Eqn. 5.4, is the mass ratio of species emitted, EI_i, to fuel burned. Values for EI_i are also given in Table 5.1. The emission of species O_3 *Short*, O_3 *Long,* CH_4, are dependent on the release of NO_x which is dictated by engine parameters, specific to individual aircraft. An average value for EI_{NOx} release for the 737-800, taken for from the IPCC Guidelines on National Greenhouse Gas Inventories, was utilised in this analysis, however **Schwartz 2011**, presents a method to approximate, given by Eqn. 5.5, which is upon engine operating conditions including pressure, P_{T3}, measured in Pascal's, temperature, T_{T3}, in Kelvin, and specific humidity, H_0, in grams of water per kilogram of dry air.

$$E_i = EI_i \times m_F \tag{5.4}$$

$$EI_{NO_x} = 0.0986 \left(\frac{P_{T3}}{101325} \right)^{0.4} \exp\left(\frac{T_{T3}}{194.4} - \frac{H_0}{53.2} \right) \tag{5.5}$$

The change in radiative forcing factor $s_{i,j}$ due to altitude for O_3 *Short*, O_3 *Long,* CH_4, are given in Figure 5.4. The forcing of CO_2, H_2O, *soot* and SO_4 does not change with altitude, and are hence given a constant factor of unity.

Table 5.1 Emission Index and $SGTP_{i,100}$ radiative forcing for each species

i	$SGTP_{i,100}$	E_i
CO_2 [K/kg CO_2]	3.58E-14	3160 [g/kg fuel]
H_2O [K/kg H_2O]	4.85E-15	1230 [g/kg fuel]
Soot [K/kg sulphate]	2.01E-10	0.04 [g/kg fuel]
SO_4 [K/kg sulphate]	-6.19E-11	0.2 [g/kg fuel]
O_3 (Short) [K/kg NO_x]	7.97E-12	7.7 [g/kg fuel]
CH_4 [K/kg NO_x]	-3.90E-12	7.7 [g/kg fuel]
O_3 (Long) [K/kg NO_x]	-9.14E-13	7.7 [g/kg fuel]
Contrails	2.54E-13	n/a
Cirrus	7.63E-13	n/a

This method does not provide a definitive approach to the effect or absolute values of emissions, but is useful to estimate relative emission, by accounting for the effects of flight altitude for a range of pollutant species, and not just CO_2. This allows computation of the method with a reasonable degree of accuracy. Only the cruise section of the flight has been considered during this analysis, as the remaining cycles would be comparatively similar for each given flight i.e. the variation in cruise conditions does not affect the LTO cycle.

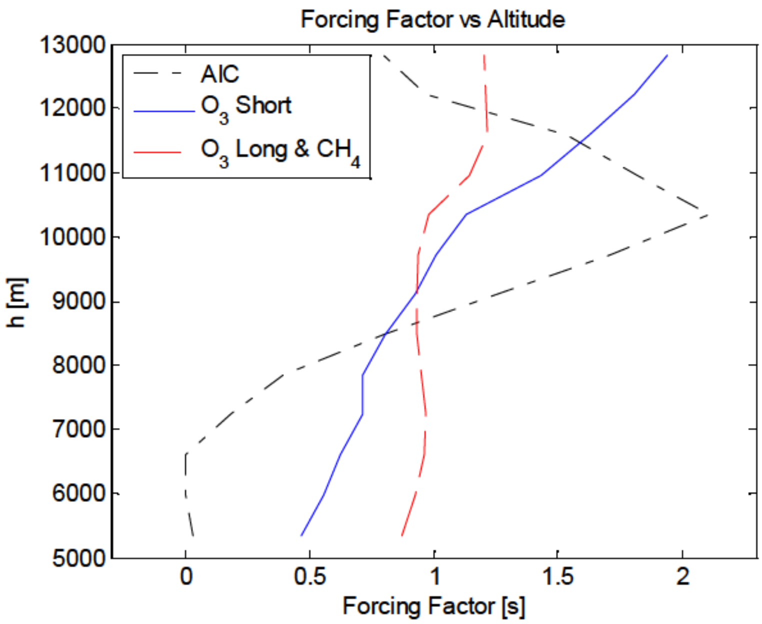

Figure 5.4 Relationship between emission forcing factor, *s*, and altitude, *h* **Schwartz 2009**

The results of the analysis, presented in Table 5.2, further strengthen the case to reduce aircraft flight speed and operating altitude. This reduction is most prevalent in the case of Aircraft Induced Cloud (AIC) formation, which is highly dependent on altitude, demonstrated in Figure 5.4.

This analysis has been performed using optimised conditions for both h and M. It is visible however from Figure 5.4 that a further reduction in flight altitude would result in further reduction in radiative forcing due to emission release despite the increase in m_F, which would occur as a result of a deviation from the optimum point. At this point, the trade-off between increased fuel consumption for a decrease of environmental impact would have to be made by the operator.

Table 5.2 Change in SGTP due to emissions as a result of flight parameter variation on 3000km flight - B737

	Normal Flight	Flight at Reduced Mach & Altitude
m_F	8625.5	8301.8
h (m)	11000	8300
h (ft)	36089.24	27230.97
Forcing Factor (AIC)	1.447396014	0.785862462
Forcing Factor (O_3S)	1.548097175	0.79018154
Forcing Factor (O_3L & CH_4)	1.155631023	0.91045275
ΔT Gas	1.51E-05	1.45E-05
ΔT AIC	3.15E-06	1.71E-06
ΔT Total	1.83E-05	1.62E-05
% Decrease Gas	n/a	3.75%
% Decrease AIC	n/a	45.71%
% Decrease Total	n/a	10.99%

5.5 Implications of a Reduction of Altitude and Flight Speed

A variation in flight regime for lower cruise speed and lower altitude does hold implications for aircraft operators. Aircraft at this altitude would become prone to increased levels of turbulence typical of flight at such altitudes, which could increase pilot workload, through IFR only flight, and could increase passenger discomfort.

Accustomisation to increased traffic at lower flight levels may be required by ATC to accommodate flight at lower cruise altitudes, while maintaining sufficient separation between aircraft. In reality, it may not be feasible that aircraft could operate exactly at individual optimum conditions, as this would cause unrealistic constraints on ATC.

Other implications could include decreased available recovery time in the event of a stall or dive, however the risk presented by these could be minimised through measures such as increased or specific pilot training. Stall speed however would decrease with altitude, which would reduce the likelihood of stall given this flight regime.

5.6 Summary

It is apparent from this analysis that a reduction of either flight altitude or cruise speed alone does not produce a significant reduction in fuel consumption from the LRC flight condition, however through parallel variation of both Mach and altitude, it is clear that this potential does exist. This analysis, therefore demonstrates that LRC speed trajectories are not necessarily fully optimised flight profiles.

The industry resistance to the potentials available through a reduction in flight speed and altitude is an example of 'Carbon Lock-in'[3] **(Unruh 2000)**, which if overcome, could allow significant benefits through efficiency improvements. At present however, the tendency in aircraft design is to focus on maximising productivity through financial return, with little thought given to environmental implications.

From the perspective of the airline, any time lost through cruise speed reduction could be recouped if attention was directed towards minimising aircraft turnaround time. Generally, maximising productivity and aircraft usage is a primary driver of operation, however in circumstances where this does not dictate schedules i.e. if the aircraft must be parked or unused overnight the savings available through fuel reduction could be of greater magnitude than the cost associated with the additional flight time.

From the environmental perspective, the significant benefits of flight speed and altitude reduction should outweigh the financial implications to the airlines. However motivation to make significant changes for ethical reasons will inevitably carry less influence than financial considerations.

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[3] Carbon Lock-in is the condition which creates persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages **UNRUH 2000**

6 Air Travel

The often neglected issue with carbon trading schemes is that the practice of emission trading and purchase of offsets does nothing to directly reduce aviation emissions. These trading mechanisms are (or should be) ways with which to mitigate the damage of (unavoidable) emission release. When taking a flight is unavoidable, a method with which to assess the impact of individual flights would greatly increase the options available to the passenger to select the most environmentally friendly flight.

This chapter explores the options available to passengers for reducing emissions, through intelligent flight evaluation and emission offset schemes, finally proposing the introduction of legislation within the industry to induce sustainability.

6.1 Flight Selection

There are many factors which influence ticket price, and many components to flight cost breakdown. The cost of fuel represents a significant component to the price of each ticket, however it is often not the case that the shortest, direct flight, or flight which requires the least fuel is also the cheapest. This phenomenon is frequently observed when airlines hold a monopoly on a direct route or on city pairs, enabling freedom through price adjustment based on increased demand and convenience.

The results of the analysis conclude that there is often no relationship between environmental impact (fuel burn/fuel required) and ticket price. On the contrary, in many cases flight options with large, excessive detours would often be the cheapest travel option. The author of this thesis has, for example, first-hand experience of this, flying several times with significant detours to save on ticket cost. These flights have included from Glasgow (GLA) to Barcelona (BCN) via Ibiza (IBZ), and from Glasgow (GLA) to Budapest (BUD) via Paris (CDG). In both instances, direct flights, or flights with lesser detours, were available, only at a significantly higher price.

In certain instances however, it is the case that the direct or shortest distance flight does offers the cheapest route option. This is frequently observed in the presence of a low cost carrier, or when several airlines offer the same or similar services, forcing competition.

6.2 Emission Estimation & Compensation Scheme Effectiveness

The discussed complexity of accurately estimating fuel consumption causes significant deviation between the mass of fuel, and therefore CO_2, estimated per flight by each carbon offset supplier. In an attempt to overcome these difficulties, several organisations, such as **ICAO 2012** and **Atmosfair 2012**, have developed intuitive CO_2 emission calculation methodologies. Several airlines too provide this service, such as Air France/KLM, by way of online carbon or emission calculators. In the case of the airlines however, the complex estimation methods are not required given their access to real consumption data. Despite this, it cannot be concluded that the airlines' predictions are the most accurate given the perceived economic implications of publishing such figures. As a result of this, it can be problematic to arrive at a scientifically sound evaluation for a given offset supplier beyond that which is published or stated by the supplier.

Of the 27 offset providers for which detailed information was available online, the price to offset one tonne of CO_2e ranged from 4.05 € to 34.27 €. The average price per tonne was 11.85 €/t with a standard deviation of 6.55 over the entire data set. This analysis illustrates the lack of correlation between the costs each provider values to compensate one tonne of $CO_{2e.}$

Using this information, a comparison is performed to assess whether such (low) costs could feasibly remove, or in this case, prevent release of, one tonne of CO_2 from the atmosphere.

Table 6.1 details the equivalent electricity generated, in both joules and kWH, which would result from the consumption of 316.54 kg of fuel, equating to the release of approximately one tonne CO_2 tonne using a typical diesel generator. Table 6.2 details the fuel price per kg and price for the mass of fuel consumed in this example. A large proportion of projects occur in developing countries, which makes it considerably easier to prove they would not have occurred without the financial support provided by the offsetters, as per the requirement of an *additional* project, hence the price of fuel is estimated using prices defined by the Nigerian oil index.

Table 6.1 Electricity generated through the equivalent consumption of 316.54 kg fuel which equates to the release of one tonne CO_2.

CO_2 (kg)	Fuel (kg)	Energy (Joule)	Electricity (J)	Electricity (kWH)
1E+03	316.45	13449.36	4539.16	1260.87

Table 6.2 Cost per kg, and cost for 316.54 kg diesel, taken as average price for diesel, Nigerian oil index 2012

Cost/kg (€/kg)	Total Cost 316.34kg Fuel (€)
0.89	282.19

The German 'Renewable Energy Sources Act' (**EEG 2012)** defines the minimum prices which must be paid to the supplier for energy produced through renewable means. This is similar to the prices set by the UK authorities which are paid to suppliers who 'sell' electricity back to the national grid. Both include as a percentage, the costs which are required to build and maintain the generating source. The prices of electricity generated using solar technologies and both small and large wind turbines, defined by **EEG 2012**, are therefore used to calculate price the equivalent electricity generated using the diesel generator would cost to buy, as presented in Table 6.3.

It can be observed through comparison of Table 6.1 and 6.3 that in the cases of both electricity generation through wind power, the price of offset is fully recoverable, and in the case of solar power, falls only just short. This implies that provided a nominal fee is charged for the electricity provided by these new green generation methods, which is anything up to the cost of the fuel which would have been required to produce that energy using the diesel generator, then the cost of offsetting one tonne of carbon is dependent on the fee charged, and not on the price paid by the offset customer.

Table 6.3 Cost to consumer for 1260.87 kWH electricity EEG 2012

Price Wind (€)	Price Wind Large (€)	Price Solar (€)
112.6	61.4	314.59

This illustrates the potential return available through selling carbon offsets for-profit. The issue at this point, ceases to exist in the field of science or engineering, but rather becomes an issue of ethics.

6.3 The Flight Evaluator

Several organisations have performed airline evaluations, including Atmosfair's 'Airline Assessment Index,' **AAI 2012**, however this practice only serves to differentiate between airlines and does not differentiate between individual flights or routes, which may result in an unfair comparison being made. A flight evaluation tool the '*Flight Evaluator'* has therefore been developed to assess flight options based on cost, trip time and efficiency.

There are currently many possible methods of purchasing airline tickets. These include; direct from the airline, through a third party such as travel agent or through an online flight search engine. These search engines generally include options to arrange or choose flights by trip time, price, airline and route etc, whereas at present there is no simple or straightforward way of selecting or sorting flights by fuel consumption or environmental impact.

The fuel burn estimation method presented in Section 4, allows the possibility of predicting fuel consumption, which allows direct comparison between the environmental impact of specific flights or routes. The concept is applied to a booking system to estimate both absolute and relative emissions over the desired route or set of city pairs. Presented in such a way, the system could be incorporated into an online website booking service, thus allowing travellers the option of choosing or sorting flights based on the environmental impact.

To illustrate the potential of the *Flight Evaluator*, analysis is performed on a single trip between Madrid (MAD) and Hamburg (HAM). This route was chosen as there is only one standard carrier (Lufthansa) that offers the route directly, with no low cost carriers offering the service. The direct flight between MAD and HAM is subsequently considerably more expensive than the indirect options, despite consuming the least fuel of the possible route options allowing a significant saving in fuel costs for the airline over the other airlines.

Performing a route search online, presents several possible indirect travel options. These routes have been filtered to include only the cheapest option per airline operating the same route i.e. the flight evaluator only identifies the cheapest flight when several pricing options exist for the same airline and route i.e. due to the time of the flight etc. The system also does not include route options which are more expensive than the available direct flight, or beyond the flight with the least fuel burn since passengers would not, except in special circumstances pay more for a longer travel time. The *Flight Evaluator* therefore presents a total of seven possible flight routes, which are presented in Table 6.4, and illustrated graphically using a route map as per Figure 6.1.

Table 6.3 highlights the potential for disparity between the cost of a ticket, distance travelled, and the m_F per passenger. Interestingly, the longest flight available is also the second cheapest, and the two shortest flights are the first and second most expensive. Each of these flights occurs within the first flight section for each aircraft, which is fairly typical of aircraft operations worldwide.

Table 6.4 *Flight Evaluator* Possible Route Options, including route aircraft, price, GCR distance and stop over aircraft, between Madrid (MAD) and Hamburg (HAM), typical day

Airline	Stage 1 A/C	Via	Airport Code	Stage 2 A/C	GCR Distance (km)	Price (€)	m_F (kg)
TAP Portugal	A319	Lisbon	LIS	A319	2709	303	68.79
Aeroflot	A320	Moscow	SVO	A320	5181	453	143.09
Swiss Air	A319	Zurich	ZRH	A319	1931	516	47.62
Air Berlin	A320	Palma	PMI	A321	2203	517	53.81
Turkish Airlines	B737-800	Istanbul	IST	A321	4697	528	122.05
KLM	B737-800	Amsterdam	AMS	B737-800	1837	682	47.97
Lufthansa	B737-300	Direct	n/a	n/a	1778	717	47.17

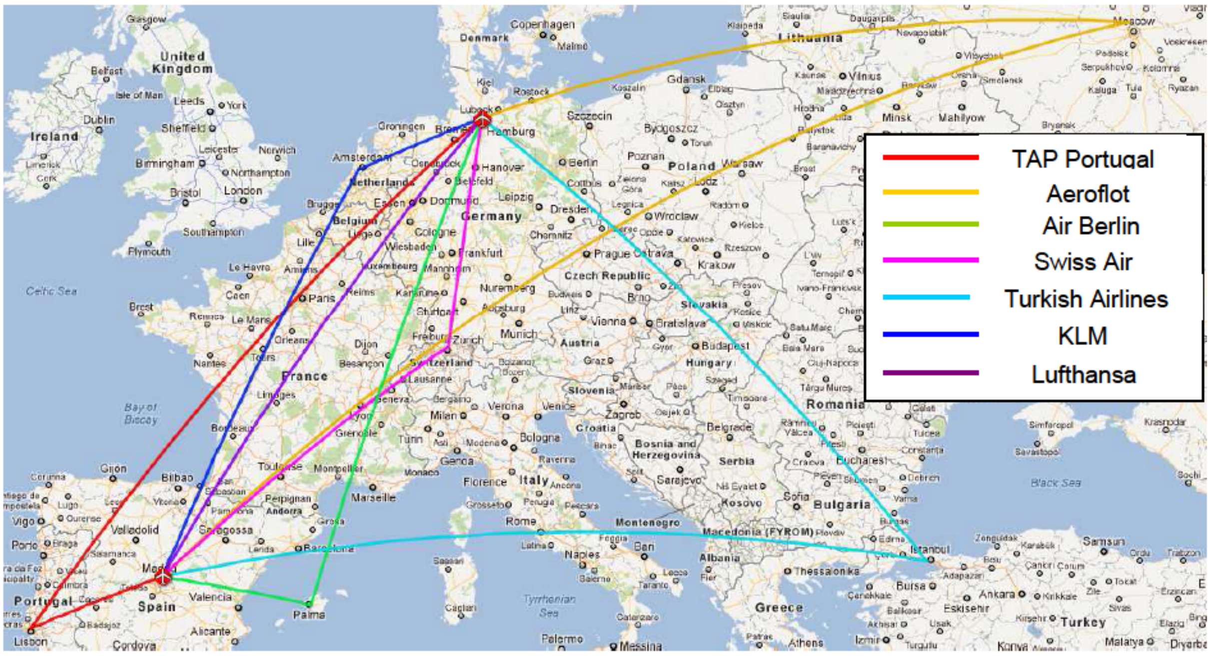

Figure 6.1 Route Map of possible flight options, between Madrid (MAD) and Hamburg (HAM), typical day, as in Table 6.3.

Figures 6.2 - 6.4 present the flight data by graphically depicting the absolute values of cost, price and time against one another.

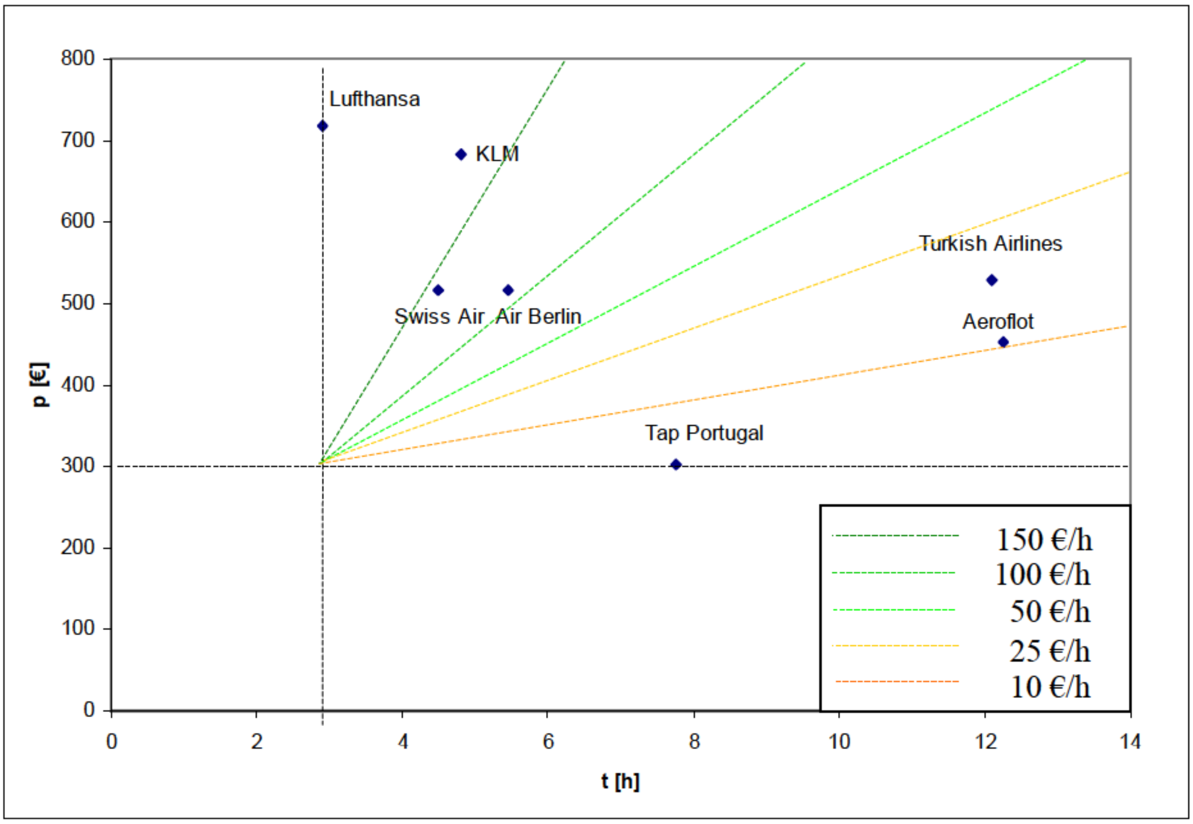

Figure 6.2 Spread of ticket price vs. trip time for flights - Madrid (MAD) and Hamburg (HAM)

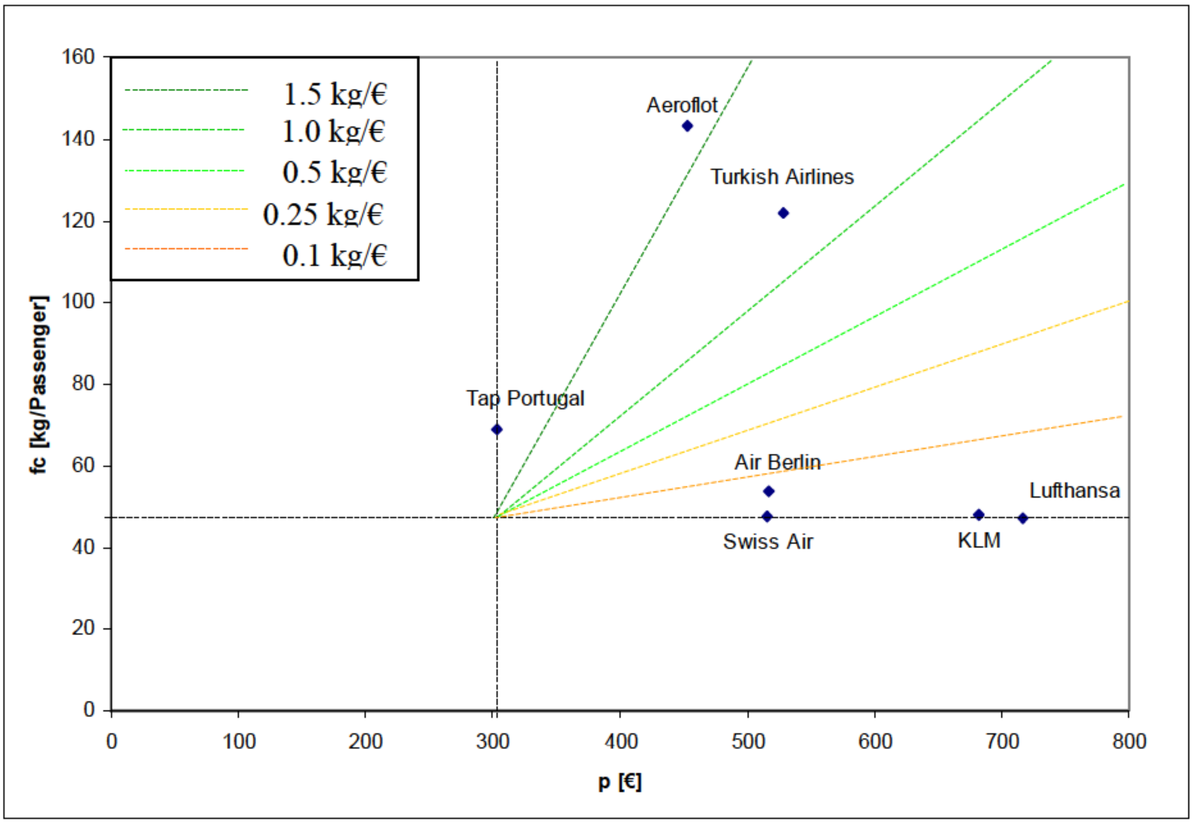

Figure 6.3 Spread of fuel consumption vs. ticket price for flights - Madrid (MAD) and Hamburg (HAM)

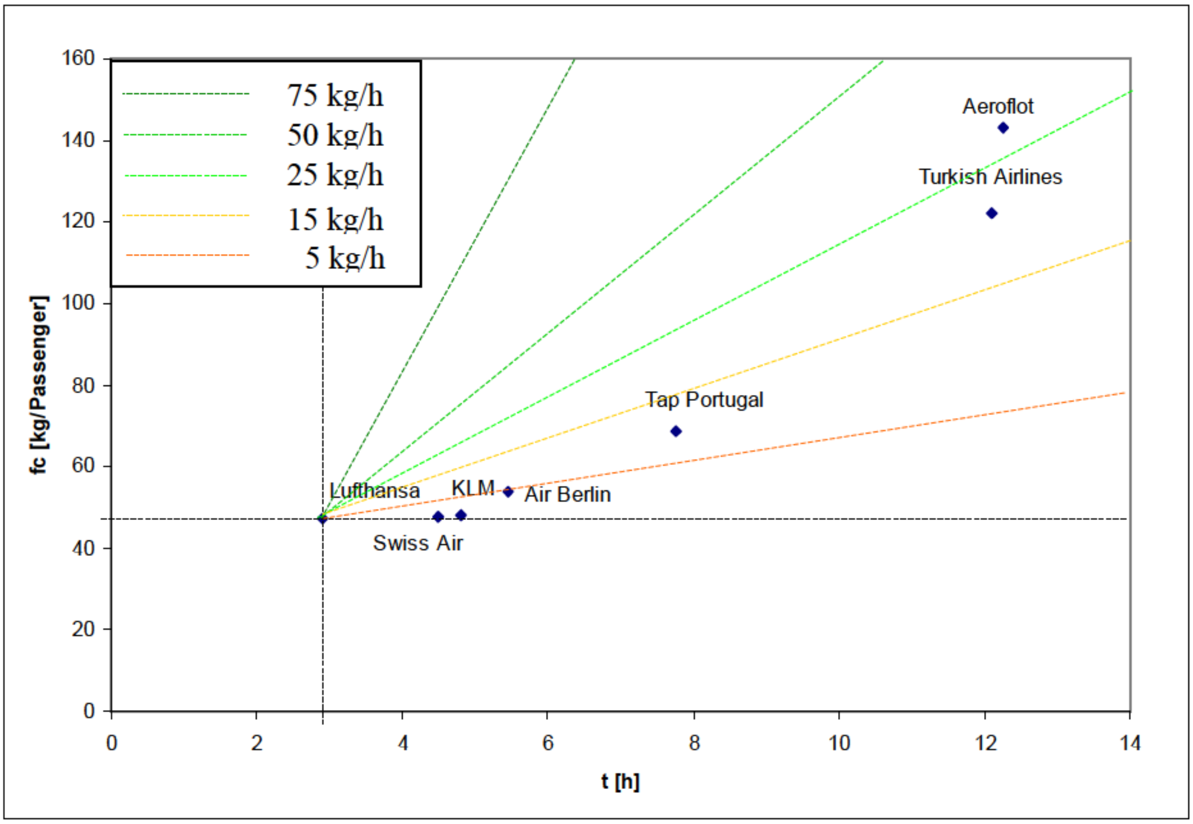

Figure 6.4 Spread of fuel consumption vs. total trip time for flights - Madrid (MAD) and Hamburg (HAM)

The horizontal and vertical dashed lines on Figures 6.2 - 6.4, represent the lowest value for each axis. The point at which they cross is referred to the ideal condition. The coloured dashed lines represent lines of constant change relative to this ideal condition as per the legend on each figure. The purpose of these lines is to clearly illustrate each flights position relative to the best possible option. This will allow the traveller to make their choices based upon their specific requirements.

While these graphs provide helpful tools, for many, their addition may prove only to complicate matters further, by appearing to 'overload the user with information. To prevent this, the flights are also presented using a ranking system, again based upon relative efficiency, time and price.

$$X_p = 1 - \frac{P_x - P_{Min}}{P_{Max} - P_{Min}} \tag{6.1}$$

$$X_t = 1 - \frac{t_x - t_{Min}}{t_{Max} - t_{Min}} \tag{6.2}$$

$$X_{m_F} = 1 - \frac{m_{F,x} - m_{F,Min}}{m_{F,Max} - m_{F,Min}} \tag{6.3}$$

The ranking is calculated using Eqns. (6.1 - 6.3), which provide a rank based on the attributes of each flight. This ranking is indexed to between 0 and 100, with 0 being the least efficient or worst, and 100 being the most efficient or best. Presented in this way, the data the A-G energy efficiency labelling system as per **(EU 2006)**[4] is applied to the output of the flight evaluator, as per Table 6.5. The raking is also presented using the spider diagram charts given in Figure 6.5, whereby the flights with highest area coverage represent the better or more efficiently flight option.

Table 6.5 Relative ranking output from Flight Evaluator

	X_p	
TAP Portugal	100	A
Aeroflot	64	D
Swiss Air	49	E
Air Berlin	48	E
Turkish Airlines	46	E
KLM	8	G
Lufthansa	0	G

	X_t	
Lufthansa	100	A
Swiss Air	83	B
KLM	80	B
Air Berlin	73	C
TAP Portugal	48	E
Turkish Airlines	2	G
Aeroflot	0	G

	X_{mf}	
Lufthansa	100	A
Swiss Air	100	A
KLM	99	A
Air Berlin	93	A
TAP Portugal	77	C
Turkish Airlines	22	F
Aeroflot	1	G

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[4] EU Directive 2006/32/EC is applicable to 'Energy End-use Efficiency and Energy Services'. To ensure complete suitability, the introduction of an aviation specific directive would be advised

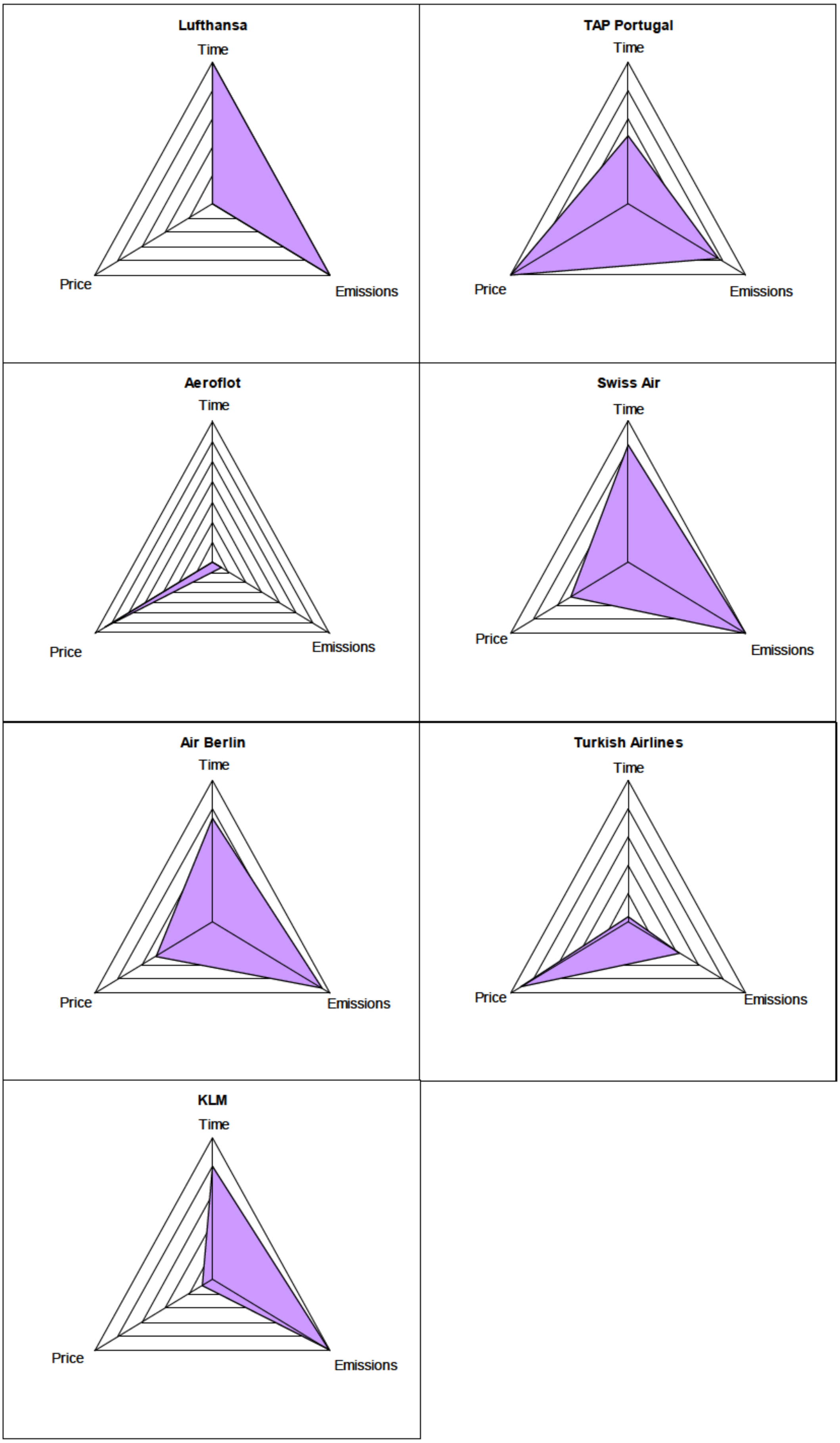

Figure 6.5 Spider diagrams generated using the Flight Evaluator

6.3.1 User Customised Weighting System

Employing similar methods to those presented in 6.3, a fully customisable flight ranking tool is created to include both user Labour Rate, given *L*, and user carbon compensation rate, *C*. The labour rate variable, in *p/t*, is equivalent to the user's salary, providing a useful benchmark for all travellers who directly evaluate their time in monetary terms, such as done by for businesses. The Compensation Rate variable, in p/m_{CO2}, is the amount the passenger is willing to pay to compensate per one tonne of CO_2. This feature provides a useful comparison with which to evaluate flight options against offered compensatory devices, and highlights an important issue in the practice of carbon compensation.

The effective ticket price, P_{eff}, calculated using Eqn. 6.4. Eqn. 6.5, is then used to rank the user price, $P_{eff,}$ based upon the weighting system which is automatically applied via the user input variables. This ranking is again evaluated on a scale from 0-100.

To provide illustration of the system, predefined rates for *L* and *C* of 6 €//h leisure, 20 €//h business, and 0 €/tCO_2 indifferent, 25 €/tCO_2 green, respectively, are used in the analysis. The results of which are presented in Tables 6.6 and 6.7 which allowing direct comparison of the '*efficiencies*' of X_p, $X_{t,}$, and X_{mf} according to predefined input.

$$P_{eff} = P + L(t_x - t_{Min}) + C(m_{F,Pax,x} - m_{F,Pax,Min}) \tag{6.4}$$

$$X_{P_{eff}} = 1 - \frac{P_{eff,x}}{P_{eff,Max}} \tag{6.5}$$

Table 6.6 Flight Evaluator Leisure traveller Green and Indifferent customised ranking

Leisure					
Green			**Indifferent**		
Airline	**Ranking**		**Airline**	**Ranking**	
TAP Portugal	100	A	TAP Portugal	100	A
Swiss Air	58	E	Aeroflot	54	D
Air Berlin	52	E	Swiss Air	50	E
Aeroflot	9	E	Air Berlin	48	E
KLM	6	F	Turkish Airlines	35	E
Lufthansa	4	G	KLM	6	G
Turkish Airlines	0	G	Lufthansa	0	G

Table 6.7 Flight Evaluator Business traveller Green and Indifferent customised ranking

Business					
Green			**Indifferent**		
Airline	**Ranking**		**Airline**	**Ranking**	
TAP Portugal	100	A	TAP Portugal	100	A
Swiss Air	75	D	Swiss Air	54	D
Air Berlin	67	E	Air Berlin	48	E
Lufthansa	35	F	Aeroflot	25	F
KLM	33	F	Turkish Airlines	3	G
Aeroflot	7	G	Lufthansa	1	G
Turkish Airlines	0	G	KLM	0	G

Tables 6.6 and 6.7 demonstrate that due to the low cost of carbon offsetting, unless significant sums are willing to be wagered for the offset per tonne, then in almost every instance, it is more economical to take the flight which best suits the user according to the price, then time indexes. This highlights an important and disturbing issue in the current model of aviation, that the environmental impact is getting ignored, not due to the fault of the passenger, but due to the construct of the system. Unless interjectory action is taken to change this, these practices will exist, and be accepted despite their environmental impact.

6.4 Political Influence within Aviation

The booking scheme presented in Section 6.3 will inevitably force competition between airlines providing similar services. The ranking system and flight labelling would help to increase passenger awareness of the consequences of each particular journey or flight. This would serve to reward airlines with highest efficiency and lowest environmental impact.

Introduction of competition based upon emission reduction will not however be welcomed in an industry which already struggles to retain profitability. As fuel prices continue to rise and encroach on available profit margins, measures such as the flight evaluator encouraging tougher competition would be met with strong resistance within the industry. Environmentally positive competition will therefore not arise voluntarily, but will require legislative action to encourage adoption by the industry. This issue is summarised well by **Hirsch 2005**, stating;

> *"Intervention by governments will be required, because the economic and social implications of oil peaking would otherwise be chaotic … Expediency may require major changes to existing administrative and regulatory procedures such as lengthy environmental reviews and lengthy public involvement"* ***Hirsch 2005***.

Mensen 2003, define three branches or tools, which can be used to create influence within the aviation industry. These branches, defined as fiscal policy, administrative policy and regulatory policy instruments are represented by Figure 6.6. Sections 6.4.1 – 6.4.3 discuss the potential for utilisation of these tools to specifically influence a reduction in fuel burn promoting sustainability within the industry.

It is important that policy which is introduced rewards those who operate efficiently and provides incentives for airlines and operators to follow suit. This is a further example of the limitation of voluntary carbon trading, as they provide airlines no incentive to increase fuel efficiency.

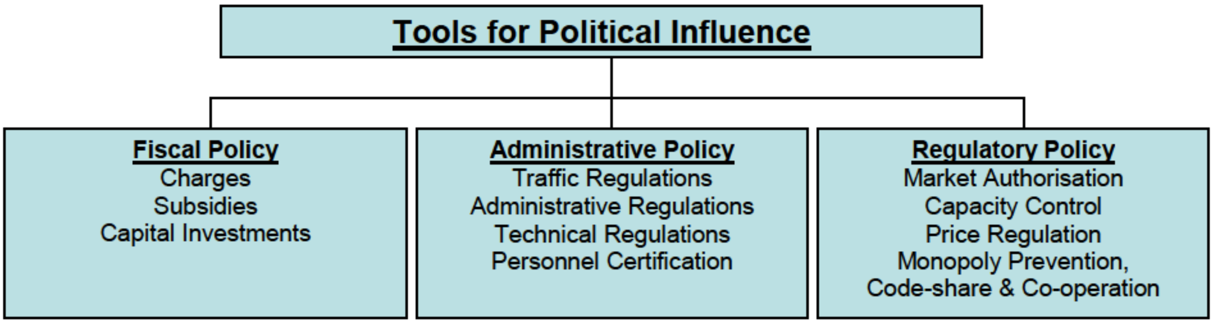

Table 6.8 Branches of political and regulatory influence. Reproduced from **Mensen 2003**

6.4.1 Fiscal Policy

Air transport currently enjoys an ‘unjustified competitive advantage over other modes of transport’ **(BUND 2007)**, through tax breaks and exemptions. Environmentally speaking, fiscal policy should favour low pollutant modes of transport, such as rail. The introduction of aviation fuel tax and the addition of VAT would help reduce the dichotomy between transportation inequalities, going some way towards fairly aligning legislation applied across all transport sectors.

The UK ‘Air Passenger Duty’ or German ‘Air Passenger Taxes’ are fixed fees dictated by country of origin and destination, providing operators no incentive to reduce fuel burn. Such taxes, result in little aside from potential growth-reduction effects resulting from higher ticket price.

The introduction of a tax on aviation fuel would not only provide incentives to reduce fuel burn, but also raise substantial revenue. This revenue could be re-directed elsewhere, such as, for example, towards development of greener transportation methods. The German Federal Environment Agency, estimate that by 2020, the release of 14 million tons of carbon dioxide would be prevented as a result of the introduction of a 0.30 € per litre tax on kerosene **(Matthes 2008).**

Past attempts to introduce such a tax have however encountered vehement resistance from within the industry. **Lufthansa 2010** argue that taxes are counterproductive stating that:

> *"Aviation is the only global industry to have already pledged its unconditional support for climate protection. By 2050, carbon emissions stemming from fossil fuels are to be cut in half relative to 2005 levels"* ***Lufthansa 2010***.

The tax would need to be applied universally throughout block areas or countries such as by EU, or by UN agreement, otherwise imposition of fuel tax would allow opportunity for operation malpractice such as 'tankering'[5], or traffic re-direction.

6.4.2 Administrative Policy

Administrative policy, such as the introduction of flight altitude or flight speed restriction, as discussed in section 5, offers a great source of, as yet, unexplored potential for emission reduction. These policies could be extended to influence aircraft design, forcing mandatory inclusion of efficient technologies and optimum design parameters, such as high aspect ratio wings. This could further extend requirements for mandatory upgrades of technologies including, for example, winglet retrofitting to existing aircraft. Short haul flights or flights below a defined range of 1000 km for example, could be banned, and replaced with a clear promotion of alternate greener transport, such as rail. Restriction of flight speed and definition of a minimum range also provides the additional benefit of increasing the desirability of alternative modes of transport over flight options.

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[5] Tankering is the term given to the practice of flying with additional fuel than is required when operating to/from a country that imposes aviation fuel tax. This practice enables airlines to bypass paying fuel tax.

6.4.3 Regulatory Policy

Perhaps the area with largest potential for policy induced efficiency improvement is to ban the practice of selective publication through implementation of legislation which demands that airlines and operators publically open up their data. The analysis performed in Section 3, for example would not have been made possible were it not for the acquisition of drag polar data for several aircraft, which serves as the perfect example of what may be achieved through the release of only a very small amount of data. **Simos 2010** indicates a similar desire within the industry stating that;

> *"...inefficiencies cannot be eliminated, but they can be reduced. Public transparency is as powerful a tool as coercion for reducing CO2 emissions. At a minimum, transparency is a prerequisite to fair regulation"* ***Simos 2010.***

Aircraft cannot be copied or re-created using this data hence no competitive advantage would be lost in it release. Further, operators, especially those who operate aircraft of competing manufacturers, can and often do, exercise their right to receive detailed data for aircraft they have, or would consider to purchase, leaving only the public, the end user of these products, in the dark regarding the aircraft. Transparency within aviation will do nothing except highlight areas of inefficiencies, which if dealt with correctly, will drive the industry towards a more efficient future.

In this regard, given that the flight evaluator is limited to information available from the payload-range diagrams, it cannot accurately discern between aircraft specific operational or technological modifications if these are not specifically reflected in published payload-range data. While this limits the applicability of the method, it would also encourage airlines to adopt public release of consumption data to better reflect any positive changes or modifications the airline has carried out on their fleet.

This policy, which could be implemented through, for example, adoption of an *SAE Standard of Recommended Practice to 'Specify Fuel Efficiency'*, using the fuel metric proposed in Section 4 to provide reference to aircraft fuel efficiency. Adoption of this would actively reward airlines that have pursued emission reduction techniques, through improved public and eco-image leading to increased client-customer relationships.

Such a policy would not only improve transparency, it also enable enhances scientific research in the field of aviation, which may be the only way the industry can or will ever achieve the efficiency improvements required to achieve sustainable growth.

7 Conclusion

Aviation is fast approaching a crucial point in its history, where the future of the industry is somewhat uncertain. The industry has achieved a high level of technological maturity. Remaining potential for efficiency improvements will continue to diminish, and only to be fully realised at great expense.

Current growth in aviation is a classic example of 'Jevon's Paradox', which states that increases in efficiencies lead to increased, not decreased, levels of consumption. This phenomenon is not a sustainable one.

It is not acceptable, or sustainable, for the industry to rely heavily on carbon offsetting, and it must recognise the pressures that this practice imposes on every other sector. It must be also be realised that efficiency improvements do not substitute avoidance, and legislation must begin to reflect this especially when there are alternate modes of transportation available.

The industry must take responsibility for its actions, and realise that continuous growth may not be required, or indeed be appropriate. Crucially, the industry must realise that to satisfy sustainability, growth rates must be matched with, or exceeded by, efficiency improvements. The point at which this unachievable should alert the industry that growth cannot continue.

Air travel and aviation are not often discussed within the context of overconsumption. However the issues the industry will soon face are echoed by those industries facing similar shortages and decline through ever increasing, unchecked growth. Similar to the issue of overfishing for example, air transport has simply become too easy, too cheap, and too available. Unlike fishing stock decline, the damage caused by aviation, is almost immeasurable, and the true effect may not be witnessed for some time.

As with the LtG predictions, this thesis does not intend to portray air transportation negatively. On the contrary, the intention is to stress the importance of working to achieve sustainability, a goal which is both possible, and essential, and continual, unrestrained growth is not a requirement of overall industry prosperity. Air travel has the potential to be a sustainable industry, without the need for carbon schemes, offsets or credits. This will however, only occur if appropriate measures are taken to achieve this.

The implementation of legislation, such as that discussed, is an example of what is required within the industry to ensure it achieves this goal. Sustainability is not something which will occur naturally, but a goal that must be worked towards. Simple steps such as allowing open access to data, promoting alternate means of transport for shorter distances, optimising aircraft design for intended purpose, the implementation of new aircraft configurations, the introduction of fuel tax and the development of algae based biofuels will all provide significant contributions to the problem of sustainability. Passengers, operators and manufacturers must each play their part in working together towards this common goal.

The benefits and opportunity provided by aviation are unparalleled, and the possibility of intercontinental and international travel is a luxury for which there is little or no comparable substitute. It is for these reasons that the industry must achieve sustainability, to prevent the deprivation of aviation from future generations.

8 References

Bibliography

AAI 2012 Atmosfair Airline Index 2011.
http://cdn.atmosfair.de/atmosfair_Airline_Index_2011_en.pdf

ACARE 2011 ACARE flightpath 2050.
http://ec.europa.eu/transport/air/doc/flightpath2050.pdf

AGAPE 2010 AGAPE 2010
http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/agape_final_report_summary.pdf

AIRBUS 2011a AIRBUS, The Future by Airbus, 2011.
http://www.airbus.com/innovation/future-by-airbus/

AIRBUS 2011b AIRBUS, Global Market Forecast, 2011.
http://www.airbus.com/company/market/forecast/

ATAG 2012 ATAG 2012: Global Aviation Sector Commits to Support Sustainable Development. http://www.atag.org/our-news/press-releases/54.html?tmpl=pressrelease

ATMOSFAIR 2012 ATMOSFAIR. Carbon Calculator Methodology, https://www.atmosfair.de/en/corporate-services/business-travel/co2-reporting/methodology-of-the-vdr-standard-co2-calculation-of-corporate-travel/ 2012

BOEING 2012 BOEING Market Forescast 2011.
http://www.boeing.com/commercial/cmo/

BOON 2006 BOON, B.H., SCHTOTEN, A. and KAMPMAN, B. Compensation schemes for air transport. Proceedings of the Tourism and Climate Change Mitigation Conference, 11–14 June 2006, Westelbeers, The Netherlands 2006

BOWS 2005	BOWS, A., UPHAM, P. and ANDERSON, K. Growth scenarios for EU and UK aviation: Contradictions with climate policy, Tyndall Centre report for Friends of the Earth, The University of Manchester. 2005
BUND 2007	BUND 2007: Für Steuergerechtigkeit über den Wolken. Einführung einer Kerosinsteuer im inländischen Flugverkehr, Bund für Umwelt und Naturschutz Deutschland (BUND), Berlin.
CERON 2007	CERON, J.P. & DUBOIS, G. Limits to tourism? A Backcasting Scenario for a Sustainable Mobility in 2050. In P. Burns and M. Novelli (eds) Tourism and Mobility Amsterdam: Elsevier/Butterworth-Heinemann. 2007
COHEN 2011	COHEN, S.A., HIGHAM, J.E.S. & CAVALIERE, C.T. Binge flying: Behavioural addiction and climate change. Annals of Tourism Research, 38(3), 1070-1089. DOI: 10.1016/j.annals.2011.01.013, 2011
DEYOUNG 1955	DEYOUNG, John; HARPER, Charles W.: Theoretical Symmetric Span Loading at Subsonic Speeds for Wings Having Arbitrary Plan Form. NACA Report 921, 1955.
EASA 2008	BERDOWSKI. Z. van den BROEK-SERLÉ, F.N. JETTEN, J.T. *et al.* Survey on standard weights of passengers and Baggage, Final report. Reference EASA 2008.C.06/30800/R20090095/30800000/FBR/RLO. 2008
EEG 2012	VERGÜTUNGSSÄTZE, Degression und Berechnungsbeispiele nach dem neuen Erneuerbare-Energien-Gesetz (EEG) vom 04. August 2011 (*‚EEG 2012'*)
EGELHOFER 2008	EGELHOFER, R. Aircraft Design Driven by Climate Change. Munich Technical University, Institut für Luft- und Raumfahrt, Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen, Universität München. 2008
EU 2006	EU. DIRECTIVE 2006/32/ec of the European parliament and of the council of 5 April 2006 on Energy End-Use Efficiency and Energy Services and Repealing Council Directive 93/76/EEC http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:114:0064:0064:en:pdf

EUROPA 2011 EUROPA 2011 http://ec.europa.eu/transport/strategies/facts-and-figures/all-themes/index_en.htm

GILL 2007 GILL. M, HUMPHREYS. J: Aviation and Climate Change: Public Opinion and the Scope for Action Report for enoughsenough 2007 http://www.woodnewtonassociates.co.uk/analysis/Reports/Aviation%20and%20Climate%20Change%20Final%20Report.pdf

GOSSLING 2007 GOSSLING, Stefan. BRODERICK, John. UPHAM, Paul. PEETERS, Paul. STRASDAS, Wolfgang.: Voluntary Carbon Offsetting Schemes for Aviation: Efficiency, Credibility and Sustainable Tourism. 2007.

HAMBURGER ABENDBLATT 2012 Hamburger Abendblatt. Issue Wednesday 21 December 2011

HERRMANN 2010 HERRMANN, S.: Untersuchung des Ein_usses der Motorenzahl auf die Wirtschaftlichkeit eines Verkehrs_ugzeuges unter Berücksichtigung eines optimalen Bypassverhältnisses. Graduation Thesis, Technical University Berlin, 2010

HIRSCH 2005 HIRSCH, Robert, L. BEZDEK, Roger. WENDLING Robert: Peaking of World Oil Production: Impacts, Mitigation & Risk Management, United States Department of Energy, 2005.

HÖRNER 1951 HÖRNER, Sighard F.: Fluid Dynamic Drag. Otterbein Press, Dayton Ohio, 1951.

IATA 2011 IATA Annual Report 2011. http://www.iata.org/pressroom/Documents/annual-report-2011.pdf

ICAO 1993 ICAO: International Standards and Recommended Practices, Environmental Protection Annex 16, Volume II Aircraft Engine Emissions (second Ed.), 1993

IEA 1998 IEA: World Energy Outlook 1998 Edition, International Energy Agency/Organization for Economic Co-operation and Development, Paris, 1998.

IPCC 2001	IPCC: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories 2001 www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_5_Aircraft.pdf
KOHLER 2008	KOHLER. M. O., RADEL. G. DESSENS. O. SHINE. K. P *et al.* Impact of Perturbations to Nitrogen Oxide Emissions from Global Aviation. Journal of geophysical research, vol. 113. 2008
KOLLMUSS 2007	KOLLMUSS, A, BOWELL, B. Tufts Climate Initiative Voluntary Offsets For Air-Travel Carbon Emissions Evaluations and Recommendations of Voluntary Offset Companies, 2007 http://sustainability.tufts.edu/downloads/TCI_Carbon_Offsets_Paper_April-2-07.pdf
KROO 2005	KROO, I.: Nonplanar Wing Concepts for Increased Aircraft Efficiency. VKI lecture series on Innovative Configurations and Advanced Concepts for Future Civil Aircraft Stanford University, U.S.A, 2005.
LUFTHANSA 2010	LUFTHANSA : Policy Brief: Compulsory levy: Air travel tax penalises German airlines, policy brief 2010. http://presse.lufthansa.com/fileadmin/downloads/en/policy-brief/07_2010/LH-PolicyBrief-July-2010-Compulsory_levy.pdf
LUFTHANSA 2011	LUFTHANSA : Balance Sustainability Report. http://verantwortung.lufthansa.com/fileadmin/downloads/en/LH-sustainability-report-2011.pdf 2011
MATTHES 2008	MATTHES, F., S. GORES, V. GRAICHEN, R. HARTHAN, P. *et. al*: Politikszenarien für den Klimaschutz IV - Szenarien bis 2030. Umweltbundesamt. Dessau-Roßlau, 2008.
MEADOWS 1972	MEADOWS, D. MEADOWS, D, RANDERS, J, BEHRENS, W.: The Limits to Growth, Second Edition Revised, Signet. ISBN 0-87663-165-0, 1972
MEADOWS 1992	MEADOWS, D. MEADOWS, D. RANDERS, J.: Beyond the Limits. Chelsea Green, 1992
MENSEN 2003	MENSEN, H.: Handbuch der Luftfahrt. Springer. Berlin, 2003.

MEYER 2004 MEYER, Audrey.: Contraction and Convergence Global Commons Institute UK: Proceedings of the ICE - Engineering Sustainability. 2004

MONBIOT 2006 MONBIOT. G. Selling Indulgences http://www.monbiot.com/2006/10/19/selling-indulgences/

NITA 2012a NITA, Mihaela: SCHOLZ, Dieter: Estimating the Oswald Factor from Basic Aircraft Geometrical Parameters. In: DGLR: Deutscher Luft- und Raumfahrtkongress 2012, 10-12 September 2012, Berlin (abstract submitted and accepted).

NITA 2012b NITA, Mihaela: Contributions to Aircraft Preliminary Design and Optimization. Doctoral Thesis, Politehnica University of Bucharest, Faculty of Aerospace Engineering & Hamburg University of Applied Sciences, Faculty of Engineering and Computer Sciences, Department of Automotive and Aeronautical Engineering. 2012.

NY TIMES 2008 New York Times 2008. http://www.nytimes.com/2008/05/02/business/worldbusiness/02iht-air.4.12528774.html

READ 2005 READ P. & LERMITT, J.: Bio-energy with carbon storage (BECS): A sequential decision approach to the threat of abrupt climate change. *Energy* 30 (14), 2654 – 2671, 2005.

SCHWARTZ 2009 SCHWARTZ, Emily. KROO, Ilan, M.: Aircraft Design: Trading Cost and Climate Impact, Stanford University, Stanford, CA 94305. 2009

SCHWARTZ 2011 SCHWARTZ. E. Aircraft Design for Reduced Climate Impact. Department of aeronautics and astronautics and the committee on graduate studies of Stanford University. 2011

SIMOS 2010 SIMOS, D. Transparency in Aviation Emissions: An open letter. 2010 http://www.lissys.demon.co.uk/Transparency_in_Aviation_Emissions.html

TURNER 2008 TURNER, G, M: A comparison of The Limits to Growth with 30 years of reality. CSIRO Sustainable Ecosystems, GPO Box 284, Canberra City, ACT 2601, Australia, 2008

UHEREK 2006	UHEREK 2006 http://www.atmosphere.mpg.de/enid/618cec9fd627dbd798dd2f2f09d0abc3,0/Information_2/Low_cost_airlines_-_impacts_61j.html
UN 2011	UN. Human Development Report. 2011 http://hdr.undp.org/en/reports/global/hdr2011/download/
UNRUH 2000	UNRUH, Gregory, C.: Understanding Carbon Lock-In. Instituto de Empresa, Maria de Molina 12, Madrid 28006, Spain, 2000.
WCED 1987	UN. Report of the World Commission on Environment and Development: Our Common Future. http://www.un-documents.net/wced-ocf.htm
WORLD BANK 2011	WORLD BANK. State and Trends of the World Carbon Market. 2011 http://siteresources.worldbank.org/INTCARBONFINANCE/Resources/StateAndTrend_LowRes.pdf

Appendix A –Fuel Metric Derivation

A.1 Breguet Equation

Range is calculated by integrating the specific air range. Breguet assumed that V, E and c are constant values. The aircraft mass however changes due to fuel burn.

$$r_a = -\frac{dx}{dm_F}$$

$$r_a = \left(-\frac{dx}{dm_F}\right) = \left(\frac{dx}{dt}\right)\left(-\frac{dt}{dm_F}\right) = \frac{V}{Q}$$

$$\frac{V}{Q} = \frac{VE}{cgm}$$

$$R = -\int_{m_1}^{m_2} \frac{VE}{cgm}\, dm = \int_{m_2}^{m_1} \frac{VE}{cgm}\, dm$$

The famous *Breguet Range Equation* is then

$$R = \frac{VE}{cg} \ln\left(\frac{m_1}{m_2}\right)$$

The constant factor in this equation is called the Breguet factor B and is define as

$$B = \frac{VE}{cg}$$

Shortened

$$R = B \ln\left(\frac{m_1}{m_2}\right)$$

A.2 Calculation of the Breguet Factor from a Payload-Range Diagram

The idea is to extract B from a payload range diagram. So, re-arrange the *Breguet Range Equation* for B to yield

$$B = \frac{R}{\ln\left(\frac{m_1}{m_2}\right)} \tag{A.1}$$

R is the range for which the fuel mass

$$m_F = m_1 - m_2 \tag{A.2}$$

is burned. m_1 is the mass of the aircraft before the flight (with trip fuel and reserve fuel) and m_2 is the mass of the aircraft after the flight (without trip fuel, but still with reserve fuel).

A.3 Fuel Mass Fractions

From A.2

$$\frac{m_F}{m_1} = 1 - \frac{m_2}{m_1}$$

With the definition of a fuel mass fraction

$$M_{ff} = \frac{m_2}{m_1}$$

$$m_F = m_1 \left(1 - M_{ff}\right) \tag{A.3}$$

The fuel mass fraction may be divided into the various flight phases and related mission segment fuel mass fractions in which fuel is consumed. Going from shut-off (SO) to take-off (TO) all mission segment fuel mass fractions multiplied yield

$$M_{ff} = \frac{m_{SO}}{m_L} \times \frac{m_L}{m_{LOI}} \times \frac{m_{LOI}}{m_{DES}} \times \frac{m_{DES}}{m_{RES}} \times \frac{m_{RES}}{m_{CLB}} \times \frac{m_{CLB}}{m_{DES}} \times \frac{m_{DES}}{m_{CR}} \times \frac{m_{CR}}{m_{CLB}} \times \frac{m_{CLB}}{m_{TO}} = \frac{m_{SO}}{m_{TO}} = \frac{m_2}{m_1}$$

m_x is the mass at the <u>beginning</u> of the respective flight phase. Taxi-out is not included because the calculation here starts with maximum take-off mass m_{MTO} at break release as starting mass m_1 .

$$M_{ff} = M_{ff,L} \times M_{ff,LOI} \times M_{ff,DES} \times M_{ff,RES} \times M_{ff,CLB} \times M_{ff,DES} \times M_{ff,CR} \times M_{ff,CLB} \times M_{ff,TO}$$

If e.g. the fuel mass fraction for a flight phase is 0.994, then at the end of that flight phase the aircraft mass is 0.6 % less than at the beginning of the very same flight phase. The total sequence of flight phases is given in Figure A.1.

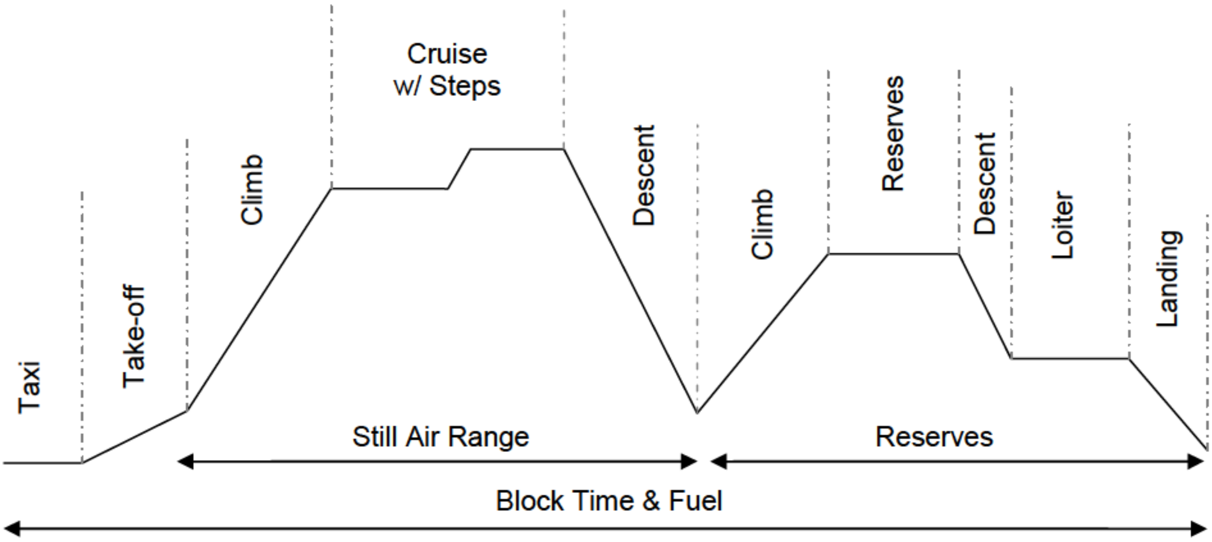


Figure A.1: Sequence of commercial flight phases consisting of a normal flight carried on to an alternate airport

Let us combine the mission segment fuel mass fractions that are concerned with take-off, climb, descent and landing. The fuel consumed in these flight phases cannot be calculated from Brequet but is given from experience

$$M_{ff,LTO} = M_{ff,TO} \times M_{ff,CLB} \times M_{ff,DES} \times M_{ff,L} \times M_{ff,CLB} \times M_{ff,DES} \quad .$$

The other mission segment fuel mass fractions for which the fuel consumed can be calculated from Breguet are combined to

$$M_{ff,CR-RES-LOI} = M_{ff,CR} \times M_{ff,RES} \times M_{ff,LOI} \quad .$$

By definition both newly defined fuel mass fractions multiplied give

$$M_{ff} = M_{ff,LTO} \times M_{ff,CR-RES-LOI} \quad .$$

Substituting this into the original fuel mass fraction equation;

$$M_{ff,LTO} \cdot M_{ff,CR-RES-LOI} = \frac{m_2}{m_1}$$

which is re-arranged to give

$$M_{ff,CR-RES-LOI} = \frac{m_2}{m_1 \cdot M_{ff,LTO}} \quad .$$

We now apply the general equation A.1 for *B*, which in this full case is

$$B = \frac{R_{CR} + R_{RES} + V_{LOI} \cdot t_{LOI}}{\ln\left(\dfrac{M_{ff,LTO} \cdot m_1}{m_2}\right)} \quad . \qquad \text{(A.4)}$$

$$R_{RES} = k_{RES} \cdot R_{CR} + R_{ALT}$$

The required reserves follow from **FAR Part 121** and **CS-OPS**. **FAR Part 121** requires for

International reserves: k_{RES} = 0.10 (according to **CS-OPS** also lower e.g. 0.05)
t_{LOI} = 1800 s
R_{ALT} = 200 NM = 370400 m (for passenger aircraft with $n_{PAX} > 100$)
Domestic reserves: k_{RES} = 0
t_{LOI} = 2700 s
R_{ALT} = 200 NM = 370400 m (for passenger aircraft with $n_{PAX} > 100$)

The numerator in A.4 contains the total range flown with the fuel

$$m_F = \left(M_{ff,LTO} \cdot m_1\right) - m_2$$

given as fuel mass fraction in the log-function. Note, the flight phases (abbreviated LTO) that cannot be calculated with Breguet have been taken out from considerations.

The fuel mass fractions for each segment of the LTO cycle were calculated as 0.994, which when combined (0.994^6) give us

$$M_{ff,LTO} = 0.95929 \quad .$$

B is calculated at three points in the payload-range diagram:

- Point 1: range at maximum payload / maximum payload
- Point 2: maximum range / payload at maximum range
- Point 3: ferry range / zero payload

$$B_1 = \frac{R_1 + R_{RES} + V_{LOI} \cdot t_{LOI}}{\ln\left(\frac{M_{ff,LTO} \cdot m_{MTO}}{m_{MZF}}\right)}$$

$$m_{MZF} = m_{OE} + m_{MPL}$$

$$m_{F1} = m_{MTO} - m_{OE} - m_{MPL} = m_{MTO} - m_{MZF}$$

$$B_2 = \frac{R_2 + R_{RES} + V_{LOI} \cdot t_{LOI}}{\ln\left(\frac{M_{ff,LTO} \cdot m_{MTO}}{m_{MTO} - m_{MF}}\right)}$$

$$m_{F2} = m_{MTO} - m_{OE} - m_{PL2}$$

From point 2 to point 3 the aircraft takes off with maximum fuel (MF) mass i.e. with full tank.

$$m_{MF} = m_{F2} = m_{F3}$$

$$B_3 = \frac{R_3 + R_{RES} + V_{LOI} \cdot t_{LOI}}{\ln\left(\frac{M_{ff,LTO} \cdot (m_{OE} + m_{MF})}{m_{OE}}\right)}$$

Linear interpolation is then taken to find *B* between point 1 and point 2 and between point 2 and point 3. B_1 is used for the entire range from zero to max payload range. The linear interpolation is calculated using;

$$B(r) = B_i + (r - r_i)\left(\frac{B_{i+1} - B_i}{r_{i+1} - r_i}\right)$$

Between point 1 and point 2: $i = 1$

Between point 2 and point 3: $i = 2$

A.4 Calculating Required Fuel Mass

Mission segment fuel mass fractions are calculated from A.1 for those flight phases where the Breguet equation can find an answer.

$$\frac{m_1}{m_2} = e^{\frac{R}{B}}$$

$$\frac{m_2}{m_1} = e^{-\frac{R}{B}}$$

For the three specific flight phases CR, RES, LOI

$$M_{ff,CR} = \frac{m_{DES}}{m_{CR}} = e^{-\frac{R_{CR}}{B}}$$

$$M_{ff,RES} = \frac{m_{DES}}{m_{RES}} = e^{\frac{R_{RES}}{B}}$$

$$M_{ff,LOI} = \frac{m_L}{m_{LOI}} = e^{\frac{V_{LOI} \times t_{LOI}}{B}}$$

The fuel fraction for a standard (STD) flight is

$$M_{ff,STD} = M_{ff,L} \times M_{ff,DES} \times M_{ff,CR} \times M_{ff,CLB} \times M_{ff,TO}$$

The fuel remaining (REM) onboard is

$$M_{ff,REM} = M_{ff,LOI} \times M_{ff,DES} \times M_{ff,RES} \times M_{ff,CLB}$$

The taxi-out fuel is neglected because the maximum mass of the aircraft is considered the maximum take-off mass which the aircraft is allowed to carry when it is lining up on the runway. The aircraft has a higher mass on the apron call the taxi mass to allow for sufficient taxi fuel.

With A.3 we finally calculate the standard (STD) fuel consumption of the aircraft (without reserves)

I) For range between point 1 and point 3:

$$\boxed{m_{F,STD} = m_{TO}\left(1 - M_{ff,STD}\right) \quad . \qquad \text{(I)}}$$

Between point 1 and point 2: $m_{TO} = m_{MTO}$

Between point 2 and point 3: $m_{TO} = m_{OE} + m_{MF} + m_{PL}(R)$

II) For range *R* on the left of point 1 the take-off mass m_{TO} is initially unknown. From A.2

$$m_F = m_1 - m_2$$

$$\frac{m_F}{m_2} = \frac{m_1}{m_2} - 1$$

$$m_F = m_2\left(\frac{1}{M_{ff}} - 1\right)$$

$$m_{F,REM} = m_{MZF}\left(\frac{1}{M_{ff,REM}} - 1\right)$$

This left over fuel is the reserve fuel that contains the fixed amount of reserve fuel and the variable amount of reserve fuel that depends on distance flown in cruise. The total fuel used is

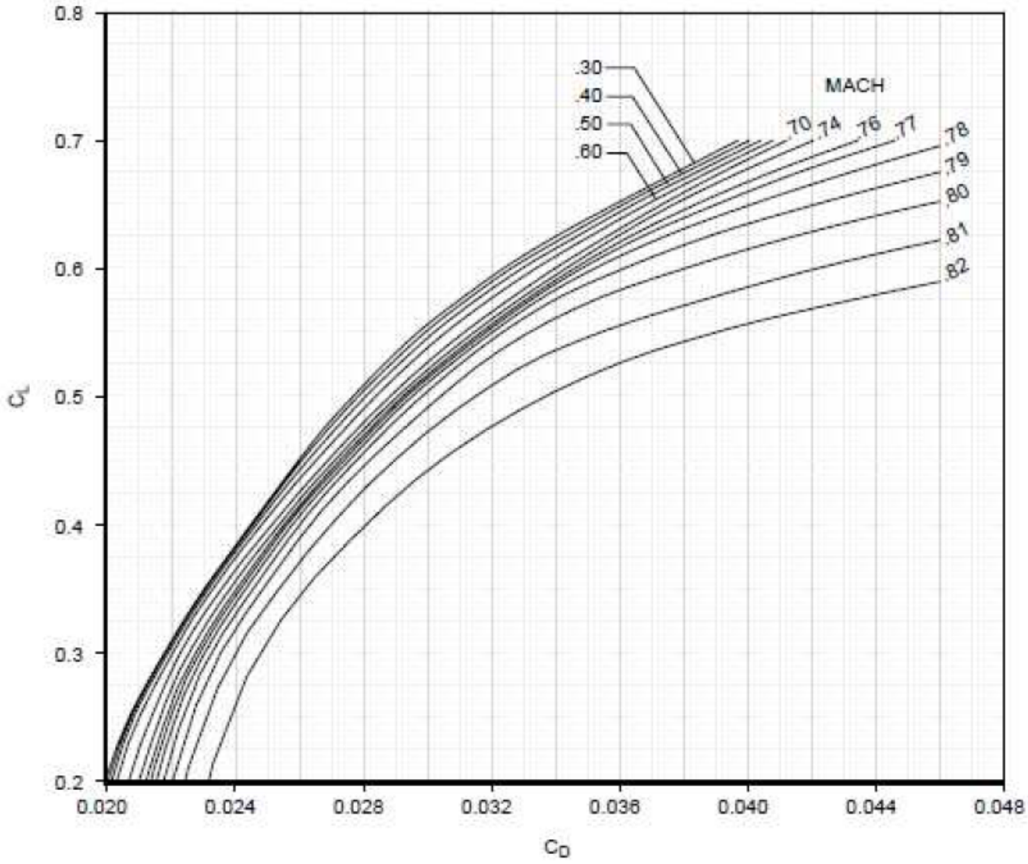
$$m_{F,TOTAL} = m_{MZF}\left(\frac{1}{M_{ff,TOTAL}} - 1\right)$$

and

$$m_{F,STD} = m_{F,TOTAL} - m_{F,REM} \quad . \qquad \text{(II)}$$

Appendix B - Boeing 737-800 Drag Polar

High Speed Drag Polar
Mid-Cruise CG (26.2% MAC)
Nominal Reynolds Number Schedule



Appendix C – Hermann SFC Estimation Method

C1 - Hermann 2011 Fuel Consumption Estimation

$$c = \frac{0.697\sqrt{\frac{t}{t_0}}(\phi - \vartheta - \frac{\chi}{\eta_{comp}})}{\sqrt{5 \times \eta_{diffuser} \times (1 + \eta_{BT} \times BPR)(G + 0.2 \times Ma^2 BPR \frac{\eta_{comp}}{\eta_{BT}}) - Ma \times (1 + BPR)}}$$

Parameter *G* is given by;

$$G = (\phi - \frac{\chi}{\eta_{comp}})\left(1 - \frac{1.01}{\eta_{Comp}^{\frac{\kappa-1}{\kappa}}(\chi - \vartheta)(1 - \frac{\chi}{\phi \times \eta_{Comp}\eta_{Turb}})}\right)$$

Where is the ratio of Turbine Exit Temperature to aircraft ambient temperature;

$$\phi = \frac{TET}{T(h)}$$

Parameter *G* is given by;

$$\vartheta = \frac{T}{t} = 1 + \frac{\kappa - 1}{2} Ma^2$$

Parameter *x* is given by, where OAPR is the compressor *Overall Pressure Ratio*;

$$\chi = \vartheta\left(OAPR^{\frac{\kappa-1}{\kappa}} - 1\right)$$

Diffuser efficiency is estimated using;

$$\eta_{diffuser} = 1 - \frac{0.7Ma^2(1 - \eta_{Nozzle})}{1 + 0.2Ma^2}$$

Arbitary efficiency *BT* is the combined nozzle and turbine efficiencies;

$$\eta_{BT} = \eta_{Nozzle} \times \eta_{Turbine}$$