Optimisation of the Aircraft Cost Index for Air Travel Emissions Reduction

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

The aviation industry is facing a tough challenge to achieve carbon neutral growth from 2020. The industry's emissions continue to grow at a substantial rate, spurred by a 5% per annum increase in demand and a lack of large scale solutions to reduce its dependence on oil.

A promising mitigation measure is the use of the Cost Index (CI) tool, its purpose being to balance the cost of time and the cost of fuel. The faster the flight, the more fuel is used and therefore costs increase. However, slower flights increase time-dependent costs, such as crew and maintenance costs. The CI value is entered into the aircraft flight management system to determine the speed of the flight.

Analysis from this thesis reveals that CI could result in emissions savings of at least 1% on a flight-by-flight basis, comparable with other measures that can be implemented in the short-term. However, evidence suggests that airlines are currently misusing or miscalculating their CI values, resulting in higher costs and emissions.

The aim of this thesis is to develop a novel method of calculating CI to make it practical and easy to use for airlines on a day-to-day basis. This was done by undertaking multiple CI calculations for different flight parameters and finding the CI value which minimises costs. This takes into account time-dependent costs, fuel costs and any carbon pricing to be applied, as well as any costs relating to passenger delay.

The model also has a dual purpose of helping in the understanding of future impacts on an individual flight basis. It is found that in general the CI follows trends in jet fuel costs. However, when delay is added this has the most significant impact on the CI. Conversely, the addition of a carbon price, which is a key policy strategy in the industry to reduce emissions, had a negligible effect on the CI and resulting emissions. Future policy will need to recognise that these flight-by-flight interactions are important in order to find solutions that lead to meaningful CO_2 reductions in the industry.

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List of Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
BtL	Biomass-to-Liquid
CCC	Committee on Climate Change
CDM	Clean Development Mechanism
CI	Cost Index
CNS	Communication, Navigation and Surveillance
CO_2	Carbon Dioxide
CTA	Controlled Time of Arrival
CtL	Coal-to-Liquid
DCI	Dynamic Cost Index
DECC	Department for Energy and Climate Change
ETC	Estimated Time of Arrival
EU	European Union
EUETS	European Union Emissions Trading Scheme
FMC	Flight Management Computer
FMS	Flight Management System
GNSS	Global Navigation Satellite System
GtL	Gas-to-Liquid
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation

IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LRC	Long Range Cruise
MBM	Market-based Measure
MRC	Maximum Range Cruise
MRO	Maintenance, Repair and Operations
NM	Nautical Miles
OCI	Optimised Cost Index
SESAR	Single European Sky Air Traffic Management Research

Chapter 1 Introduction

1.1 Overview

The aviation industry has grown considerably over the past 50 years. Providing one of the only transportation system that can make global business and tourism possible, the industry's total economic impact is estimated at $2.4 trillion. Carrying approximately 3.3 billion passengers and 51.7 million tonnes of freight in 2014, the industry is responsible for 35% of interregional exports of goods in value and 53% of international tourist travel. The industry has created 8.7 million direct jobs and a total of 58.1 million jobs worldwide, including indirect jobs from its supply chain and impact on tourism (IATA, 2015a).

Aviation also has a number of social benefits. It provides a wide choice and affordable access to destinations across the globe, which helps broaden people's cultural and leisure experiences. It can help to alleviate poverty and improve living standards through tourism and can often be the only means of transport to connect remote areas. Aviation also has a role in delivering emergency and humanitarian aid relief, as well as the swift delivery of medical supplies (IATA, 2015a).

But these benefits must also be weighed against the environmental issues that the industry contributes to. Noise and air quality issues have been in public eye for a number of decades, but it was not until the late 1990s that aviation's impact on climate change started to receive significant attention, with the release of the Intergovernmental Panel on Climate Change's Special Report on Aviation Emissions (IPCC, 1999). Emissions were thought to account for 2% of anthropogenic carbon dioxide emissions in 1992, with the prediction that these emissions would be 1.6 to 10 times higher by 2050. Emissions now account for about 3% of the total, but this proportion is set to become far greater in the future because of a lack of technological solutions to reduce emissions.

The following background explains further the issue of climate change and aviation and the mitigation options available. The aims and objections of the thesis in the context of using the Cost Index (CI) to reduce emissions are then discussed.

1.2 Climate Change and Aviation

Aviation emissions directly result from the amount of fuel burned by an aircraft. They are unique in that they are directly emitted into the upper troposphere and lower stratosphere, where they are subject to changes through interaction with the background atmosphere.

Figure 1-1 shows the emissions thought to relate to climate change that results from the combustion of jet fuel. CO_2 emissions are the most important because they have the greatest impact on the greenhouse effect, with the exception of water vapour. Whilst aircraft do also emit water vapour, the amounts emitted from combustion are only small compared to background levels in the lower stratosphere and it is only resident in the atmosphere for nine days, compared to a residence time for CO_2 of 30-95 years (Lee et al., 2009, Wuebbles et al., 2007).

Nitrogen Oxides (NO_X) are also emitted during the combustion cycle of jet turbines and whilst not greenhouses gases themselves, have an indirect impact through the formation of other greenhouse gases, producing ozone and decreasing the amount of methane in the atmosphere. Whether these two processes counteract each other, produce an overall warming effect or an overall cooling effect is still uncertain (Derwent et al., 2001, Stevenson et al., 2004, Wild et al., 2001).

When the right meteorological conditions are in place, an aircraft can create contrails directly and then, as they dissipate, create cirrus clouds. Whilst these are very common in areas where there is a high density of flight paths, owing to advection they can also be found in regions without any significant air travel. The overall effect can be one of both negative and positive radiative forcing; the former the result of the reflection of incoming solar radiation and the latter the result of absorption of infrared radiation from the earth's surface (Daley, 2010, Maurice and Lee, 2009). However, there is still significant uncertainty regarding the non-CO_2 emissions.

It is anticipated that these emissions will continue to see significant growth in the future as the aviation industry continues to grow at a substantial rate. Despite a number of crises that have impacted the industry since the 1950s, the industry has still seen an increasing rate of growth to present. Under the most Likely scenario world passenger traffic is set to grow from five billion to more than 13 billion revenue passenger kilometres between 2010 and 2030, at an average annual rate of 4.9%. This is expected to only reduce to 4% per annum between 2030 and 2040 (ICAO, 2013a).

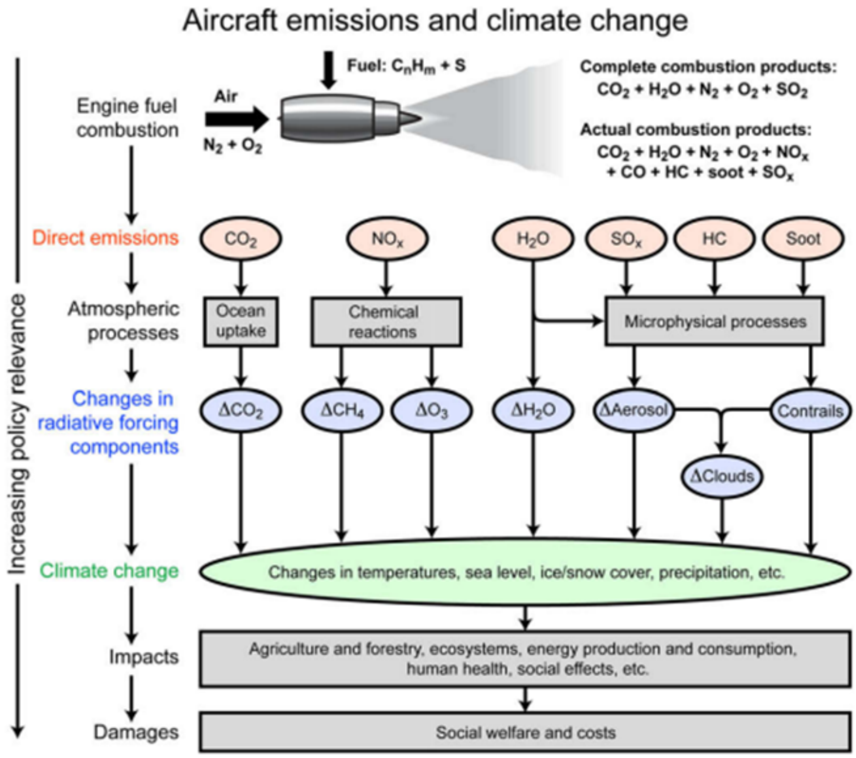

Figure 1-1 Emissions released during aircraft fuel combustion and their resulting potential impacts on climate change and welfare loss (Lee et al., 2009).

Emissions will not grow at the exact same rate as demand because new models of aircraft entering the fleet tend to have better fuel performance. However, new models of aircraft are not produced frequently because of the investment costs and the long lifetime of aircraft. Even when airlines do turn over fleets more quickly, they still tend to sell on the retired aircraft to other airlines, and therefore overall emissions may not be reduced. Another reason why this growth is not completely mirrored is that airlines are achieving better load factors of aircraft. However, with limited application of mitigating measures, emissions are set to follow a very similar trend (Lee et al., 2009)

Figure 1-2 shows the International Civil Aviation Organisation's (ICAO, 2013a) projections for CO_2 emissions to 2050, with the proportion of global fuel consumption consumed by aviation in 2050 expected to reach 70% and have increased by four to six times the 2010 value. It is also evident that even with the application of mitigation measures; there will still be a gap of 1,039MtCO_2 in 2050 compared to the target of stabilising emissions at 2020 levels. ICAO believe It is unlikely that this gap can be closed by more than 25% with the use of biofuels.

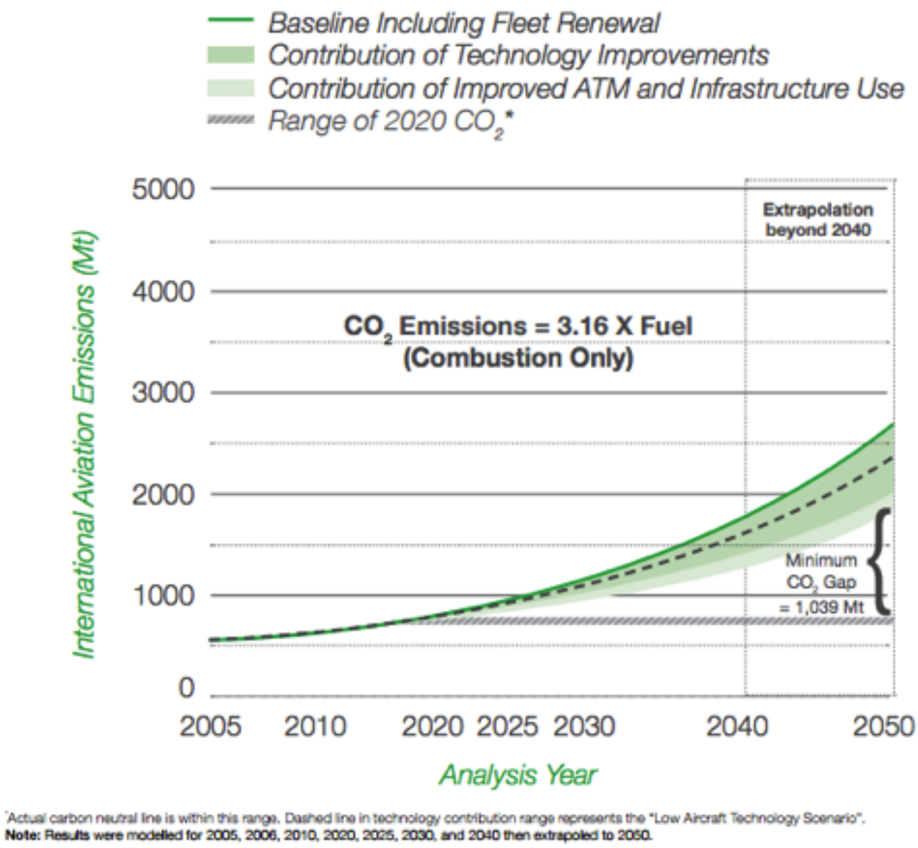

Figure 1-2: Projections for CO_2 emissions from aviation to 2050 (ICAO, 2013a)

As Lee et al. (2013) state, a key issue in reducing aviation emissions is the timing of mitigation and the end point emissions "matter far less than the 'pathway' or 'trajectory'". This is not appreciated when considering policy and climate targets, but "this concept is absolutely critical if the most cost-effective, and climate effective mitigation options are to be pursued". The analysis the Lee et al. (2013) shows that early emission reductions result in greater environmental benefits in terms of real response even if the same emissions target is reached at the same time using measures later on.

There are three key areas of climate mitigation in aviation. The first is technological improvements, such as improving aerodynamic efficiencies, weight reduction in aircraft, improving engine efficiencies and the introduction of alternative aviation fuels. The second is operational and infrastructure improvements which include streamlining air traffic management, improving airport operations and implementing new procedures, such as continuous descent for aircraft. The final area is using market-based measures, such as offsetting or carbon credits in order to put a value on carbon emissions and incentivise reductions in the aviation industry or in other sectors.

Whilst these mitigation measures will help to reduce emissions, as already stated there is still an emissions gap to stabilisation at 2020 levels. Unlike other areas, such as road transport, which has the potential to become completely electrified, there is no measure available for aircraft to reduce emissions to anything close to zero at present. In theory, the use of biofuels offers the biggest reductions in CO_2 emissions, but in reality their use is marred by a range of substantial technical, environmental and social challenges. With early mitigation measures being needed, biofuels will not be able to provide any significant contribution to emissions reduction in the near future.

The industry is therefore reliant on using a basket of smaller measures to help reduce emissions in the short to medium term. ICAO (2013) state that a technology improvement of less than 2% per annum is expected, whilst there is a goal for a 3.25% operational improvement by 2020. At present the earliest a market-based measure can be expected to affect the global industry is 2020, although a carbon price already impacts European airlines.

There is one measure that is seldom mentioned in emission reduction mitigation strategies, which could provide a very promising short-term, cost effective mitigation measure. The measure is optimisation of the Cost Index (CI) of an aircraft and is the focus of this thesis.

1.3 The Cost Index

The CI is a tool that has been available in commercial aircraft since the late 1970s and was introduced as a means for airlines to manage their fuel use (DeJonge and Syblon, 1984). The purpose of the CI is to determine the speed of an aircraft that results in the minimum cost of the flight. This is done by balancing fuel and time-dependent costs. Time-dependent costs include anything that has a flight minute cost associated with it, such as maintenance and crew costs, plus any passenger costs related to flight delay.

Essentially, the faster an aircraft is flown the lower its time-dependent costs will be. However, faster aircraft also result in higher fuel use and therefore fuel costs (Figure 1-3). The CI is calculated by dividing the cost of time with the cost of fuel. This value is then entered into the flight management computer (FMC) on departure by the pilot. The FMC uses the value along with other flight parameters for that particular day, such as wind speed and altitude, to determine the speed of the flight. The CI typically has the units of either kg/min or 100lb/hour depending on the FMC being used and can range from between 0-999 and 0-9999 depending on the system (Roberson, 2007).

The lowest CI value seen in Figure 1-3 of zero represents the maximum range cruise (MRC) of an aircraft. This is where the best fuel consumption is achieved, but would only be used where there were no time-dependent costs. From the MRC the CI represents the cost of fuel for every unit increase in flight time. If fuel costs were unimportant the max CI of the aircraft would be chosen. Even though theoretically the CI can range up to 999 or 9999, in reality the maximum speed of the aircraft is reached before this.

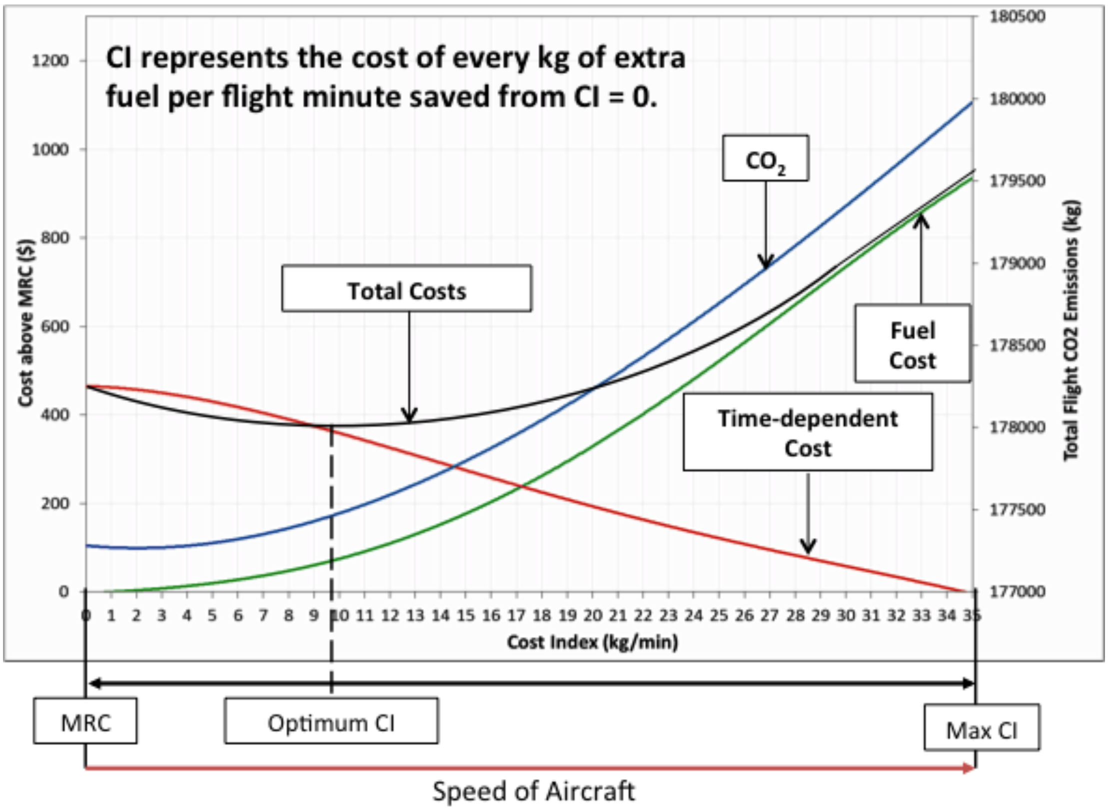

Figure 1-3: Optimum CI in relation to time and fuel costs for speeds between MRC and Max CI

However, there is evidence that airlines do not use the CI in the way intended. Airbus (1998) reports a wide variety of uses for CI and highlights the mistake made by many airlines in using CI as a speed control tool rather than one for trip cost or mission optimisation, as intended. As Burrows et al. (2001) state there is substantial evidence of airlines making elementary errors or using questionable assumptions in their calculation of CI values, resulting in airlines failing to exploit its full economic potential. Evidence gained from interviews with industry professionals for this study suggests that this is still an on-going problem. This sub-optimisation in the use of CI is not only likely to have financial impacts on airlines, but also results in higher CO_2 emissions than necessary being released on a flight-by-flight basis.

With increasing concerns over the impact that airlines are having on climate change, as well as increasing concerns about fuel costs, the CI could be a valuable tool in mitigation. It is one of the few measures that can be implemented on a very short time scale, with CI capability already present in most commercial aircraft, and its optimisation is likely to be very cost effective. It is therefore a prime candidate for the early savings that Lee et al. (2013) deem necessary to avoid the more damaging environmental impacts of aircraft emissions.

1.4 Research Aims and Objectives

The aim of this thesis is better understand the CI and find a way for airlines to optimise its use on a flight-by-flight basis. This thesis is approached with the intention of providing a practical solution for airlines in reducing their emissions and to provide a method with the potential for quick real-world application.

This will include the following objectives:

1. Understand the workings of CI, how it is currently used by airlines, its inputs and the barriers to its optimum use.
2. Examine how changing the optimum CI affects CO_2 emissions from air travel for different aircraft models, within the context of fuel use and flight time relationships at different flight distances.
3. Create a new model to provide more comprehensive calculation of the CI for airlines.
4. Use the new model to explore the sensitivity of CI to different inputs and provide future scenario analysis.
5. Provide policy recommendations and future research needs in the area of CI.

This research draws on the available literature in the area of CI, as well as the wider context of challenges within the aviation industry. Existing literature concerning CI is not comprehensive and therefore this thesis also draws from informal interviews with airline personnel from operations, engineering and environment departments. Whilst most studies concerning the CI to date have looked at small elements of its use, such as delay management, this thesis takes a much broader view of its potential optimisation. The model created will be the first of its kind with a more sophisticated calculation method, which goes beyond the simple equation, which currently exists. The thesis will also demonstrate the added value of CI in assessing future impacts on the industry, providing a flight-by-flight analysis which can aid policy and research development, something that has not been done to date.

1.5 Overview of Thesis

Each of the above aims will be dealt with in individual chapters. Chapter two will examine the potential for CI to reduce carbon emissions and by how much. This will help to provide the purpose for pursuing this area of research in terms of mitigation of the sector's climate change impacts.

Chapter three focuses on the cost factors, which affect the calculation of the optimum CI value. This takes into account both current and future costs, as well as those currently not included in typical CI calculations. Some of the barriers in calculation of these costs are also addressed.

Chapter four uses the information gathered on costs from chapter three to create a new model for calculating CI, termed the Optimised Cost Index (OCI) model. This chapter describes the processes involved in its formation and how airlines can use it in a practical way.

Chapter five uses the OCI model to test the impact that future scenarios could have on the CI and the resulting flight parameters. The scenarios are made up of impacts such as a change in jet fuel price, the application of efficiency improvements, the introduction of biofuels, changes in time-dependent costs and the impact of flight delay.

Chapter six provides suggestions for further work. This includes adjustment of the OCI for different uses by airlines, understanding of the network effects that CI can result in and recommendations regarding the results of the study in the context of wider climate change policy.

Chapter seven provides a summary of the thesis and the key conclusions.

Chapter 2 Literature Review

1.1 Introduction

The previous chapter highlighted the key areas that this thesis intends to examine and develop. This chapter will build on the foundation for this by assessing the literature in the area of CI and where it sits in the context of wider mitigation of climate change in the aviation industry. Literature examining the use of CI at present, the problems that exist with its use and the important cost inputs for calculation of CI are presented.

2.1 The CI in Context of Climate Change Mitigation for Airlines

Whilst other sectors are making headway with reducing their CO_2 emissions, the aviation industry is experiencing an increase in pressure to do so themselves. There are a number of options for mitigating the climate impacts of air travel which fall broadly into four categories:

- Airframe and engine technologies
- Improvements in Operations
- Alternative Fuel
- Economic Measures

There are various time scales for implementation associated with these measures, with aircraft and efficiency improvements offering some mitigation in the short term, to alternative fuels and new aircraft design offering larger reductions in emissions in the longer term.

2.1.1 Mitigation Measures

2.1.1.1 Airframe and Engine Technologies

Since the 1970s there has been a reduction in the energy intensity of aircraft by around 60%. These efficiency improvements are anticipated to continue, albeit at the slower rate (Committee on Climate Change, 2009). Commercial aircraft have primarily been powered by gas turbine engines for over half a century, seeing significant improvements in their use during this time. Slight improvements can continue to be made through thermal and propulsion efficiencies, but significant improvements in this area are hindered by technical constraints. In the future a more significant step in fuel efficiencies will need to be provided by new engine architectures (IATA, 2013a, Lee, 2003).

In general there are three engine technologies that are being considered for the future. The first is the advanced high bypass turbofan, which is due to be available from 2016. This could reduce fuel consumption by 16% with improvements in all technology areas including new materials, advanced combustion technologies and breakthroughs in aerodynamics. The second is geared turbofans with application for narrow-bodied commercial aircraft from 2013, with a potential 15-20% improvement in efficiency. The final design is the open rotor, which are gas turbines driving two high-speed propellers moving in opposite directions to one another, with these engines offering 25-30% reductions in fuel use (ATAG, 2010).

An important parameter in the choice of engine technology is the trade-off between fuel efficiency and NO_X emissions and noise. For example, increasing combustion temperatures and operating pressures will lead to an increase in NO_X although fuel efficiency will be increased, whilst for the measures that reduce NO_X, the opposite is true (Lee, 2003). There are also issues with noise for new engine designs such as open-rotor engines (Farriers and Eyers, 2008).

In terms of aerodynamic efficiency of aircraft there is a similar story of options for retrofitting existing aircraft compared with new technologies with greater improvement in efficiencies coming from new aircraft designs. Retrofits include wingtip devices, drag reduction coatings and natural and hybrid laminar flow technologies. Future aircraft designs include the strut braced wing, which uses structural supports to allow for large span wings without a significant increase in weight of the aircraft, and the hybrid wing body, which aims to improve fuel efficiency through the elimination of the tail section of the aircraft (IATA, 2013c).

However, like engine improvements, aerodynamic improvements also face a number of challenges in implementation. The addition of weight to the aircraft is an issue as this can counteract emissions savings and there is a fundamental issue is using completely new aircraft designs in that there is significant uncertainty in market deployment. This is a symptom of aircraft having long economic lifetimes of up to 30-40 years and therefore penetration of new designs is very slow, even when airlines do take risks on new aircraft (Åkerman, 2005).

The final area concerning airframe and engine technologies is the use of new materials. With every new generation of aircraft there has been an increase in the use of composite materials. For example when the Boeing 777 entered into service in 1997 it had a composite make-up of just 12%, whilst the newer Boeing 787 Dreamliner is made up of 50% composites (Farriers and Eyers, 2008). Whilst most damage and strength critical structural components of current aircraft are made with aluminium, new materials include aluminium-lithium alloys with lower density and higher bending strength; advanced titanium alloys with a high strength-to-weight ratio, good damage tolerance and corrosion resistance; aluminium-magnesium-scandium alloys with excellent corrosion resistance; hybrid alloys; and advanced composites composed of two or more distinct materials in the form of fibre or matrix for improved reinforcement and weight reduction. Whilst new materials show some promise in reducing emissions, the key issue with their use is affordability (IATA, 2013a).

2.1.1.2 Improvements in Operations

Issues concerning air traffic management (ATM) are currently being examined by two major programmes, NextGen in the USA and the Single European Sky Air Traffic Management Research (SESAR) project in Europe. ATM relies strongly on communication, navigation and surveillance (CNS) technologies. Many of those currently being used are fairly antiquated, but there are a number of new technologies, which could be implemented for improved operations. These include:

- Digital data-links to replace voice communications
- Global Navigation Satellite Systems (GNSS) to provide a global navigation infrastructure with the potential to also replace 2D instrument landing systems with 3D precision approaches.
- Automatic Dependent Surveillance Broadcast (ADS-B) that enables aircraft to broadcast there position, as well as display the position of other aircraft in the area. This allows for greater situational awareness with better potential for spacing and merging of aircraft.

The successful implementation of these technologies will rely heavily on up-front investment in avionics, as well as development of policies and procedures amongst numerous stakeholders, with the expected cost of these developments under SESAR and NextGen being $40 billion (IATA, 2013a).

As well as general improvements in efficiency in the system, the use of these technologies can help to enable the use of new operational procedures, such as continuous descent approaches and performance based navigation concepts.

2.1.1.3 Alternative Fuels

Finding an alternative fuel to kerosene is the only way in which emissions can be reduced to zero. However, finding this alternative is proving particularly difficult. Unlike other transport sectors, such as road transport that can make use of electric vehicles, there are limited options for aircraft owing to a number of complicating factors such as strict fuel specifications and the weight of the aircraft. A number of options have been explored including powering aircraft by hydrogen, solar and nuclear technologies. These options are marred at present by extreme technical difficulties, although hydrogen is still seen as a potential replacement post 2050. The most realistic and popular fuels for development in the medium to long term are "drop-in" fuels, which require only slight modification to existing aircraft.

There are two types of drop-in fuels, the first being synthetic fuels. These fuels are made from coal and natural gas via the Fischer-Tropsch process, in which syngas is converted to higher molecular weight hydrocarbons. The process of coal-to-liquid (CtL) has already seen significant development in South Africa since its first use there in the 1950s. Natural gas-to-liquid (GtL) has come about comparatively recently with the first commercial plant built in 1993 (Vera-Morales and Schafer, 2008).

However, most attention has been paid to the use of biofuels-to-Liquid (BtL) fuels. This is because in terms of CO_2 emissions, biofuels are the only source, which results in lower emissions than current jet fuel (Figure 2-1). As first generation biofuels are unsuitable for use in aircraft, the industry has looked towards second and third generation biofuels for a source of aviation fuel. Feedstocks that can be used include switch grass, jatropha, camellia and algae.

However, BtL production technology is still relatively immature and supplied less than 0.1% of the world's biofuel supply in 2010 (Sims et al., 2010). There are also a number of issues with the use of biofuels, such as sustainability and land use, which are discussed in Chapters 5 and 6. These issues could significantly constrain the use of biofuels in the future and the extent of their use in the future is still very uncertain.

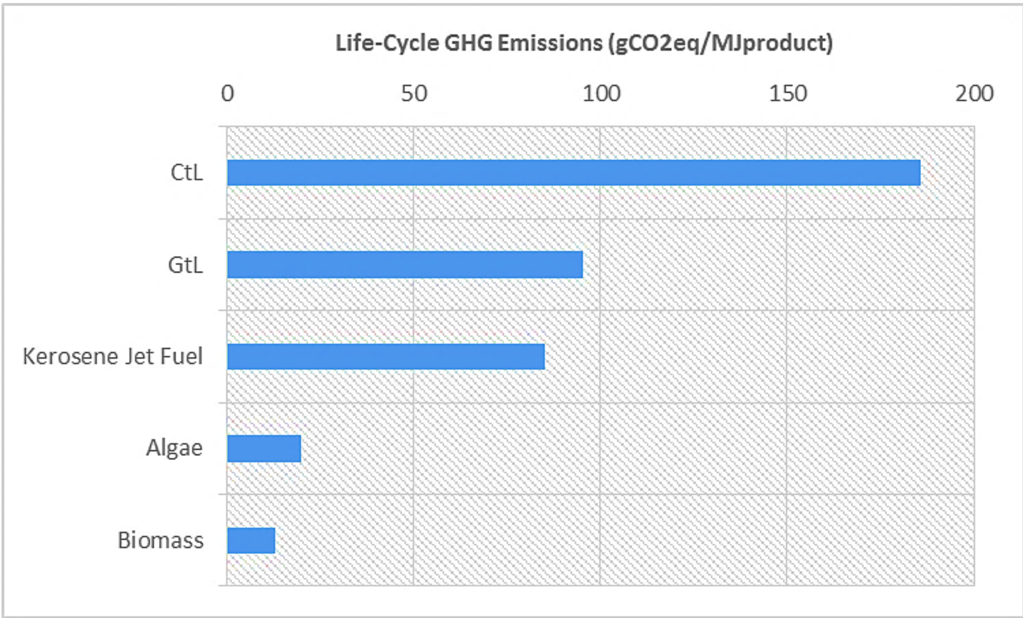

Figure 2-1 Lifecycle greenhouse gas emissions of aviation fuel (Data Source: Vera-Morales and Schafer, 2008)

2.1.1.4 Economic Measures

The final measure under consideration is a global market-based measure (MBM). This can include offsetting mechanisms, positive economic incentives and public-private investments. The main focus of economic measures at present is the implementation of a new global MBM under ICAO to be implemented from 2020. It is hoped that this will incentivise technological innovation in the industry, but also provides the option for airlines to offset their emissions through reductions in CO_2 in other sectors. This is discussed in further detail in Section 2.3.4.5.

2.1.2 Summary of Mitigation Measures

Whilst there are a range of mitigation measures available for use in the aviation industry, there are also a number of obstacles in the way of achieving reductions in CO_2. It is clear that there is no single solution, which could significantly reduce emissions, and therefore a variety of measures will be needed for more significant reduction. There is also the question of how quickly measures can be implemented, with early measures being needed for higher environmental benefits (Lee et al., 2013). Figure 2-2 demonstrates that significant reductions in emissions of more than 25% cannot be achieved before 2020. More importantly, there are only a small amount of emissions savings that can be made with measures that show technological readiness by retrofitting existing aircraft.

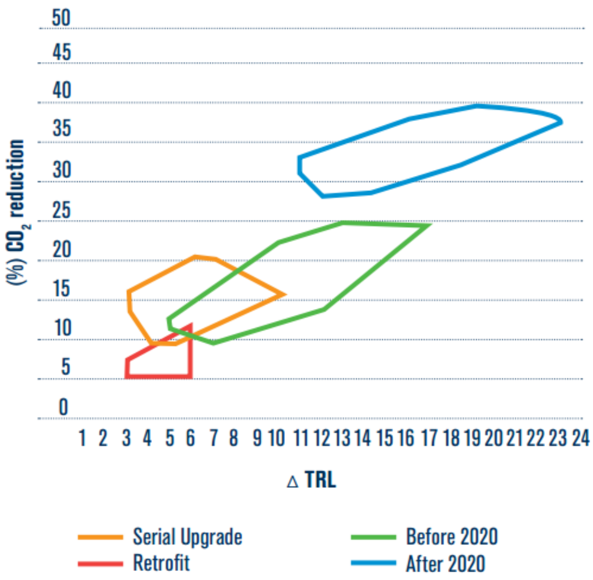

Figure 2-2: Range of CO_2 reduction potential as a function of technology readiness levels (TRL) - TRL 1 = high technology readiness, TRL 24 = low technology readiness (IATA, 2013a)

There are only a few technological measures that will be available in the short term i.e. very likely before 2020. These include active load alleviation, lightweight cabin interiors, primary composites, winglets and structural health monitoring. Table 2-1 shows the fuel, and therefore CO_2 savings, that could be made from the implementation of these measures. For the easier retrofit options emissions savings are generally only around 1%, although this can rise to 5% or 6% for weight reduction and wingtips. For other measures that may be implemented before 2020 fuel savings are similar between 1% and 5%.

In terms of other emissions reduction measures, ICAO (2013a) estimates that there could be a 3.25% improvement in operations by 2020, whilst economic measures and alternative fuels are still in development, therefore are unlikely to have a significant global impact until post 2020.

This suggests that the Cost Index, which is already available on-board aircraft and can be implemented in a short space of time, could be a key addition to this set of measures, particularly as it is not currently accounted for in most emission reduction assessments. The amount of emissions savings that can be expected from optimisation of CI values is discussed in Chapter 3, but on average they sit in the range of savings seen in Table 2-1 and potentially higher in some cases.

Table 2-1: Pre-2020 aircraft technology implementation (Data Source: IATA, 2013a)

Technology	**Availability of Technology**	**Fuel Reduction Benefits**
Retrofit		
Wingtips	2012	1 to 6%
Drag Resistant Coatings	2012	1%
High Powered LEDs for cabin lighting	2012	<0.5%
Wireless/Optical connections for Inflight-Entertainment	2012	<0.5%
Lightweight cabin interiors	2012	1 to 5%
Zonal dryer	2012	<1%
Before 2020		
Variable Camber	2015	1 to 3%
Active Load Alleviation	2012	1 to 5%
Composite Secondary Structures	2012	<1%
Landing Gear Drive	2015	1 to 2%
Adjustable Landing Gear	2015	1 to 3%
More electric aircraft architecture	2015	1 to 5%
System health monitoring	2015	1 to 4%

2.2 The Use of CI

There is limited academic literature concerning the use of CI, although studies have been undertaken since the 1980s. Some of the first work to be carried out was by Liden (1985) with analysis of the relationships between fuel use, flight time and direct operating costs. This included simulations but was constrained by the lack of computing power. However, interesting insights are gained by looking at the results.

The first thing to note is that changes in CI do not produce a linear relationship between flight times and fuel use. Liden's study showed that near the low CI values sizable variations could occur with only a negligible effect on total costs. On the other hand at higher CI values where the relationship curve becomes steeper, higher savings in fuel use and cost can be achieved with changes in CI, with smaller increases in flight time. Despite the age of this study it is still one of the most comprehensive assessments of the relationships regarding CI. However, with the improved computing power available today, there are more opportunities to assess these relationships on a larger scale.

Another early assessment of the use of CI came from DeJonge and Syblon (1984). This paper reviews the use of CI from the perspective of American Airlines, from its introduction as a fuel efficiency measure in the late 1970s. Evaluation of the fuel savings within scheduled flight times began in 1979 with a B727-200 aircraft flying with a CI of 40, a representation of the airlines minimum operating cost at the time. A fuel saving of 2.1% was achieved within scheduled flight time. However, this study does not state what the actual change in CI is.

The message of this study was that these savings were made before deregulation, which stimulated the use of hub operations, so only represent point-to-point operations. With hub operations came the need for “schedule integrity” being upheld, with a high degree of reliability in arrivals and departures being expected. The paper reports that American Airlines standards mandated that 65% of all arrivals operate within 5 minutes of schedule and 85% of departures should operate within 10 minutes of schedule with similar figures being used by other airlines. The value of DeJonge and Syblon’s study is in putting CI in the wider context of an industry reliant on tight schedules, which has become an even more important issue in recent years, moving planes through a narrow operating window with ever reducing capacities.

Studies on CI were not seen since these early papers until the late 2000’s. There are two reasons why this is likely. The first is that CI was originally introduced in the late 1970s to improve fuel efficiency in light of the oil crises at the time. However, once fuel prices became more stable it seems the importance of CI was lost somewhat. However, the late 2000’s again brought rising fuel prices, particularly with the 2008 oil shock. As already alluded to there have also been increasing problems with capacity in recent years as demand for air travel continues to grow on average at 5% per year (ICAO, 2013a). In this context many of the recent studies on CI have looked at it in terms of speed control, particularly in delay recovery.

One of the few studies that quantifies savings in fuel and CO_2 emissions from optimisation of speed profiles is that of Lovegren and Hansman (2011). Flight data was collected for 257 flights during one day for domestic US operations. Cruise fuel burn for each flight was calculated using Piano-X (an aircraft analysis software described in more detail on page 42) and atmospheric data from National Oceanic and Atmospheric Administration. The study designed improved speed and altitude profiles for these flights. The maximum fuel burn reduction for the combination of this optimisation was 3.5%. Overall a total system wide saving of 2.6% in fuel was calculated representing a reduction of 300 billion gallons of fuel and 3.2 billion tonnes of CO_2 annually.

Speed optimisation was found to have a greater effect than altitude optimisation at a fuel reduction of 2.4% compared to 1.5% respectively. The study also examined the savings if aircraft flew at long-range cruise (LRC) compared with full optimisation. Findings showed that many aircraft fly above this speed and a saving of 1.6% could be achieved by moving aircraft to this speed, a figure still higher than that of altitude optimisation. This is important as it is often assumed that aircraft fly at their LRC speed. As Liden (1985) shows, there is not a huge saving in fuel use between LRC and MRC, where optimum CI values generally lie, but above LRC reduction in CI can lead to significant savings in fuel.

Delgado and Prats (2009) find similar results to Liden (1985) that changing between smaller CI values does not have as significant an impact as when the change is from a higher CI value, by examining speed control in terms of fuel consumption. The study considers two different flights using the A320 and two typical routes within Europe. It is found that the desired CI has a big influence on the variations in fuel consumption, but higher CI values give a wider range of velocities, which can be flown without additional fuel consumption. The maximum speed reduction that can be achieved without having an adverse effect on fuel consumption is 7%, but this can increase to 15% when higher CI values are used.

Most of the other recent literature regarding CI is focussed on the issue of delay. This is an important area as CI in its current form does not take this into account and delay costs can be significant for airlines. There have been a number of suggestions as to how CI can be both used and adjusted to integrate delay. Liden (1985) added an arrival time error to the standard direct operating cost calculation, patenting the idea in 1986. However, there has been little development in the industry since this, although several other authors have also proposed a so-called "dynamic cost index" that would also take into account the cost of delay.

Cook et al. (2009) have undertaken the most comprehensive work regarding CI and delay and have produced one of the few studies to include environmental impacts in their analysis. The aim of the study has two parallel objectives; to map types of data required to build a generic, ideal dynamic CI (DCI) tool and to start building an operation prototype tool. The inclusion of environmental factors is an "acknowledgement that political position relating to emissions charges is uncertain, therefore a flexible framework" is needed to ensure both the DCI general model stays relevant should emissions charges be introduced and to allow airlines to consider their emissions in their decision making process in response to delay.

The plan was to create an "environmental decision support tool" and an "environmental signature" which provides support for collaborative decision-making between airlines and air traffic management both pre-tactically and during the flight. The considerations listed by the authors when using this as a fuel management tool include: assessment of route extension fuel penalties to reduce slot delays, avoidance of unnecessary extra fuel burn to recover delays, which are not financially worth recovering and accelerated fuel burn offsets from the potential for reducing off-stand holding at airports by freeing waiting aircraft from gates.

Related to this work there has been an in-depth assessment of the costs of delay in the context of labour, maintenance and passenger costs commissioned by Eurocontrol (2007-2008). This project produced marginal minute costs for delay for these factors for twelve different aircraft types and has helped to guide the calculations used in creating the new CI model for this thesis. However, this has not aided the understanding of how the use of a dynamic CI would affect fuel use and carbon emissions.

Mirosavljevic et al. (2012) also consider the DCI like the one discussed by Cook et al. (2009). It is found whilst positive in reducing the impact of flight delays, its application is limited. The decision must be approved by ATC and the negative impacts on fuel consumption cannot be ignored. In conclusion it is deemed that DCI could be helpful to airlines to tactically deal with the negative aspects of delay, but the concept requires great efforts by the airline by hiring new professionals and technical resources, as well as a reorganisation of the way the airline functions.

Understandably research has focused on using CI in delay recovery as an increasingly capacity constrained industry results in increasing costs for airlines in this area, as well as affecting passenger views towards certain carriers. However, its use in normal operations has received little attention despite its potential to reduce costs, as well as fuel use and carbon emissions. This may be a reflection of the lack of knowledge in the use of CI even by the airline operations departments responsible for its use. Additional hindrance results from the lack of data available and the fact that the CI used may be sensitive data that an airline may be unwilling to reveal.

Issues with the use of speed control have also been the basis for another handful of recent studies. The relationship between ATC and the use of CI is further explored by Rumler et al. (2010). In 2008 a safety alert owing to the range of speeds in airspace between identical aircraft types was issued by Eurocontrol. The authors describe how the lack of information regarding CI based flight-planning process and associated flight profiles could be an issue. The study finds that a range of 0.09 Mach for one aircraft owing to CI variations is realistic which represents a speed variation of 10% and up to 30% in climb and descent. This reduced predictability represents a challenge to ATC as speed changes of 5% have to be reported to ATC.

More generally, Akturk et al.(2014) highlight some of the issues with decision support tools regarding the recovery of delay through the use of CI. It is stated the "current standard CI does not fully capture the flexibility of controllable flight times". It is acknowledged that optimisation based decision support tools are still at the early stages of implementation at major airlines. These decisions are becoming more important owing to the growing threat of environmental regulation on fuel burn and greenhouse gas emissions. It is determined that the major difficulty with speed control is that carbon emissions are non-linear in cruise speed. The authors state that there is a critical trade-off between fuel consumption and delay minimisation and the issue is complicated by network integration effects.

Another issue relates to the design of aircraft, with airline economics now dictating the need for more flexible designs. For example, enroute performance whereby a standard Mach number is assumed (commonly the Long Range Cruise) is an oversimplification. The study shows that a speed schedule based on this is inconsistent with cost and profitability optimisation and found that CI is the most suitable method for all aircraft available today. This highlights some of the issues that have been discovered as to why CI values are not currently optimised.

Two issues can arise with the use of CI; incorrect use of the tool and/or miscalculating the costs associated with the CI equation. Airlines have been reported to use CI in a variety of different ways, as described by Airbus (1998):

- use of the CI to approximate Long Range Cruise (LRC)
- use of the CI between LRC and Maximum Range Cruise (MRC)
- higher CI if necessary for scheduling irrespective of fuel consumption issues
- cost index variation according to fuel prices irrespective of time considerations (transparent/not considered)
- use of the CI to approximate LRC, except CI = 0 for fuel critical routes
- CI calculation resulting in cruise speed between MRC and LRC
- CI calculation resulting in cruise speed slightly below LRC
- use of the CI to meet schedule requirements route by route
- use of the CI route by route differentiating by fuel price only
- adoption of CI values by adapting from other aircraft models/ manufacturers
- adoption of CI values by adapting for speed requirements only
- CI adaptation according to sector fuel price variations after an initial rigorous fuel and time calculation.

Airlines are often hindered by the complication of apportioning costs for the CI equation. Fuel costs are the most volatile aspect of the calculation and CI values need readjustment regularly to take changes into account. However, the difficulties associated with time dependent costs are more fundamental. Evidence suggests that many airlines make elementary errors in this area or make questionable assumptions, such as assuming that maintenance costs owing to flight hours are 50% of total maintenance costs (Burrows et al., 2001) and anecdotal evidence that average CI values are used for specific aircraft models over all routes.

Studies on CI are very limited, particularly in actually quantifying fuel savings that could be made by optimising its use. There is certainly evidence that it could be an important tool in reducing emissions and that there is room for improvement in its calculation and use. As Burrows et al. (2001) states “the neglect of the airline industry by accounting researchers is surprising given the special features possessed by airlines” (p.81) and there is currently a failing by airlines to exploit the potential of optimising their use of CI.

Although lacking, the literature regarding CI has touched on many of the areas that need attention if optimisation of its use is to be achieved. These areas include justification of the savings in fuel and CO_2, as well as cost efficiency, which are attainable; identification of the areas where CI calculations can be improved; and issues related to its implementation on the wider system. In order to improve the use of CI and optimise values it is first necessary to understand the costs that are involved in its calculation, as well as the general trends in airline economics, which is undertaken in the following section.

2.3 Understanding the Costs of CI

2.3.1 Trends in Airline Economics

The airline industry is a paradoxical one, with ever increasing demand but with continued marginal profits. Over the past 30 years there has been a 2.5 times increase in the number of unique city pair air services, increasing to 15,000 in 2012. Since the 1970s air transport has also more than halved prices for its customers. But despite a rise in demand that far exceeds most other goods and services (10-fold since 1970 compared to 3-4 fold for the world economy), the airline industry has struggled to make a profit (IATA, 2013b).

Looking back over the last fifteen years, since September 11 2001 the stories of airline bankruptcies and loss of profits has increased, with the industry losing billions of dollars. These losses were not only because of 9/11, but also to what Pilarski (2007) calls the "ten plagues". These include the recession, a post 9/11 fear of flying, wars in Afghanistan and Iraq, the outbreak of SARS, continued terrorist attacks across the world e.g. Spain, London, Bali, competition with low cost airlines, bankruptcy laws in the US, poor airline management policies, continuation of adversary labour regulations and lastly, rising oil prices.

It is well known that the industry is a cyclical one and this has impacts on profitability from year to year. But even in good years, on the whole airlines only achieve marginal profits, as seen in Figure 2-3. Some airlines have had greater success, such as Cathay Pacific, Singapore Airlines and British Airways, but airlines still remain the worst performing entity in the aviation industry. Figure 2-4 demonstrates how airlines struggle to make a return on capital investments compared to other sectors in the industry. The average for airlines is 4% whereas their cost of capital is 7-10%, compared to sectors such as services (including maintenance, catering and fuel), which have been outsourced by around 50% making 11% return on a 7-9% capital investment. However the highest returns are made by the distribution sectors, with travel agents seeing the highest return of an average of 44% for a capital investment of 8-11% (IATA, 2013b).

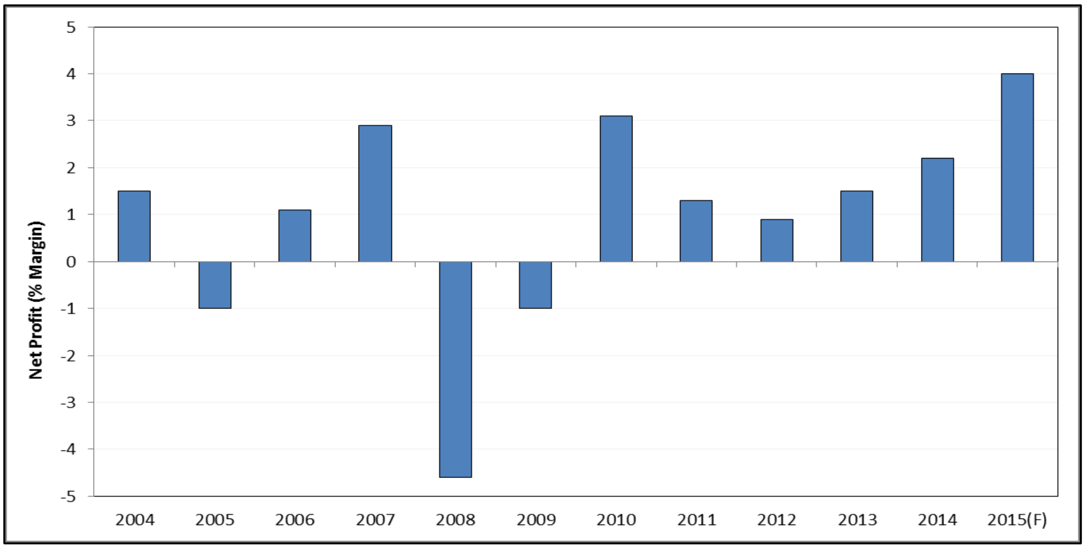

Figure 2-3: Global Net Profit % Margin of Airlines (Data Source: IATA, 2015c)

The financial future for any airline is not in any way certain. Therefore, it is important for airlines to guard as much as possible against this unpredictability. Costs therefore need to be scrutinised. A key factor is understating the difference between fixed and variable costs and the drivers of change in these costs. Before any calculation to find a truly optimum CI can be undertaken, it is vital that costs that effect CI are examined. The key costs associated with CI are analysed below, as well as other costs, which are currently not included but could have an associated impact.

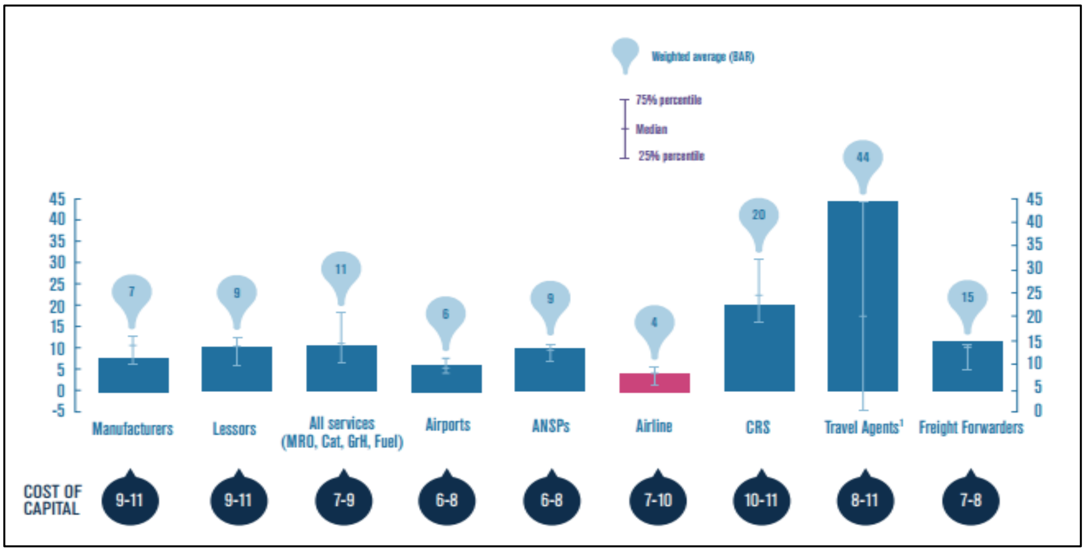

Figure 2-4: Return on Capital in the Aviation Industry Value Chain (% for period 2004-2011) (IATA, 2013b)

2.3.2 Time-dependent costs

2.3.2.1 Labour Costs

Labour costs are one of the most significant costs to airlines. One of the most in-depth studies on the cost of labour in relation to CI is that of the University of Westminster Transport Studies Group (2008a). Here the three main drivers of crew costs are presented:

1. Base country i.e. different countries have different pay expectations
2. Type of operation i.e. low cost or network carrier
3. Size of aircraft

The last two factors are important as they determine the amount of crew required on-board the aircraft. The type of operation is important as network carriers tend to have more classes, which require more cabin crew to attend to fewer seats in higher classes for increased quality of service. Network carriers also tend to pay higher wages than low cost carriers. As the aircraft size increases more crew will be required as there are legal requirements as to the number of cabin crew assigned for a certain number of passengers. Plus there are likely to be more classes with a lower ratio of flight crew to seats. Flight crew salary is also dependent on aircraft model, with larger aircraft tending to result in higher pay for its flight crew.

However, there are more complexities to this. Firstly flight crew costs are not linear when considering long-haul operations. This is because a relief pilot is required on long flights and the whole flight crew is paid no matter how long they are actually in charge of the aircraft (Swan and Adler, 2006). In addition, even though pilots are paid depending on aircraft model flown, within this there can still be a wide range of salaries based on experience. For example, a B747-400 Captain's salary can range from 110,000 euros to 205,000 euros (University of Westminster Transport Studies Group, 2008a).

The extremes of these payments are fixed salaries and payment by purely block hours. The intermediate situation is one where there is a base salary plus allowances for each block hour in excess of some threshold figure i.e. 50 hours per month (Burrows et al., 2001). In fact Airbus (1998) states that slower speeds, even with fixed salaries, will eventually increase the total block hours to the extent that additional crew must be recruited.

Labour costs can vary significantly across airlines and are a factor that airlines can control to an extent. However, they are also dependent on the prevailing economic and social factors in the airlines home country. At one point airlines saw wage costs as something out of their control but the major economic crises faced by the industry in the nineties forced airline managers to take a more active role in reducing labour costs. This was done through computerisation, use of large aircraft and restricting staff increases (Doganis, 2002).

Whilst airlines have attempted to increase labour productivity, it became apparent that they would also have to try and reduce the unit cost of labour. This has been done by the reorganisation of terms and conditions of employment with a freeze of wages, reduced staff numbers and/or agreeing higher workloads with existing staff. Another option is to offer employees shares in exchange for concessions on wages or work practices, or hiring employees based in other countries where wage rates are lower. The last strategy is for airlines to take on low wage airlines and using them to operate services on their behalf (Doganis, 2002).

Whilst labour cost can generally be considered under control of the airlines themselves, there are circumstances in which labour costs can be out of their control. For example, in 2012 the European Parliament passed new stricter rules on aircrew fatigue with a reduction in flight duty time at night by 45 minutes and alteration of rest hour requirements, which results in change in crew rosters (European Commission, 2013).

2.3.2.2 Maintenance Costs

There are three aspects to maintenance, which need to be considered: airframe; engine and APU; and components and 'rotables'. There are five categories of maintenance checks (Table 2-2). In the context of calculating the CI, it is only the A and C checks which are of importance as these depend on flight hours rather than a fixed period of time between checks and account for between 40% and 50% of the overall maintenance costs to airlines. These checks are often combined to minimise costs (University of Westminster Transport Studies Group, 2008c).

Many airlines now outsource their maintenance through power-by-the-hour or cost-by-flying-hour contractions. These contracts give airlines a way to smooth the peaks in costs associated with the age of the aircraft, which increase to maturity, level off and then rise again after about 15 years. Based on an agreed per hour price based on the ratio of flight hours to cycles, the airline must pay for exceeding the agreed usage limit. However, this is offset by the maintenance provider absorbing the risk of additional costs owing to abnormal wear and tear.

Table 2-2 Typical aircraft maintenance checks (Adapted from: University of Westminster Transport Studies Group, 2008c)

Check	**Location**	**Description**	**Duration**	**Typical Interval ***
Line/ Transit	At gate	Daily (before first flight or at each stop when in transit). Visual inspection; fluid levels and brakes; emergency equipment.	~1 hour	Per flight
A	At gate	Routine light maintenance; engine inspection	~10 hours /overnight	600FH
B	At gate	If carried out – similar to A but different tasks	~10 hours to ~1 day	N/A
C	Hangar	Structural inspection of airframe, opening access panels; routine and non-routine maintenance; run-in tests.	~3 days to ~ 1 week	18 months/ 6000FH
D	Hangar	Major structural inspection of airframe after paint removal; engines, landing gear and flaps removed; instruments, electronic and electrical equipment removed; interior fittings (seats and panels) removed; hydraulic and pneumatic components removed.	~ 1 month	72 months

*For a long-haul Boeing aircraft

For the calculation of the CI it is important to understand the marginal minute costs related to maintenance, i.e. a cost that would be affected by an extra minute of flight. When the block hour maintenance direct cost is known for a particular aircraft, it has been found by the University of Westminster Transport Studies Group (2008c) that 15% of this value gives a good indication of the corresponding unit maintenance cost. This can then be converted to marginal minute maintenance costs by using a gate-to-gate model. Total maintenance costs are apportioned 65% to airframe/components and 35% to powerplants before being distributed amongst 13 phases of flight. Over half of these costs are fixed costs and therefore discounted for the CI calculation. These fixed costs occur during high intensity phases of take-off to top of climb and top of descent to landing. The remaining proportion is allocated to the remaining phases of flights and using fuel burn as a proxy for workload to apportion the power plant costs across phases.

IATA's Maintenance Cost Task Force collates data from 48 airlines on maintenance costs. The 2013 report (IATA, 2014a) states that the global maintenance, repair and operations (MRO) bill was $131 billion including overheads. The average maintenance cost per flight hour was $1,167, with a minimum of $282 per hour and a maximum of $5253 per hour. Engines remained as the highest proportion of these costs and the amount of maintenance that is contracted by airlines also increased accounting for 65% of the direct maintenance spend.

Table 2-3: Unit Cost by Aircraft Category for 48 Airlines in Maintenance Cost Task Force (Adapted from: IATA, 2014a)

Aircraft Category	Cost per Aircraft (mil $)	Cost per Flight Hour ($)	Cost per Flight Cycle ($)
Narrow-body >100 seats	2.2	734	1,364
Regional Jet <100 seats	2.0	871	1,147
Turbo-props	1.4	741	714
Wide-body 2 engine	5.5	1,433	6,115
Wide-body 3+ engine	6.0	1,563	9,486

Focussing on wide-body aircraft as this is the area with the best potential for changes in CI, the report further breaks down these costs per flight hour into three key categories. The largest proportion of the cost (63%) is from outsourced maintenance costs, whilst labour and materials account for 17.8% and 19.2% respectively.

In practice there are so many joint costs in the separate areas of maintenance that it is very difficult for many airlines to break total maintenance costs down into separate cost categories and there is no standard way of apportioning maintenance costs amongst different aircraft models (Doganis, 2002).

2.3.2.3 Delay Costs

One of the key ways in which airlines have tried to more effectively use CI and the area there has been the most research regarding the tool, is recovering the cost of delay. The issue here is that there must be a balance between recovering delay costs and using additional fuel. There are two types of delay – pre-departure delay and en-route delay. These types of delay must be treated differently considering for en-route delays the fuelling decision has already been made, the decision must be made early in the flight to have an effect and that it will be constrained by ATC acceptance, which is often a limiting factor (Cook et al., 2009).

Delay costs consist of labour and maintenance costs, which have been described previously but also include passenger costs, which can contribute significantly. There are two categories of delay costs to consider. The first are termed “hard costs” which include rebooking and compensation for passengers of delayed flights. The other type is “soft costs” which are more difficult to calculate as this mainly encompasses revenue lost owing to the defection of passengers to other airlines (University of Westminster Transport Studies Group, 2008b).

These costs vary from country to country. For example the EU brought in new regulation ((EC) No 261/2004) in 2005 concerning passenger delay compensation. Table 2-4 shows the eligibility for compensation depending on flight distance. This covers flights departing from EU airports and operated by any airline, or arriving at an EU airport and operated by an EU airline. The compensation is based on when the aircraft doors open on arrival and not the departure time; therefore passengers do not have to be compensated if the delay time is recovered in flight. Asides from compensation, passengers are also entitled to care and help after a certain period of delay, which includes a reasonable amount of food and drink; means for communication; accommodation if delayed overnight; and transport to/from accommodation (Civil Aviation Authority, 2015).

Table 2-4: EU Air Passenger Delay Compensation

Length of Flight	**Eligible delay for compensation**	**Eligible delay for care and help**
Short-haul (<1500km)	>3 hours (€250)	>2 hours
Medium Haul (1500km-3500km)	>3 hours (€400)	>3 hours
Long-haul (>3500km)	3-4 hours (€300) >4 hours (€600)	>4 hours

2.3.3 Depreciation

Depreciation reflects the diminishing value of a capital asset with a useful economic life over the amount dictated by company policy, such as airplanes, engines and spare parts. The useful life of each of these is termed by the Internal Revenue Service and can change with amended tax laws. As well as this period of time, depreciation also requires a residual value, which basically represents the value of the object at the end of its lifetime and the base cost, which is the cost of the object new including taxes and associated expenses. Depreciation is expressed yearly as the result of these three inputs and there are four methods that are most commonly used for calculation (Radnoti., 2002).

1. Linear

$$DEPLIN = (Al - S)/n$$

   Where:

   DEPLIN = yearly depreciation

   Al = amount of airplane investment

   S = residual value

   n = economic life of airplane

   Expressed as a book value at a given year:

$$BOOK_t = Al - [(Al - S)(n/t)]$$

2. Sum of–the-year method – sums up consecutive number of years, from year one to last year of economic life of the object. If the economic life is five years, the

denominator is 1+2+3+4+5 =15. The numerator is the remaining years of the economic life e.g. first year 5, second year 4 etc. and completes the equation:

$$DEP_t = \frac{n - (t-1)}{[n(n+1)]/2}(Al - S)$$

3. Double-declining balance – this is useful when there are rapid changes in technology and objects quickly become obsolete, therefore this method has a deceleration of depreciation in the early years and is represented by the following equation:

$$DEP_t = (2/n)BOOK_z$$

4. Double-declining balance and linear – this is a combination of the previous two methods. This involves a switch from double declining balance at year n/2+1. The depreciation method switches to the linear method from double declining when the linear depreciation is larger than the double declining depreciation.

Depreciation policy varies between airlines and the policy adopted can vary costs by around 3%. Many airlines will change their depreciation policy when cost reductions are needed by either lengthening the depreciation period or increasing the residual value when profits fall. For example, Singapore Airlines used very short depreciation times in the 1970s compared to the international standard, which has been attributed to the build-up of capital for a rapid fleet renewal and to mask large operating profits. However, when in 1979 the airline was hit by the rise in the price of fuel it promptly lengthened the life of its aircraft in order to reduce costs and thereby still demonstrate a profit. Even with this the airlines depreciation period was still relatively short at 8 years. After a further lengthening of the period in 1989 to ten years with a 20% residual value, before the crisis of 2001 when the airline brought its depreciation policy in line with industry practice to 15 years and a residual value of 10%. This resulted in a reduction in costs of $151 million (Doganis, 2002).

Although depreciation is often presented as a time cost, it is not intrinsically linked to the time of a flight. It is dependent as to the airlines discretion as to whether it is included in CI calculations. It is rarely included in the literature in the CI calculation so the decision has been made to omit it here. Depreciation only has a small effect on individual flight costs but if airlines do wish to include it in the calculation of CI it is fairly easy to incorporate into it, unlike some of the other costs.

2.3.3.1 Other

There are other costs that are not usually considered in the CI calculation, but they do have a time or schedule element associated with them. Noise related costs can be one of these when there is a charge depending on the time of day (Table 2-5). This will affect flights, which are scheduled for the boundary of night periods. Arriving too early in the morning or too late at night can incur penalties if arriving outside of scheduled time in that period.

Table 2-5: London Heathrow Airport Noise Charges (Heathrow Airport Ltd. 2014)

Noise Charging Categories						
Helicopters	£1,406.00					
Fixed wing aircraft not exceeding 16 metric tonnes	£2,934.05					
	Chapter 2	Chapter 3 High	Chapter 3 Base	Chapter 4 High	Chapter 4 Base	Chapter 4 Minus
Fixed wing aircraft exceeding 16 metric tonnes – outside Night Period	£8,802.15	£8,802.15	£2,934.05	£1,745.05	£1,430.35	£836.20
Fixed wing aircraft exceeding 16 metric tonnes – Night Period	£22,005.38	£22,005.38	£7,335.13	£4,364.40	£3,575.88	£2,090.50

Some airports also charge varying amounts for air traffic services based on the time of day. For example, at Manchester Airport there are eight time periods during the day considered off-peak when airlines can benefit from lower rates depending on the weight and noise category for aircraft in question (Table 2-6).

Another charge that airlines face, which is time dependent, is parking charges for aircraft. For example at Heathrow, aircraft are allowed to be parked at the stand for the first 90 minutes for free, but then have to pay £51.26 for every additional 15 minutes or part thereof for wide-bodied aircraft, measured from chocks on to chocks off. However, parking is free between 2200 and 0559.

Table 2-6: Air Traffic Services (ATS) Charge for Passenger Aircraft at Manchester Airport (Manchester Airport PLC. 2014)

	Up to 25t	**25t to 120t**	**Over 120 tonnes** First 120t	Thereafter	**Applicable only for aircraft achieving the following QC rating**
Standard Charge	£2.33	£2.87	£2.87	£1.58	All
Off-Peak Charge:					
05:30-05:59	£2.33	£2.33	£2.33	£0.00	0.5 or quieter
06:00-06:29	£2.33	£2.33	£2.33	£0.00	All
06:30-06:59	£2.33	£2.33	£2.33	£0.00	1.0 or quieter
13:00-13:29	£2.33	£2.33	£2.33	£0.00	1.0 or quieter
13:30-13:59	£2.33	£2.33	£2.33	£0.00	All
19:00-19:59	£2.33	£2.33	£2.33	£0.00	1.0 or quieter
20:00-21:59	£2.33	£2.33	£2.33	£0.00	All
22:00-22:59	£2.33	£2.33	£2.33	£0.00	1.0 or quieter

These costs are not included in the calculation of CI by airlines at present as they are not technically flight costs. However, they can be affected by arrival and departure times governed by the speed of a flight. Whilst they are deemed to have a small impact on total costs, they may become more important in the future and therefore should be kept in mind for consideration.

2.3.4 Fuel costs

2.3.4.1 Fuel Price

Fuel prices have had a turbulent history and have been a major contributor to the success or failure of airlines. Air transport is very energy intensive, but the rise in overall fuel costs has not come from lack of improvement in efficiency but as a result of jet fuel price increases.

Figure 2-5 shows the price breakdown for jet fuel. It is clear that upstream costs are dominant, as 75% of the cost is that of crude oil. In addition taxes and royalties can be charged but are very country dependent, ranging from 0% to 27-34% on domestic jet fuel in Brazil, India and Japan.

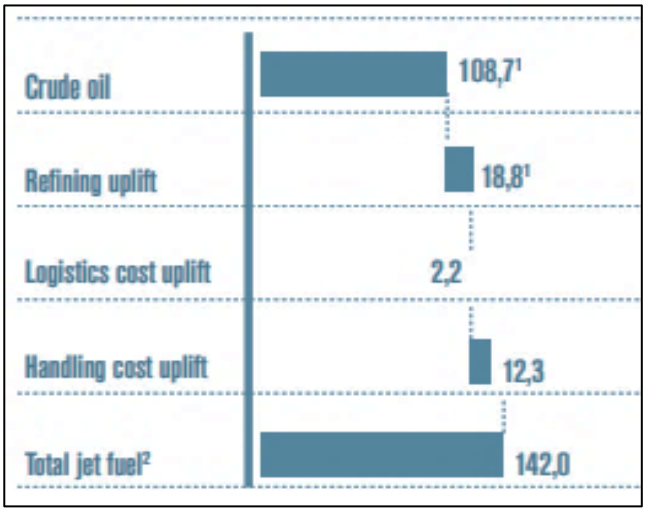

Figure 2-5: Breakdown of Jet Fuel Price (US$/bbl) (IATA, 2013b).

There are several key reasons for large changes in oil prices. Examples from the supply side include war in the Middle East, supply limitations from OPEC, political actions in countries such as Venezuela or Nigeria, or military action such as the invasion of Kuwait. Demand side impacts can also result in volatile oil prices, for example when economies grow quickly. In terms of the aviation industry in particularly, the response to economic cycles exacerbate this issue (Morrell and Swan, 2006).

Experiences with oil price shocks began in the 1970s when a series of events concerning conflict in Middle Eastern countries sent the price for crude over $100/bbl in today's prices. Volatility continued into the 1980s and early 1990s. Even until 2001 the price was still as low as $20/bbl. The following years started to see the price of jet fuel increase and by 2007 the real price of fuel had tripled. However, it was in July 2008 when the biggest price shock was experienced, with crude oil prices jumped to $145/bbl. Following this was a price collapse before a price increase again in the following years (Figure 2-6) (Hamilton, 2009). However, at beginning of 2015 fuel prices showed another drop, although there is now a slow rise again (IATA, 2015b). Figure 2-6 also shows the relationship of jet fuel production to jet fuel price. Jet fuel production was showing a steady rise until 2008 when the global recession and the resultant decrease in demand for air services significantly reduced production. However, it has seen steady growth ever since even with a subsequent decrease in jet fuel price.

Volatility in the jet fuel prices is expected to continue into the future, particularly once the reasons for the 2008 price shock are examined. Firstly there was not a big reduction in supply as with other oil price shocks. However, there was a failure to increase production between 2005 and 2007. One reason for this is Saudi Arabia reducing its excess capacity. This stagnation in production was met with a strong growth in global demand for oil, particularly from emerging economies such as China. There is also another possible reason that had not been present in previous oil price shocks: the role of speculation. It has been suggested that the purchase of the oil as a financial asset rather than a commodity introduced a bubble in which investors sought to take positions in commodity future contracts. The number of buys soon exceeded the number sold for expiring contracts. The result was that eventually the bubble burst on commodity index trading funds that were holding a quarter of a trillion dollars' worth of futures contracts. It is argued that as the futures price was driven up, this also stimulated an increase in the spot price of oil (Hamilton, 2009).

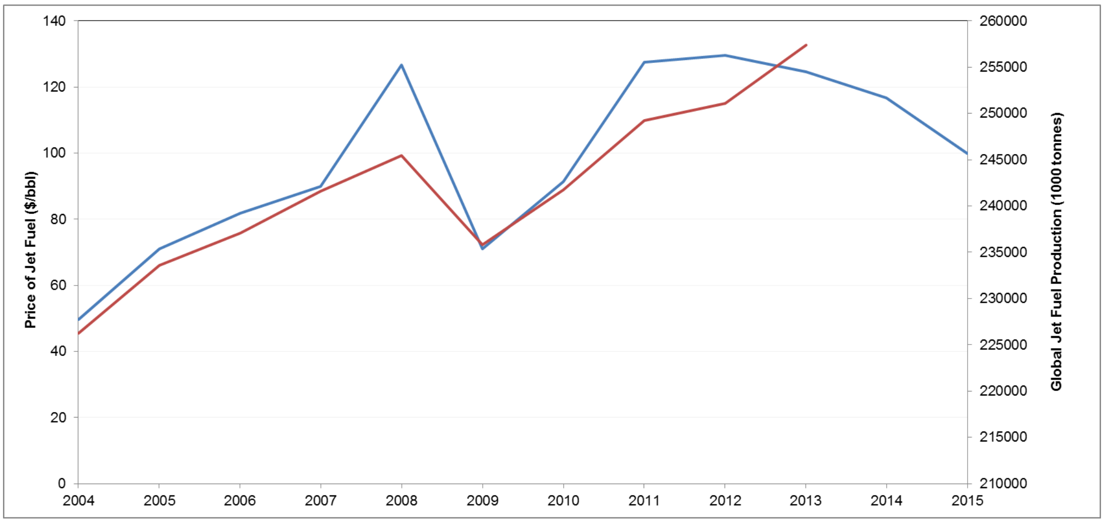

Figure 2-6: Annual Average Price of Jet Fuel and Global Jet Fuel Production 2004-2015 (Data Sources: IATA, 2014b, IEA, 2015b).

Fuel prices can vary substantially between and even within countries because of different tax regimes and production and distribution costs (Burrows et al., 2001). Airbus (1998) state that the variability between countries affecting one sector to another, should be a key consideration for airlines, prompting them to consider adopting different CI values for different routes and should be regularly readjusted.

As Figure 2-7 demonstrates, airline profits and jet fuel price appear to be strongly linked. Therefore, reduction in fuel costs are one of the key aims for airlines to protect profits. However, there are more intricacies to jet fuel prices that meet the eye and do not just depend on the costs of crude oil. The following sections describe how refining costs, hedging and subsidies also play a part in determining the overall cost of fuel.

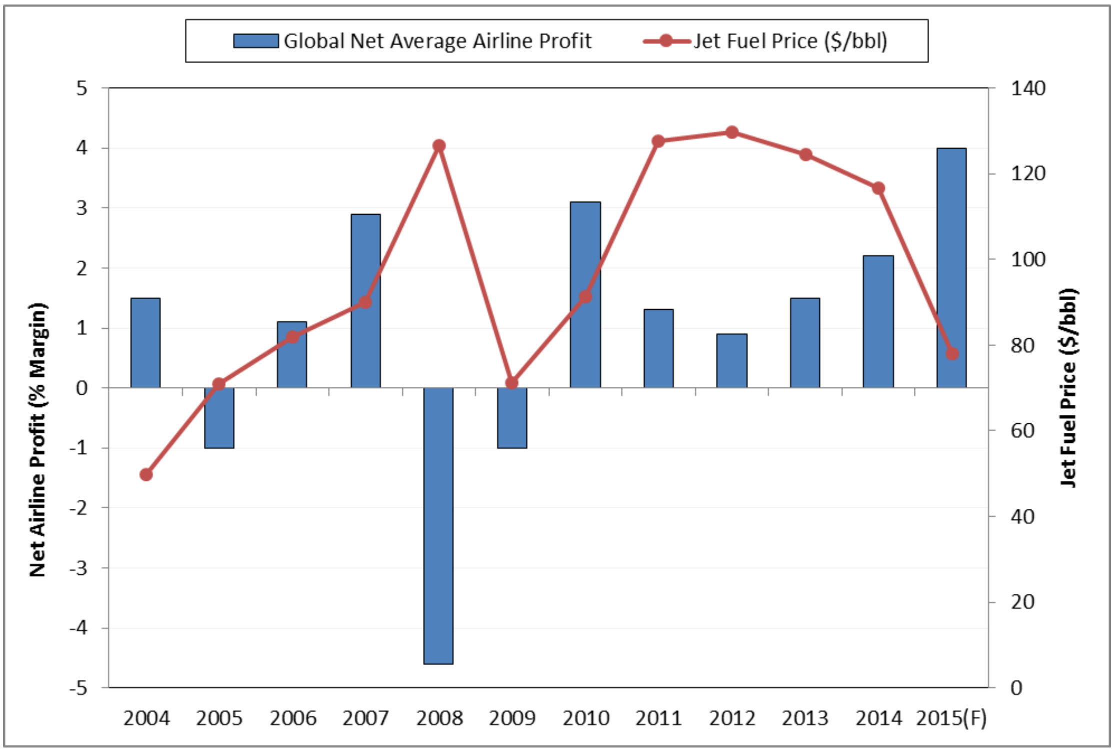

Figure 2-7: Global Net Average Airline Profits and Jet Fuel Price from 2004 to 2015 forecast (Data Source: IATA, 2015c)

2.3.4.2 Refining Costs

The price of jet fuel is not only dependent on the price of crude oil, but also on the cost of refining the raw product to jet fuel. The difference between the price of crude and that of the refined product is referred to as the crack spread. There are a number of values which may affect the crack spread, such as geopolitical issues, seasonality, tax increases, currency weaknesses and refinery maintenance (CME Group, 2013).

Currently global demand growth is centred towards middle distillates, with jet fuel accounting for an 8% increase from 2014 to 2015. Jet fuel refining is predicted to remain important in this area of refining in the years to come. As Figure 2-8 shows the largest growth area for middle distillates is the Middle East. Here demand is only set to increase for middle distillates by 0.6mb/d by 2019, whilst refinery output could rise by 1.3mb/d by 2019 with the difference being exported to other countries (IEA, 2014).

In terms of the historical crack spread for jet fuels (Figure 2-9), in recent years there has been an increase from around 6$/bbl in 2002-03 to over $40/bbl in 2015. However, the percentage mark-up has remained relatively stable at around 24%. One of the reasons why there have been increases has been lack of investment in refinery capacity, but this is set to change with significant investment in refinery capacity going forward as high value middle distillates are favoured (IATA, 2008). Global demand growth remains heavily centred towards middle distillates including jet fuel and this market will remain significant in both global product trade and refinery margins in years to come (IEA, 2014).

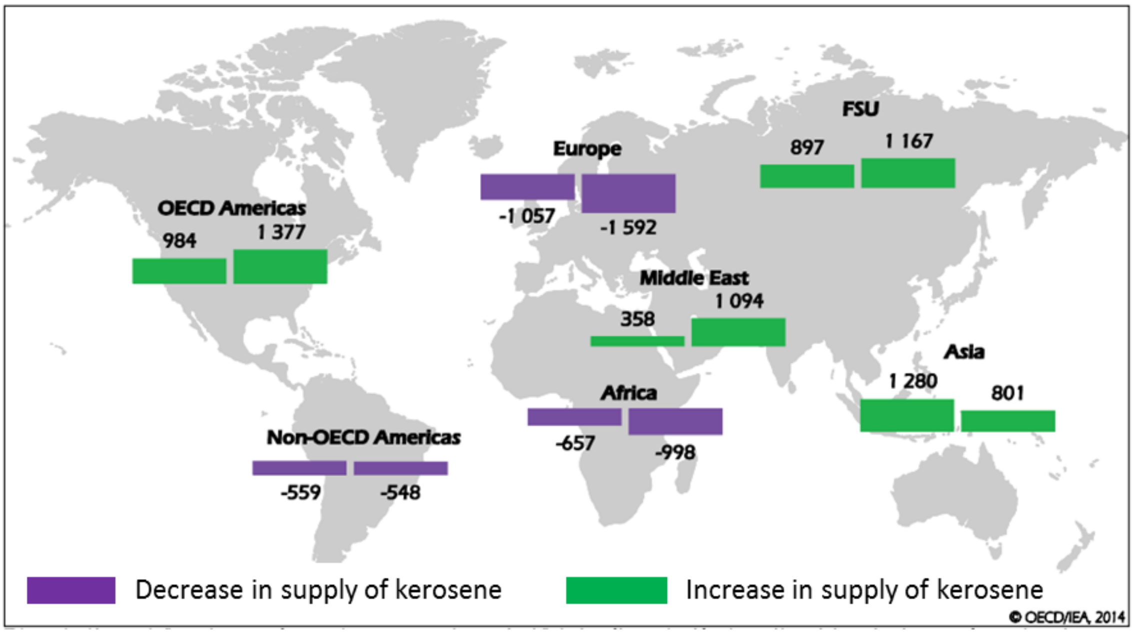

Figure 2-8: Product supply balances between 2013 and 2019 (thousand barrels per day) for gasoil/kerosene (IEA, 2014).

When oil prices do increase, refineries tend to put the burden on the airlines with increased jet fuel prices. This spurred Delta Airlines to buy its own refinery in 2012 as at the time they believed that $2.2 billion of their $12 billion a year cost of jet fuel went to profit for the refiner. It sunk $420 million into capital whilst generating $100 million of loses. Whilst it can be claimed that this year the airline was paying 50 cents a gallon less, this is mainly because of the fact that oil prices have significantly decreased. In fact they are making the same saving in fuel costs of nine cents a gallon compared to their competitors as they were before acquiring the refinery (Helman., 2015). It is therefore unlikely that airlines will follow Delta's lead in becoming their own refiners and will continue to rely on the financial position of the refiners from which fuel is sourced.

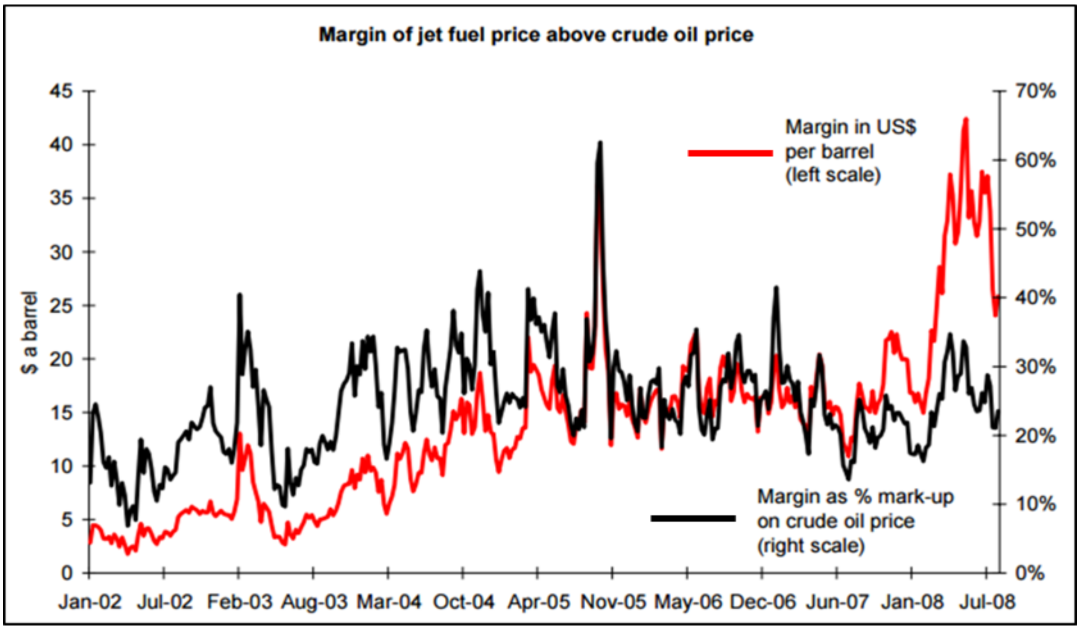

Figure 2-9: Jet Fuel price mark-up over crude oil (IATA, 2008)

2.3.4.3 Fuel Surcharges

Fuel surcharges have been used by airlines to cushion the effect of fuel prices on revenues. Not all airlines take up this option, especially low cost airlines. The result is that passengers can now face significant fuel related costs on top of the basic airfare. The reasons why this is an attractive option to airlines include the creation of a large fixed element to the ticket price; to generate significant contributions to airline costs from passengers flying on reduced price tickets (e.g. those through frequent flyer programmes or staff concessions); and avoidance of commission to travel agents as these are calculated from the basic fare.

Not only have surcharges increased, but they have also become more complex. It is common for airlines to apply them in bands depending on distance flown and airlines such as British Airways also apply varying surcharges to different classes to reflect the allocation of resources in terms of space and weight. However, the pattern of fuel surcharge application across the world does differ. In Europe, it is widespread and is often transparent to the customer, whilst Asian airlines also generally apply surcharges, transparency varies more significantly between airlines. In contrast, US airlines generally choose to internalise fuel costs, instead resulting in higher basic fares (Air Transport Department Cranfield University, 2010).

2.3.4.4 Fuel Hedging

In order to protect themselves against volatile jet fuel prices, many airlines chose to hedge a certain proportion of the fuel they purchase, typically between one and two thirds. The benefit of this for an airline is that it increases predictability in total costs, cash flows and profit. Most hedges involve the purchasing of an oil future, which is basically a cash bet on what the price of oil will be on a particular date. It is usual for airlines to hedge between one- and two thirds of their fuel costs and most look forward 6 months. It is unusual for hedges to be longer than one year and very rare to be more than two years in advance (Morrell and Swan, 2006).

There are various ways in which airlines can hedge their fuel price. These are the most commonly used methods:

1. Plain Vanilla Swap – these are over the counter contracts, which rely on a future floating price exchanged for a fixed price. The actual commodity is not exchanged and contracted obligations are settled in cash. There needs to be a specific volume of fuel, certain duration and an agreed fixed and floating price. These contracts are usually settled through financial institutions.
2. Futures Contract – these contracts are based on an agreement to buy/sell a specific quantity of fuel for a certain price at a designated time in the future. Unlike plain vanilla swaps, these are executed through commodity exchanges so therefore eliminate the risk of either party defaulting on payments. Only a small percentage of futures contracts actually result in the delivery of the actual commodity. Although, like plain vanilla swaps there is an agreed price for the commodity to be paid at a certain point in the future, daily cash payments are made to each other to offset their positions. This requires the buyers and the sellers of the contract to post a margin, which is a small percentage of the initial value of the contract e.g. 20%. Losses are drawn from the margin until a maintenance margin is reached e.g. 10%., with airlines (the buyers) posting additional money to the exchange when the level drops below the maintenance margin.
3. Forwards Contracts – these contracts vary from the previous two examples as they typically involve the actual delivery of the commodity. The airline will agree with its

fuel supplier a set quantity of fuel to be delivered at a set price on a set future date. Like with the previous examples if the set fuel price is lower than the actual fuel price then the airline makes a savings but conversely, if the set fuel price is higher than the actual fuel price then the airline will make a loss (Bazargan, 2010).

The main exchanges offering fuel hedging future contracts are the International Petroleum Exchange (IPE) in London and NYMEX in New York. As jet fuel is rarely traded at these exchanges, Brent crude or Brent gas oil are used as a substitute (Air Transport Department Cranfield University, 2010).

Whether hedging is good or bad for airline profits is not the concern of this research, but it should be noted that changes in hedging may not always be a result of fuel prices. Airlines may use their positions to move profits backwards and forwards by timing the sale of their oil futures to be misleading in their financial reporting (Morrell and Swan, 2006). Therefore, it is important that these changes are included in the oil price for calculation of the CI.

The drop in fuel prices at the beginning of 2015 has shown some clear winners and losers of fuel hedging. United, Southwest and Delta all saw loses owing to hedging, with a higher fuel price compared to the spot price. For example EasyJet had a typical hedging price of $950 per tonne at 80% but the jet fuel price in January 2015 was only $600, meaning a total loss owing to hedging of $490 million. Others benefitted, such as American Airlines who have not signed a hedging contract since 2013. However, this needs to be put in the context of lower spot prices for jet fuel. For example, whilst Delta lost $1.2 billion by hedging, the airline still gained $1.7 billion from lower fuel prices (Myers., 2015, The Economist, 2015).

2.3.4.5 Carbon Emissions Charging

The aviation industry is facing pressure to reduce its contribution to global climate change. To date it has received very little regulation in terms of reducing emissions. With demand for air travel increasing at an average of 5% per year, the likelihood of emissions decreasing or even stabilising without invention is small.

The European Union planned to include aviation in the European Union Emissions Trading Scheme (EUETS) from 2012 when there was no indication that ICAO had any intention to implement a global measure to reduce emissions. This would affect flights that both departed and arrived from airports in Europe and would include the emissions from the entire flight, even if it was a flight from outside of the EU. However, this stimulated hostility from a number of countries and threats of a trade war were floated (Carbon Market Watch, 2013a).

The 26 countries which opposed this formed the “coalition of the unwilling” and implemented retaliatory measures. For example, China froze $14 billion worth of Airbus orders and the US senate passed the EUETS Prohibition Act of 2011. This act prohibits any operator of aircraft in the US from participating in the EUETS and this has now been signed into law. Owing to this international pressure the European Commission suspended the EUETS plans for international flights but only pending the implementation of regulation on an international level led by ICAO (PWC, 2012).

At its meeting in 2013 there was a decision to develop a global MBM scheme for aviation with a view for implementation from 2020. The resolution also states a number of stipulations for MBMs implemented by ICAO. These include supporting sustainable development and developing global aspiration goals to ensuring there is not an inappropriate economic burden on the industry and that the principle of common but differential responsibilities is taken into account (ICAO, 2013b).

There are three types of market-based measures currently being considered by ICAO (2013b):

1. Global Mandatory Offsetting – the aim of this measure is to cancel out or neutralise emissions from the aviation industry by offsetting emissions in a different sector. Emissions units quantify the amount offset and can be bought, sold or traded. Airlines would be required to purchase a certain number of these units in order to offset an agreed CO_2 target and would need to conform to eligibility criteria to guarantee genuine reductions.

2. Global Mandatory Offsetting with Revenue – this is generally the same as the above scheme but in addition revenue would be generated by applying a fee to each tonne of CO_2 e.g. a transaction fee. The revenue would then be used for agreed purposes i.e. climate change mitigation.

3. Global Emissions Trading – this would involve a cap-and-trade approach with emissions capped at an agreed level for a specific compliance period. Allowances equivalent to one tonne of CO_2 would be created for all the emissions of the global

aviation industry under the cap. These allowances are either distributed to airlines for free or auctioned. The latter also provides revenue generation. At the end of the compliance period airlines have to surrender allowances equal to their emissions during the period. They can buy and sell emissions allowances from or to other airlines at this time depending on whether they meet their targets.

Whichever scheme is chosen, there will be additional costs to the airline that will depend on fuel use. Therefore, this becomes a variable fuel related operational cost, which must be considered within the CI calculations for airlines. This is examined further in the Chapter 5 scenario analysis.

2.4 Summary

Analysis of the literature review reveals that whilst there is significant potential for CI to play an important part in emissions mitigation from aircraft, there are still many areas concerning it use that are under-researched. There are only limited calculations of the emissions savings, which could be made by optimising the CI, conducted for only a limited number of aircraft models. Whilst there have been attempts to develop better CI calculations in the context of delay recovery, very little attention has been paid to its optimisation for normal operations. There also needs to be a lot more attention paid to the reasons why airlines are not currently optimising their CI values.

It is clear from this analysis that the cost inputs into the CI calculation are in no way straightforward. Crew and maintenance costs, which make up the large majority of time-dependent costs in normal flight operations, are complex. Not only do they include the challenge of separating the flight cycle and flight minute costs, but they also include the complexity of cumulative costs, which need to be included in the calculation. The situation is future complicated by the regular presence of delay in the airline system and therefore the additional costs of time associated with reducing this must be balanced against the additional costs of fuel.

Costs on the fuel side of the CI equation are more straightforward. Whilst there are still underlying intricacies in calculating fuel costs, such as refining margins and fuel hedging policy, these are still relatively easy to calculate. The issue with fuel costs for airlines is with their volatility and they are much harder to predict going forward compared with time-dependent costs. Added to this is the increased likelihood of a market-based measure being introduced into the industry, which will impose a carbon price for every kilogram of fuel burned. Again this leads to significant uncertainly, in the short term over the market measure, which will be imposed, and in the longer term, the costs associated with its implementation.

Overall it is apparent that airlines need a simple and cost effective method of calculating optimum CI values. This will be addressed with a new model, which takes a new approach to determining CI values for individual flights. This is described in Chapter 4 after a more complete analysis of potential emissions savings from CI is carried out in Chapter 3.

Chapter 3 The Cost Index effect on fuel use and carbon emissions

3.1 Introduction

This chapter will explore how the CI described in the previous chapter can have an impact on CO_2 emissions, therefore providing the justification for this thesis. Even a small change in CO_2 emissions from altering CI values is desirable owing to issues discussed previously with the lack of large scale solutions for emissions reductions in the aviation industry. If ICAO's (2013a) aim for stabilisation of emissions at 2020 levels is to be realised then a number of smaller measures will be needed, which can be implemented in the short to medium term to achieve this.

This chapter aims to quantify the level of carbon savings that could be achieved from changes in optimum CI value. This is in the form of a broad overview of six different aircraft models across six different flight distances. The methodology for assessment of the aircraft and the resulting impacts on carbon emissions in the context of practical changes in CI values is explored with examples of real world impacts.

3.2 Methodology for assessing fuel use for Cost Index values

3.2.1 Piano-X and Data Inputs

Piano-X is an aircraft analysis software based on Piano, used to assess the performance of aircraft. It was chosen for analysis owing to its availability and based on its use worldwide by airframe and engine manufacturers, in major environmental studies and by ICAO (Lissys Ltd., 2010). This software allows flight profiles to be created by adjusting performance characteristics. Figure 3-1 shows two of the key dialogue boxes used in this study. The first allows inputs of different aircraft weights, including passenger numbers and cargo on board the aircraft. The second allows flight profiles to be produced for different speeds and flight altitudes. There are four pre-determined speed levels available with the economy speed equivalent to the maximum range cruise (MRC) of the aircraft, as well as the option for manual entry of the cruise Mach. The default is for a design range but a specific flight distance can be entered instead. Allowable altitudes are also inputted here. In addition there are three other dialogue boxes for change in the thrust, drag and fuel flow; emissions indices; and fuel reserves and allowances. These latter parameters remained constant for all flight profiles created.

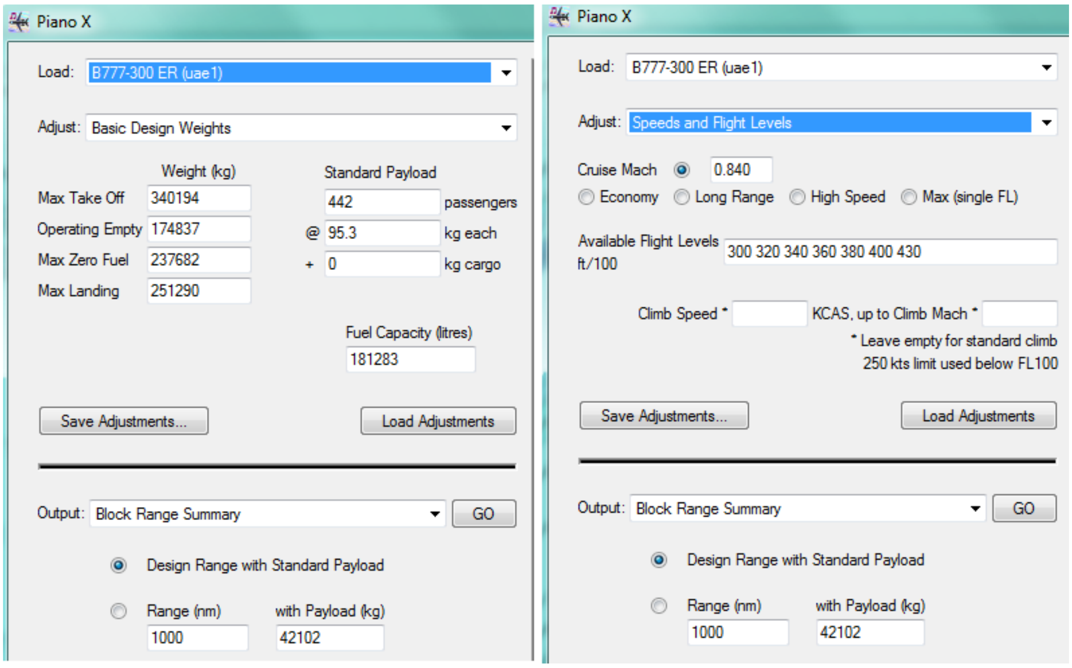

Figure 3-1: Piano-X "Basic Design Weights" and "Speeds and Flight Levels" dialogue boxes (Lissys Ltd., 2010).

Six aircraft models were used for comparison between CI and carbon emissions. These were the A300-600R; A340-600; A380-800; B767-300ER; B777-300ER and the B787-8. The choice of aircraft was based on the available aircraft in Piano-X and is representative of different aircraft sizes and age, split equally between the two main aircraft manufacturers of Airbus and Boeing.

Distances between 1000NM and 6000NM were used at 1000NM increments to represent the different design ranges of the aircraft and examine the effect of distance on CI and carbon emissions. Initially distances of 500NM and 7000NM were also included but are not presented here as they do not add any additional value to the analysis. Passenger numbers were taken from the manufacturers based on typical seating configurations provided by Boeing and Airbus, representing maximum passenger loads. Although it is acknowledged that aircraft rarely fly with full passenger loads, these are solely used for the purpose of comparison between aircraft types.

Table 3-1: Key Specifications for Aircraft used in Piano-X (Boeing, 2015, Airbus., 2015)

Aircraft	Average Range (NM)	Typical Capacity (no. of passengers)	Typical Cruising Speed (Mach)	Maximum Take-off Weight (kg)	First Year Service
A300-600R	3913	267 (2-class)	0.79	171700	1988
A340-600	7882	359 (2-class)	0.82	362760	2001
A380-800	8207	544 (4-class)	0.85	569000	2007
B767-300ER	6070	238 (3-class)	0.80	186880	1988
B777-300ER	7825	386 (3-class)	0.84	351530	2004
B787-8	7850	242 (3-class)	0.85	227930	2011

Firstly the economy speed setting was found for the aircraft in question in order to obtain the MRC. Flight profiles were generated for incremental Mach numbers above this, typically at 0.002 Mach intervals in order to obtain detailed flight profiles. This was done until the maximum speed of the aircraft was reached and Piano-X was unable to generate further flight profiles. This was repeated for each aircraft and for each distance.

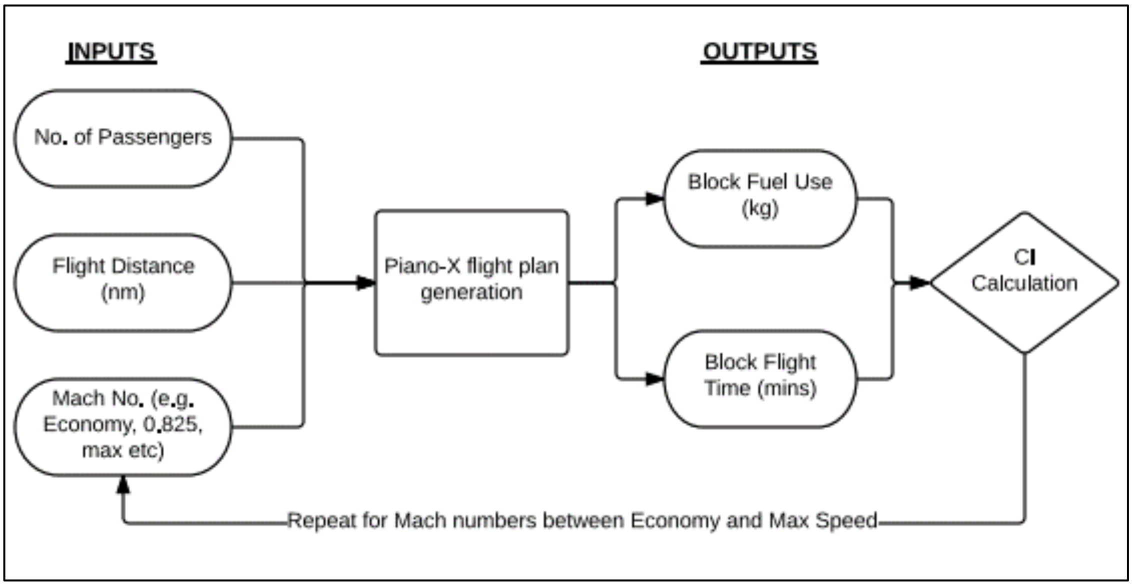

Figure 3-2: Cost Index generation process using Piano-X

Figure 3-3 shows a typical output from Piano-X using the Block Range Summary option. This is generated for each aircraft for every different Mach number and flight distance entered. Three key pieces of data are extracted: the block time in minutes, the block fuel in kg and the total carbon emissions of the flight, which were then entered into Excel.

```
Piano-X Copyright © 2008 Lissys Ltd / D.Simos ( www.piano.aero )


Loading plane: B777-300 ER (uae1)....Done.
Licencee: University of Leeds DTC/LCT

 RANGE REPORT  {fixed block distance & payload}
 ____________

 {TOW 308695.kg./ OEW 174837.kg./ Fuel 91756.kg./ Payload 42102.kg.}

 Range mode: fixed mach, step-up cruise

 Climb schedule: 250./ 316.kcas/ mach 0.783 above 27045.feet

 Cruise at Mach = 0.840  {FL 320 340 360 380}

 ICA 32000.feet, 491.ktas, 307.kcas, CL=0.51, 73660.newtons/eng=MCR-29%
 FCA 38000.feet, 482.ktas, 268.kcas, CL=0.51, 56475.newtons/eng=MCR-30%

              Distance      Time      Fuelburn
              (n.miles)     (min.)     (kg.)
              _________     ______    _______
 Climb           100.        15.        4800.   {S.L to ICA}
 Cruise         4788.       592.       74708.   {ICA to ICA}
 Descent         112.        19.         541.   {ICA to S.L}
              _________     ______    _______
 Trip  total    5000.       627.       80049.
 Block total  =========     642.       81291.

 Emissions: taxi,t/o  climb   cruise  descent  app,taxi   total
 (kg.NOx)     20.1    154.3   1464.1     1.8      3.6    1643.9
 (kg.HC)      0.91     0.20     6.82     2.89     1.50    12.31
 (kg.CO)       8.4      1.8    192.6     26.5     13.9    243.1
 (kg.CO2)    2492.   15169.  236076.    1710.    1434.  256881.

 Manoeuvre allowances:
 taxi-out      195. kg. {extra to t/o mass}      5.0 min.
 takeoff       594. kg.                          1.5 min.
 approach      259. kg.                          3.0 min.
 taxi-in       195. kg. {taken from reserves}    5.0 min.

 Reserves {at landing mass 227794.kg.}:

 Diversion distance          200. n.miles
 Diversion mach            0.582
 Diversion altitude        20752. feet
 Diversion fuel             3893. kg.

 Holding time                30. minutes
 Holding mach              0.382
 Holding altitude           5000. feet
 Holding fuel               2916. kg.

 Contingency fuel           4045. kg. {5.% of mission fuel}

 Total Reserve fuel        10854. kg.
```

Figure 3-3: Example output from Piano-X with three key data extracts highlighted in red.

1.1.1 Calculating the Cost Index

As individual costs for aircraft vary considerably, a representative CI value is used instead to provide a comparison of aircraft models. CI values were calculated in order to demonstrate the relationships that result, rather than demonstrating absolute values. Working from the MRC where CI=0, the CI represents the cost of fuel for every minute of flight time saved above this value. The CI at each Mach was calculated according to Equation 1. It should be noted that this is not the standard CI equation used by airlines as this analysis works backwards from already known flight profiles. The actual CI equation uses real costs for the calculation directly.

$$CI_X = \frac{(F_X - F_{MRC})}{(t_X - t_{MRC})} \qquad [1]$$

Where:

CI_X = Representative Cost Index at Mach number X

F_X = Block fuel use in kg at Mach number X

F_{MRC} = Block fuel use in kg at Maximum Range Cruise

t_X = Block flight time in minutes at Mach number X

t_{MRC} = Block flight time in minutes at Mach number MRC

The relationship between block flight time and block fuel use could then be plotted with indicative CI values shown for each aircraft model.

1.1.2 Case Study – comparison of real flight speeds with LRC and MRC speeds

To provide more of an insight into the actual speeds that are currently being flown a case study was used to compare actual Mach speeds over a flight profile compared to the LRC and MRC speeds for that flight. The route chosen for this was London to Hong Kong based on real aircraft data being made available by the major international airline that provided collaboration for this thesis, referred to Airline X from this point on.

This data covered one year's worth of flights for 2013 for a daily flight on the route. This is a daily night flight and therefore the data consists of 364 entries of data for each flight. The data supplied was date of flight; ramp weight of the aircraft; departure fuel; arrival fuel; flight time; wind speed; International Standard Atmosphere (ISA) deviation; and flight levels. This data was used to provide the weight of the aircraft, distance flown and altitude for specific flights to be entered into Piano-X to calculate the MRC and LRC speeds adjusted for wind conditions.

As only average speed for the entire flight is available from the Airline X data, real time speed for the whole flight profile were taken from Flight Aware (2013) for a two week period in June and July 2013, which allowed for these flights to be matched with the Airline X data. Flights were divided into those that were on time, those that were late departing but arrived on time, those that departed on time but arrived late and those that were late both arriving and departing. For each the Mach speed and altitude were plotted and compared to the LRC and MRC speeds for that flight. The number of Mach numbers above LRC and MRC were recorded and compared to the total number of Mach numbers at cruise (defined as being above 30,000 feet) to give the percentage of time spent above these values.

1.1.3 Validation

This methodology was validated using the real aircraft data provided by Airline X for a B777-300ER for a daily flight over one year with a known CI value. Piano-X outputs were generated for each Mach number for the average distance flown of the flight between Hong Kong and London Heathrow. Taking real flight conditions into account, such as wind speed and altitude the output for this know CI value from Piano-X was compared with the flight data from Airline X. The flights outputs matched very well, with a slightly higher fuel use from the real flight of approximately 600kg which can be accounted for by holding at Heathrow, which was not included in the flight distance used in Piano-X.

Data was also analysed for trends, which might affect real flights that need to be considered with the use of CI values. The airline data was divided into six groups based on distance and maximum flight level (Table 3-2). For each group the distance and maximum flight level were entered into Piano-X and the fuel burn and flight time were found for each at the know CI value. The flight time was then adjusted for the wind speed to examine its effect on the actual flight time compared to the modelled flight time, which is based on zero wind speed.

Table 3-2: Characteristics of six groups of real airline data

Group	Distance (NM)	Max Flight Level	Fuel Burn (kg)	Flight Time (min)	Wind (kt)	ISA Deviation (°C)
1	5552/3	320	102432	750	-29.6	0.1
2	5552/3	340	100823	748	-27.5	-0.5
3	5552/3	360	98981	738	-21.6	0.5
4	5552/3	380	97750	739	-22.2	1.3
5	5619	340	102890	755	-26.1	-1.3
6	5619	360	100356	764	-29.9	-1.6
Average	5557	340	100743	747	-26.3	0.0

Wind speed largely accounted for the difference between fuel burn of the Piano-X flight and the real flight as seen in Figure 3-4 (a). However, it is evident that in two cases this does not hold, with large gaps between the real and modelled fuel burn values for wind speeds corresponding to groups one and five. An explanation is found from examining Figure 3-4 (b). When the maximum altitude is constrained to FL320 and FL340 the fuel burn gap is still wide, this corresponds to the wind speeds where there was also a significant gap between the real data and the Piano-X data for groups one and five. Although not as strong as the correlation between wind speed and fuel burn, there is still a significant correlation between flight level and fuel burn found for the years' worth of real flight data. This reason for this is that there is less drag at higher altitudes owing to a reduction in air density. Related to this, ISA deviation is also correlated to fuel burn as higher air temperatures result in lower air pressure and less drag.

The validation undertaken highlights the need for the new model of optimising CI to consider the impact of wind and altitude conditions on a flight. Whilst the FMC will automatically adjust the CI for the wind conditions on a particular day, in order for the model to work the estimated impact needs to be know in advance to ensure that the scheduled flight time is still met and whether conditions will affect overall delay. The model will automatically adjust the flight parameters to represent this but will not change the optimum CI value itself to avoid double counting when the FMC makes its own adjustment for these conditions.

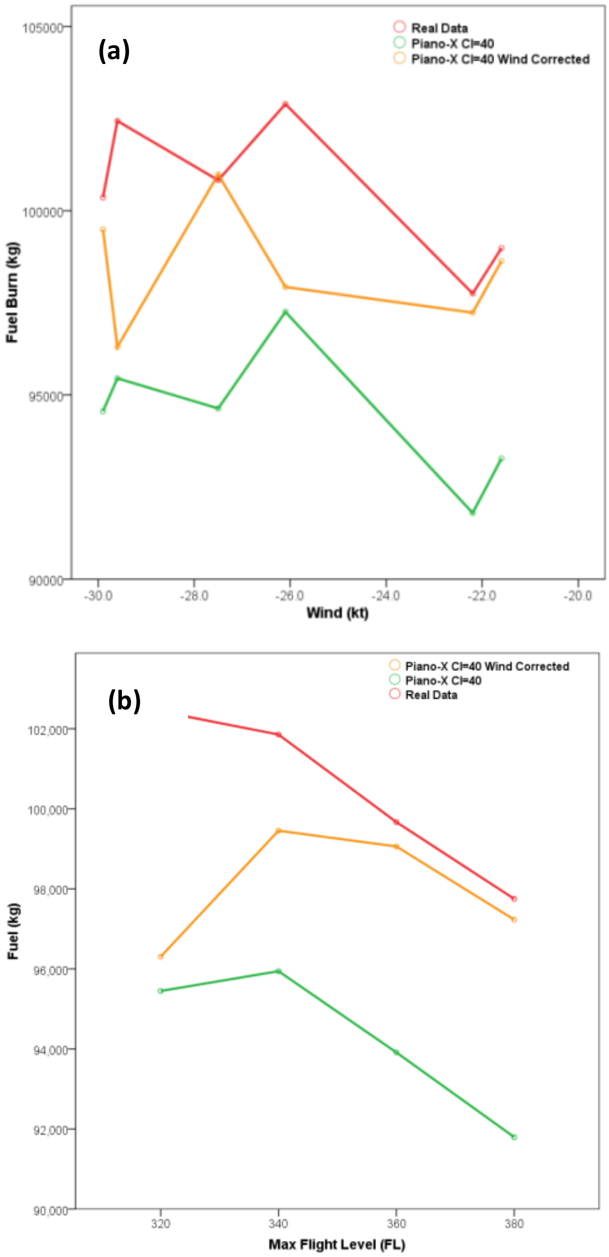

Figure 3-4: (a) Difference between fuel use for real data and Piano-X data at varying wind speeds (b) Difference between fuel use for real data and Piano-X modelled data with varying maximum flight level

1.2 Results

1.2.1 Relationships between fuel use and flight time

It is evident from Table 3-3 that there are significant differences between all aircraft types evaluated in this study regarding CI and the block fuel and time of a flight. The saving of changing from a CI value that equals Max Speed to MRC could reach 12.3% for the Airbus 340-600. However, it is more likely that an aircraft is flying closer to LRC in normal flight operations. The difference between MRC and LRC is much smaller at between 0.6% and 1%. However, this magnitude of change should not be understated as this is still a significant saving for the aviation industry.

Comparing this with the impact of flight time it can be observed from Table 3-3 that the change is smaller than that of fuel use for Max Speed to MRC at between 3.0% and 5.1%, but higher for the change in CI between LRC and MRC of between 0.7% and 2.3%.

Table 3-3: Effect of changing CI value on block fuel and block time between MRC and LRC/Max speed for design range of the aircraft

		% Difference MRC to Max	% Difference MRC to LRC	CI LRC	CI Max
Airbus A300-600R	Block Fuel	1.12	0.6	20	20
	Block Time	3.0	2.3		
Airbus A340-600	Block Fuel	12.3	1.2	80	80
	Block Time	4.9	1.7		
Airbus A380-800	Block Fuel	6.9	1.0	103	103
	Block Time	4.0	1.7		
Boeing B767-300ER	Block Fuel	3.4	0.5	14	14
	Block Time	5.1	2.3		
Boeing B777-300ER	Block Fuel	3.4	0.7	42	42
	Block Time	3.0	1.7		
Boeing B787-8	Block Fuel	4.5	0.6	24	78
	Block Time	3.7	0.7		

Figure **3-5** demonstrates the relationship between fuel use, flight time and CI for the six flight distances analysed. The relationship shows that with time savings coming at the expense of extra fuel use at higher CI values. The relationship is non-linear and also suggests that negative CI values are possible. In theory this is true, although an airline would have no reason to choose a negative CI value as it would result in longer flight times and increased fuel use. The relationship found here is the same as that found by Liden (1985).

The smaller aircraft i.e. B767-300ER and particularly the A300-600R, have smaller ranges of flyable CI values before maximum speed is reached and the relationship between flight time and fuel results in much flatter curves than for the larger aircraft. Whilst at low CI values the larger aircraft also demonstrate this relationship, as CI increases the relationship curve becomes steeper. This is significant as at higher speeds, greater fuel savings can be made by lowering CI for the same change in flight time compared to where the curve is flatter. Conversely at this point if speeds are increased and flight time is reduced, more significant fuel penalties will occur, particularly above the LRC.

The general relationship found here is the same as those found in earlier studies. Most notably Liden (1985) describes how variations in CI near the optimum value have a negligible effect on total costs and at smaller CI values where the optimum usually lies there is a much smaller change in fuel use than at higher CI values. Therefore the effect on total cost here is less.

It is evident that flight distance has an important impact on the relationship between fuel burn and flight time. Overall the B777-300ER performs the best across all flight distances with the lowest fuel burn over all CI values and quick flight times. The B787-8 also performs well and becomes more competitive with the B777-300ER at higher flight distances. Whilst the A380-800 also demonstrates quick flight times, its fuel burn is substantially higher than the other aircraft models with the exception of the A340-600. The slowest planes are two smaller aircraft – the B767-300ER and the A300-600R particularly at higher flight distances where these aircraft models are not routinely used. However they still have better fuel consumption than the A380-800 and the A340-600.

For all aircraft the general trend with increasing distance is for the relationship curves to become more curved. This trend along with the steeper relationship curves for larger planes suggests that there is more to gain from optimising CI values for long-haul flights. However, even small changes for smaller planes should not be discounted because of the higher number of flights in this category, meaning there could be a high cumulative saving in fuel and CO_2.

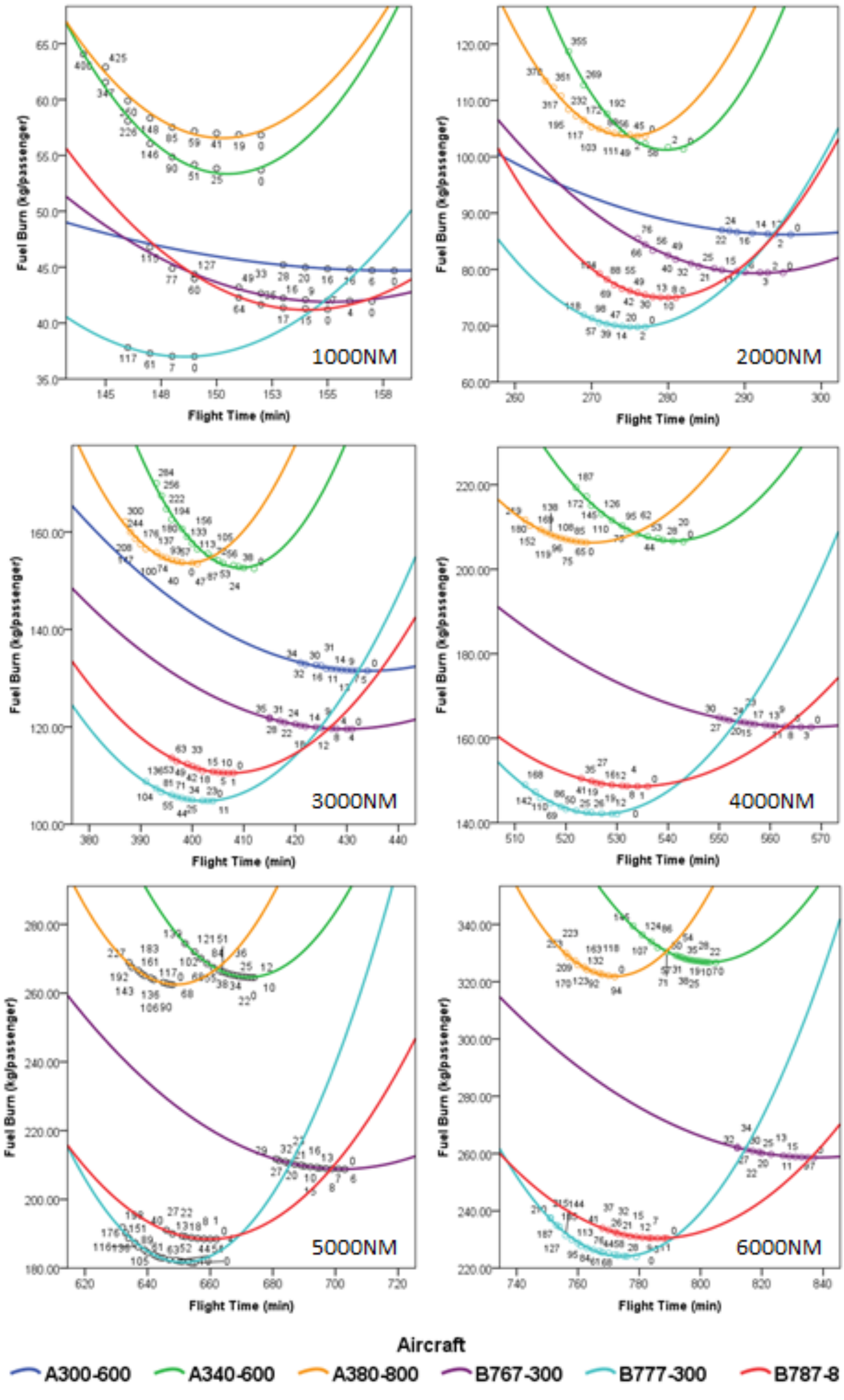

Figure 3-5: Relationship between fuel per passenger and flight time for six aircraft types between 1000NM and 6000NM flight distances (A300-600 is unable to fly the last three distances) with labelled representative cost index values.

3.2.2 Impact on carbon emissions

3.2.2.1 Six Aircraft Models

Changes in carbon reductions will happen at the same rate as that of fuel use as they are directly proportional. However, in absolute terms carbon emissions are just over three times higher than fuel use. There is not a linear relationship between distance and CO_2 emissions. In fact the relationship varies for different aircraft types. This is particularly the case for CO_2 emissions across all CI ranges, i.e. between Max speed and MRC.

Figure 3-6 shows the percentage difference in CO_2 emissions between MRC and Max speed for the six aircraft models over their design ranges. The two long-haul Airbus models (A380-800 and A340-600) have significantly higher percentage differences than the others, particularly the Boeing models. Whilst this indicates that higher savings could be made from optimising CI values for these aircraft models, it should be remembered from the previous section that they have much higher fuel use than the other models to begin with. Therefore even with this change, they may still not be as fuel efficient as other models. However, with long aircraft lifetimes, airlines that already own these Airbus models could see these results as evidence of a good reason to focus on these aircraft in the first instance in an attempt to reduce CO_2 emissions through optimising CI values.

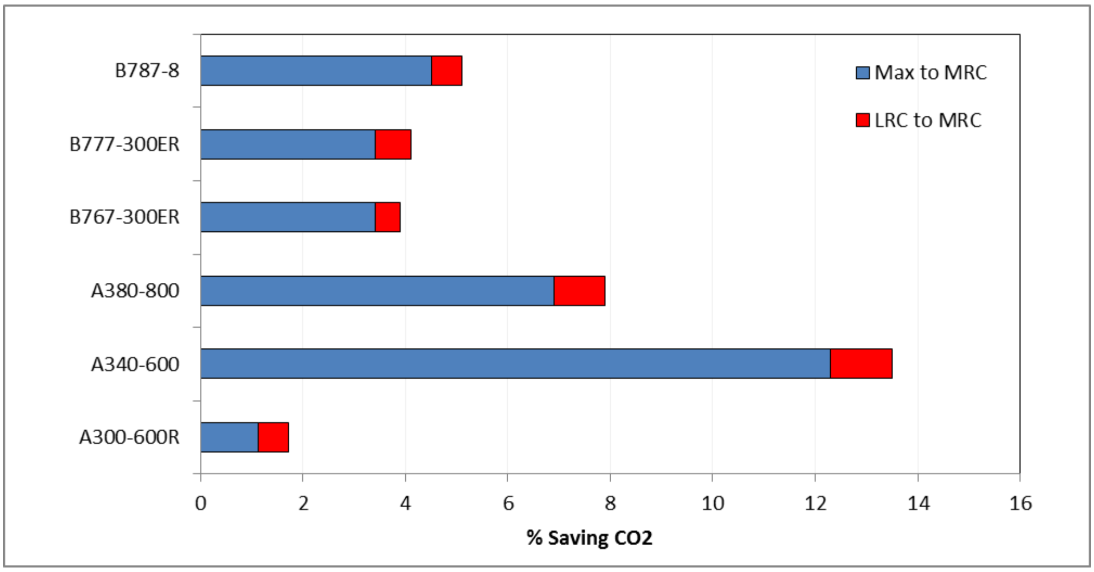

Figure 3-6: Percentage difference in CO_2 emissions between Max Speed and MRC for six aircraft model for their design ranges

Figure 3-7 shows the difference in CO_2 emissions over different flight distances. The general trend is for an increase in the difference between MRC and max speed in CO_2 emissions with increasing distance. However, most of the aircraft do not see a completely linear trend. The A380-800 sees the sharpest rise, overtaking the A340-600, which begins to plateau, after 3000NM. Again, the Boeing models see less dramatic rises in the difference in CO_2 emissions, but the B777-300ER does see a sharper increase after 4000NM to be on par with the A340-600 at 6000NM. This adds to the evidence that higher potential for CO_2 reductions lies at the higher flight distances. We assume here that aircraft will be flying close to their LRC speed, however in reality this might not be the case. Therefore the following section looks at a real life example to further assess the savings that could be made from optimising CI values.

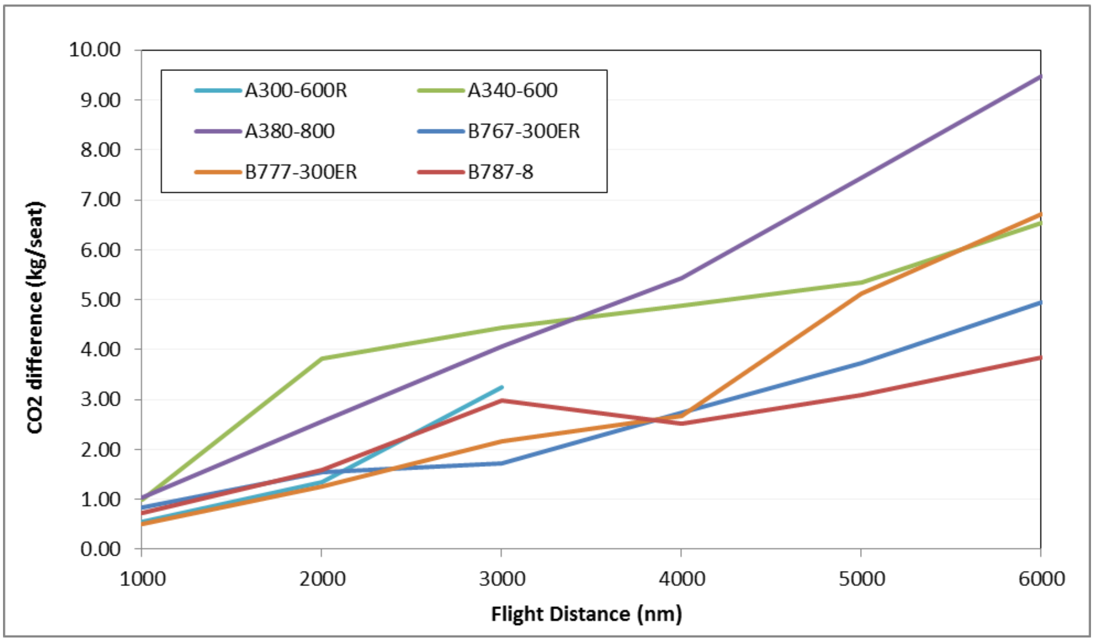

Figure 3-7: Difference in CO_2 emissions between MRC CI and LRC CI values for different aircraft models over six distances

1.2.1.1 Case Study – comparison of real flight speeds with LRC and MRC speeds

A typical flight profile can be seen with the LRC and MRC speeds shown for comparison in Figure 3-8. From the data collected it is apparent that in most cases for the flight examined over a two week period, the majority of the time aircraft are flying above their LRC speed, in some cases quite considerably. There was not a great variation between those flights that were on time and those that were late departing/arriving. For the on time flights, on average the aircraft was flying above LRC during cruise 80% of the time and for delayed flights 84% of the time. In fact the lowest proportion of time spent above LRC was 51%. This is backed up by results by Lovegren and Hansman (2011), which found that a majority of flights exceeding their LRC speeds.

Therefore it can be deduced that there is significant potential for reduction in fuel use. As described in the previous section, above LRC higher reductions can be made in fuel for smaller increases in time than between LRC and MRC. As LRC represents a 1% penalty in fuel on MRC, if aircraft are flying above LRC then it is reasonable to assume that savings of around 1% in fuel are realistic, as optimum CI values usually sit between LRC and MRC.

If the aircraft was flying as expected at LRC then the saving to where an optimum CI value is likely to be, at between LRC and MRC, is only 0.13%. However, the average cruise speed for the flights examined was Mach 0.86, a speed 3% higher than LRC. This translates to a saving of 8.5% in CO_2 emissions moving to the mid-point between LRC and MRC. Therefore, depending on how close to LRC airlines are currently flying their aircraft the saving is likely to be at least 1% if not significantly higher.

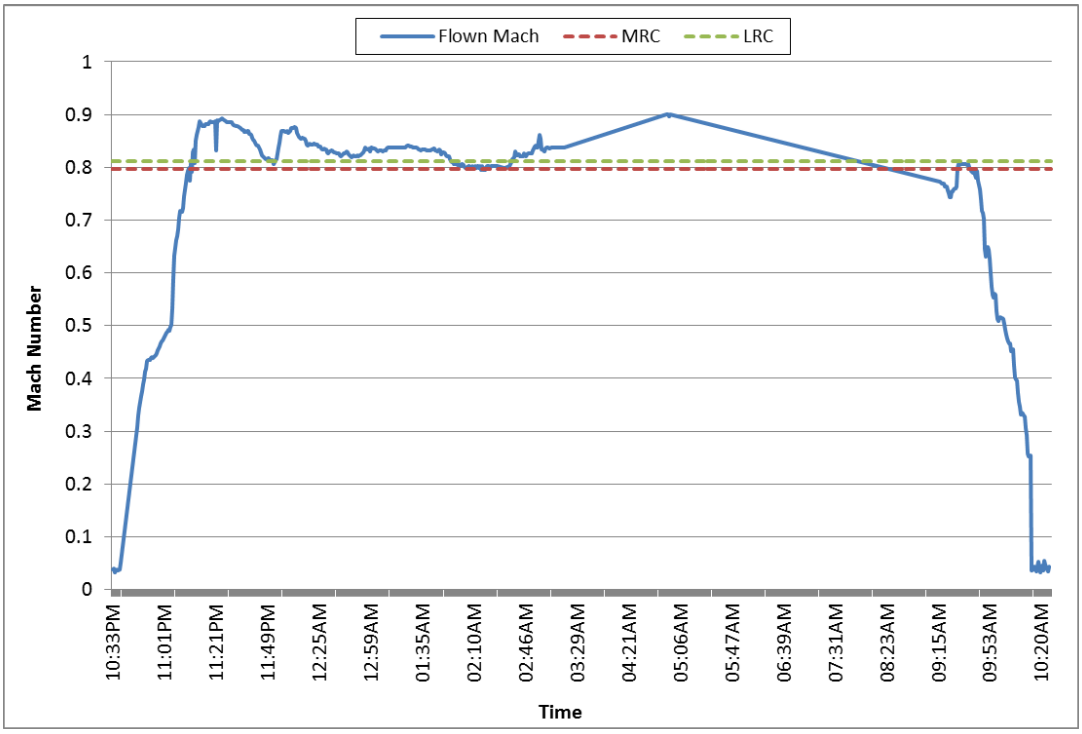

Figure 3-8: Example flight Profile London to Hong Kong with real Mach speed compared with LRC and MRC for the flight

1.3 The potential for fuel reductions for aircraft using Cost Index

The results demonstrate that CI is more complex than it first appears. The relationship between fuel burn and flight time is not linear and CI values can vary widely depending on aircraft model and flight distance. The comparison of six aircraft models has highlighted some clear differences in performance for flight time and fuel burn.

Before CI is even considered, this highlights the importance of airlines choosing the right model of aircraft for the best fuel efficiency. The use of CI curves can be a useful way for an airline to see the impact on fuel use over different distances and speeds and can therefore help in decision making depending on purpose of a particular aircraft purchase (e.g. planned route to be used on). It may be assumed that older aircraft are less fuel efficient than newer models. However, the evidence found here does not support this. For example, one of the newest aircraft models – the A380-800 – has high fuel use compared with much older aircraft models such as the B767-300ER.

This is one of the contributors to a decline in orders for the A380-800. Originally designed to compete with the B747-400, the A380-800 has actually declined in popularity along with its rival. Airlines instead now seem to prefer lighter twin engine aircraft, which are now capable of similar ranges to the superjumbos (Hepher, 2015). This has hit Airbus much harder than Boeing, which have the popular B777-300ER to fall back on, as well as the introduction of the B787-8 Dreamliner. One of the reasons relates to what has been discovered from the results, which the A380-800, whilst achieving good flight times, performs poorly in terms of fuel burn per seat. When it is considered that the A380 has 158 more seats (in the standard configuration used in this research) than the B777, but has a weight 228,806kg heavier than it according to Piano settings, it is evident that the extra passenger load is not able to compensate for the extra weight of the aircraft, resulting in the B777 being a more fuel efficient option for airlines.

Overall the CI curves show that it is the larger aircraft that will benefit the most in reducing the CI for CO_2 emission reductions. In general, as distances increase the more extreme the curves become, demonstrating that at higher CI values there is more potential for fuel burn reduction with a small change in flight time. Both these observations suggest that the optimisation of CI should be prioritised for long-haul flights, to maximise benefits. These relationships are the same found by Liden (1985).

Over the six aircraft models used in this study, a saving of at least 1% was found by making adjustments to CI values, which resulted in an average addition of 10 minutes of flight time. Results from the real world case study indicate that savings could be a lot higher for relatively small changes in flight time as aircraft often fly above their LRC speeds. Figure 3-9 shows an example of the buffer time available for a long-haul flight between Hong Kong and London over a period of 4 months. It is evident that there is sufficient buffer time to accommodate a change in flight time of 10 minutes. In this example, the departure time is scheduled at 11.55PM local time but the majority of flights leave between 12.15AM and 12.35AM. Therefore even on departure this time could be made up. Further to this the flight is scheduled to arrive at 05.40AM local time at London Heathrow, but the majority of arrivals are early, arriving between 05.00AM and 05.20AM. There are a small number of late arriving flights that can be attributed to late leaving flights from Hong Kong with over 40 minutes delay, suggesting a non-routine reason for a late departure, such as maintenance problems or excessive holding times and therefore these instances would have to be dealt with individually.

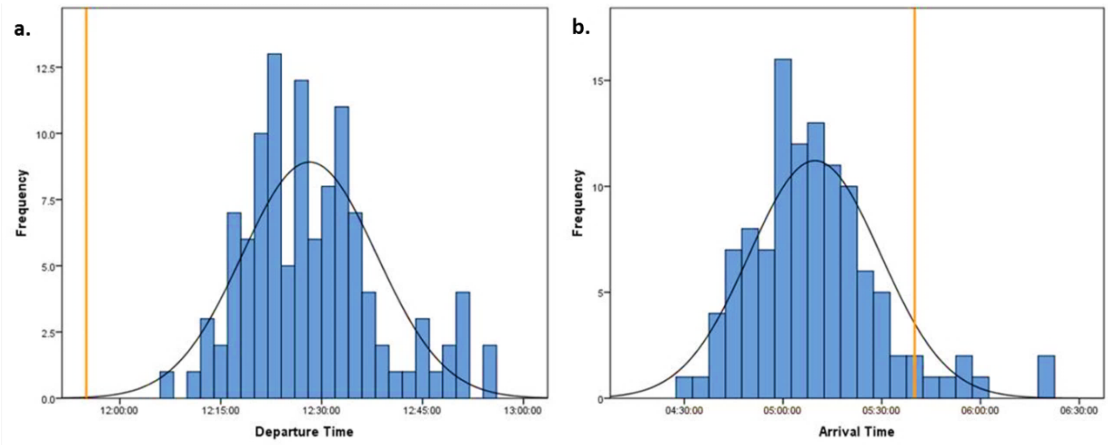

Figure 3-9: a. departure times and b. arrival times for a real flight example. Orange line shows scheduled a. scheduled departure time and b. scheduled arrival time for the flight (Flight Aware, 2013).

However, it must be considered that there will be buffer time needed for other eventualities, particularly in the case of short-haul and low cost flights that generally fly tighter schedules. Analysis of the relationships between different flight parameters to help identify the most important ones to focus analysis on was undertaken. In normal operations it is clear that wind speed has the strongest effect on flight time when real flight data for this route is considered, showing a strong linear relationship (Figure 3-10). There is a similar, albeit not as strong, relationship with fuel use. This flight faced an average headwind of 26kt. When validation was conducted the Mach speed was adjusted to take wind speed into account. Although there is evidence of the relationship between fuel use and flight time with ISA deviation, this is not as significant compared with the effect of wind.

It is difficult to calculate the absolute savings that may be made by changing the CI value owing to the differences in airline operational practices. However, it is certain that airlines that regularly fly their aircraft above the LRC speed have the most to gain in terms of reducing fuel use. However, there are advantages of changing CI values when below LRC. It must be considered that even a saving of less than 1% over a high number of flights can have significant absolute effects. Burrows et al. (2001) also holds this view, stating that although savings may seem modest as a reflection of the relatively flat cost curve, savings of even $150 per sector by an airline which serves 20 similar sectors daily would produce an annual saving of around $1.1 million.

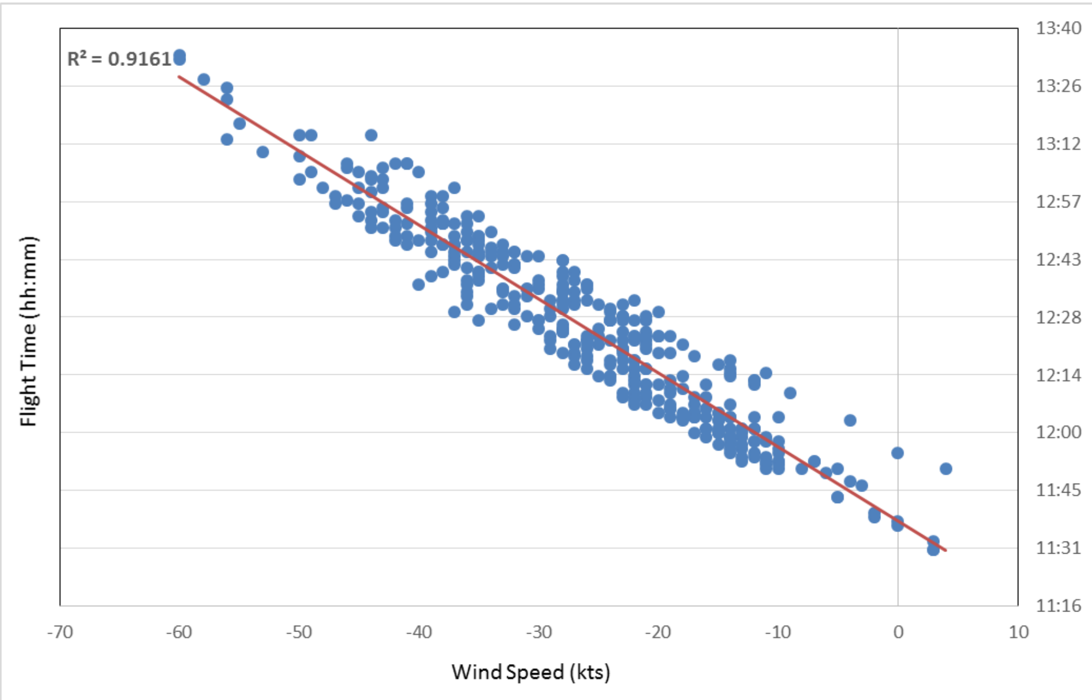

Figure 3-10: Relationship between real wind speed and flight time for B777-300ER data for a year's worth of flights in 2013.

The other advantage to airlines of using the CI to reduce fuel use is that the CI technology is already available and only requires a number to be entered into existing flight management computers. This is in contrast to a lot of other technologies that might only give slightly higher gains in fuel savings but require a lot more development and investment. Therefore CI can start achieving fuel and carbon savings today unlike other technologies, which will be brought in over time.

Although fuel and carbon savings are intrinsically related, it is interesting to look at carbon savings in their own right. There is not a uniform trend in the carbon savings that can be made between aircraft types and distance (Figure 3-7).

The most likely explanation for this is the design of each aircraft. Aircraft are designed with a specific range in mind. The A380-800 and A340-600 are designed for long-haul operations almost exclusively and therefore have poor environmental performance at lower speeds. It is likely that the B777-300ER sees increases its emissions as the flight distance gets higher as its original design was for a medium haul aircraft with extended range capabilities added later, therefore it is not as affected by long range design attributes that result in poor performance at smaller distances.

1.4 Summary

This chapter has examined the extent to which CI can save fuel and CO_2 emissions through its optimisation. Results show that there is significant potential for these savings. It is evident that long-haul flights show the most potential for reductions in the first instance as well as certain aircraft models, such as the A380-800. From real flight speed data combined with evidence from Lovegren and Hansman (2011) that contrary to popular belief that aircraft fly around their LRC speed, many aircraft are flying higher speeds than this. This suggests that savings of at least 1% in fuel and CO_2 are achievable through the optimisation of CI, if not significantly more.

To put this in context, this makes CI a very good candidate to contribute to the basket of measures that the aviation industry needs to stabilise its emissions. With the expectation that larger scale solutions such as biofuels, will be slow to penetrate the industry, a number of smaller measures to control emissions in the interim were discussed in Chapter 2. With the majority of these measures only producing small savings of less than 5% by 2020, this highlights the need for the use of multiple measures to stabilise emissions. ICAO aims for a 2% improvement in fuel efficiency per annum in the short term, with the objective of stabilisation of global CO_2 emissions at 2020 levels through incremental improvements in efficiency (ICAO, 2013a).

With the justification for optimising CI values for emissions reductions presented, the following chapters approach the task of creating a way in which airlines can more effectively find their optimum CI values on a flight-by-flight basis. The following chapter uses information from the literature review to create a new model for the calculation CI, which is more sophisticated that the current method of using a single equation.

Chapter 4 Improving the Cost Index Calculation

4.1 Introduction

In the previous chapter the carbon savings that could be achieved from optimising CI values were demonstrated. This chapter looks to find a practical way of airlines to do this, building on information obtained in Chapter 2. It is evident that at present airlines have difficulty with the calculation, particularly regarding accounting for cumulative costs and factoring in flight delay. The aim is to create an Optimised CI (OCI) model for airlines to more easily calculate optimum values for every flight. The model will be flexible and transparent, allowing for airlines to understand the processes involved and customise for their own use.

4.2 Creating a new Cost Index model

4.2.1 Model processes

The OCI model is created with the aim of providing an easy to use interface to calculate CI values, initially using the CI calculation and then adjusting for additional costs and schedule restrictions. Figure 4-1 presents the processes involved in the OCI model. Produced using Excel, the basic premise of the model is to avoid constraining all costs to the traditional CI equation, but to instead use additional calculations to determine the optimum CI value. The model is set up in such a way that the CI is calculated on a flight-by-flight basis, taking into account the specific aircraft, flight characteristics for that day and up-to-date costing information.

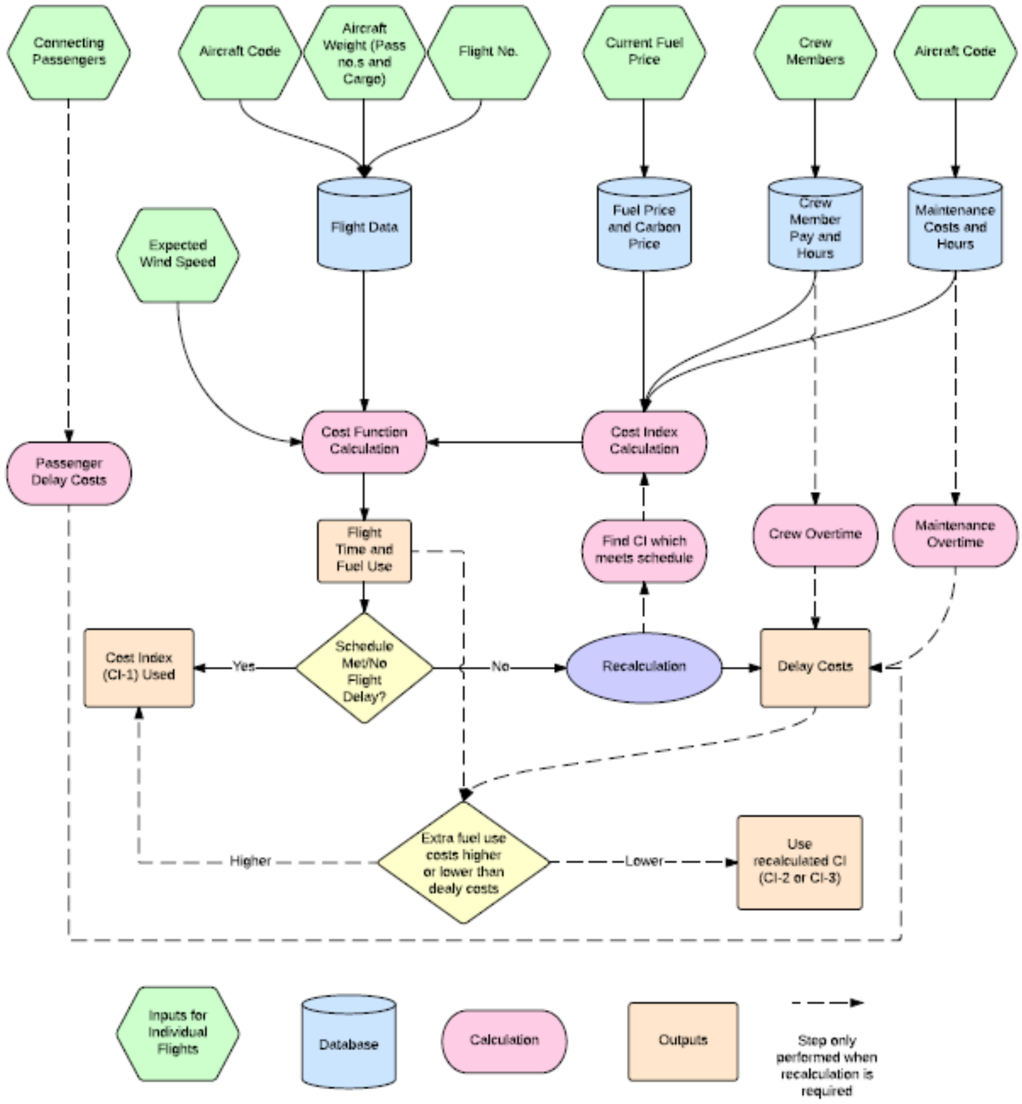

Figure 4-1: Cost Index Calculation Model Processes

4.2.1.1 Excel Model Set-up

The following describes in more detail the way the model has been created and how it is intended to be used by airline operations.

Interface Page

This page provides inputs to be entered into the model by the airline. This is the only part of the model that airline operations should have to use on a regular basis. For each flight there are six key inputs:

1. Flight No. – this links to the data in the flight database, which holds information for the route, including the normal scheduled flight time as well as the range of data relating to different flight speeds. The flight number will be selected from a drop down list linked to the database.

2. Aircraft Code – this is needed to pinpoint the specific aircraft being used for the journey. Even for the same model of aircraft, individual aircraft will have varying maintenance costs depending on age and number of hours already flown for the month in question. The aircraft code will relate to the maintenance database, which in practice would hold information on the entire fleet of aircraft for an airline.

3. Average Wind Speed – this would represent that average wind speed expected for the flight in question. As this model is designed to be used as close as possible to the departure of the flight it is anticipated that a good estimate would be available to the flight planning department.

4. Crew Members – space is provided for input of all crew members on the flight in question. Each crew member, both flight crew and cabin crew, have their own unique code. Using a drop down list, each crew member is linked to the crew costs database.

5. Cargo Weight – simply the kilograms of cargo being carried on the flight, which is, linked to the Flight Data.

6. Number of Passengers – total number which is linked to the Flight Data.

7. Connecting Passengers – this requires the number of passengers for each class that are connecting for each onward flight to be entered. This will be linked to delay.

Once all of these inputs have been entered the user can then press the calculate button. The optimal CI is displayed from the calculation page in both kg/min and 100lb/hour as different flight management systems use different units. The corresponding Mach number, flight time, fuel use, total flight cost and emissions of CO_2, NO_X, hydrocarbon and carbon monoxide emissions are also displayed.

Crew Costs Database

This database contains all personnel, both for cabin crew and flight crew. The details contained here consist of:

- Basic salary ($/year)
- Duty pay ($/minute)
- Hours flown this month
- Hours remaining this month
- Flights remaining this month (mins)
- Flight time for remaining flights (mins)
- Flight time available for this flight (mins)

The idea behind this database is that this will keep track of whether crew are likely to exceed the maximum number of hours before overtime payments need to be paid. If flight time does result in overtime needing to be paid then these extra costs are factored into the CI equation. The data concerning which member of crew is on the flight will be extracted from the drop-down list from the interface page.

In order to take account of cumulative crew costs the time available for the flight in question is calculated by the flights already flown and the scheduled time for the flights remaining (Equation 4-1).

$$T_F=(T_M-T_F)-T_R \qquad [4\text{-}1]$$

Where:

T_F = Time available for the flight in question

T_M = Maximum time available per month for crew member before overtime

T_F = Time already flown this month by crew member

T_R = Time needed for other flights remaining to be flown this month

Maintenance Costs Database

The maintenance costs database is similar to the crew costs database. The database is comprised of each aircraft in the fleet and the particular aircraft in question is extracted from the dropdown list on the interface page. The data consists of the following for each aircraft:

- Maintenance Costs for 'A' and 'C' checks
- Hours flown this month
- Contract hours
- Hours still scheduled for this month (excluding current the flight)
- Hours remaining

The maintenance costs for 'A' and 'C' checks will be the costs that go into the initial CI calculation which is the best estimate for time-dependent maintenance costs provided by University of Westminster Transport Studies Group (2008c). The other information relates to the use of power-by-the-hour contracts. This information is used in the case of extra flight time and is used to calculate any penalties that might result from the maintenance company for exceeding contracted flights hours.

Fuel Calculation

This worksheet contains the spot price of jet fuel taken from the interface page along with the percentage of fuel that is hedged and the hedging price. It is anticipated that the latter two will need occasional adjustments by the airline but not as regularly as the spot price of fuel, therefore are not included on the interface page. The other fuel related cost included here is the carbon price, if applicable, which is proportional to the amount of fuel used. As this value is for every kilogram of CO_2, it is converted to every kilogram of fuel by multiplying it by the CO_2 conversion index of 3.157. The total cost of fuel is calculated in Equation 4-2.

$$F_C=(\%F_H*F_{HP})+(\%F_S*F_{SP})+(CP*EF) \quad [4\text{-}2]$$

Where:

F_C = Fuel Cost (\$/kg)

$\%F_H$ = % of jet fuel that is hedged

F_{HP} = Jet fuel hedge price (\$/kg_{fuel})

$\%F_S$ = % of jet fuel that is not hedged and subject to the spot price

F_{SP} = Jet fuel spot price ($\$/kg_{fuel}$)

CP = Carbon price ($\$/kg_{CO2}$)

EF = Emissions Factor to change the carbon price from $\$/kg_{CO2}$ to $\$/kg_{fuel}$ (in this case EF = 3.157)

The carbon price is determined by the amount of allowances that need to be purchased rather than those given to the airline for free in the early years of emissions trading schemes. So the carbon price in these years is likely to be only a proportion of the full market carbon price. A more in depth measure of CO_2 pricing can be undertaken by setting an emissions target for each aircraft and divided amongst individual flights. The model can then be set to calculate penalty payments for exceeding carbon caps for the airline.

Flight Information

This page contains the details for all flights in the airline (or a subsection of flights using a particular aircraft). It also contains the flights that passengers connect to, operated by other airlines in the network. The information displayed for each flight consists of:

- Flight code
- Origin
- Destination
- Distance
- Scheduled Departure Time
- Scheduled Arrival Time
- Schedule Duration
- Transfer time for passengers at origin airport
- Departure Terminal
- Arrival Terminal

Additionally flights operated by the airline using the system also display the minimum turnaround time for aircraft at the destination. For flights operated by other airlines the rebooking fee is also displayed. Most of these inputs are for use with the next worksheet that calculates delay costs.

Delay Costs Database

Delay costs are one of the more complex areas for airlines to account for. Ideally airlines will know all the costs associated with passenger delay, such as rebooking and providing compensation, plus knowing how many passengers will be owed these costs. However, if these are not known for any reason, the model also accommodates this by using generalised costs in the basic model. It should be stressed that this is not the ideal situation and airlines should strive to use the advanced model to obtain the most accurate CI values.

BASIC MODEL

Using data from the University of Westminster Transport Studies Group (2008b) delay costs are given in dollars per minute based on eleven groupings of delay time (Table 4-1). Reactionary multipliers are also included which account for costs associated any knock on effect on the system from the initial delay.

Delay minutes are taken from the initial calculation of the CI value and assigned to one of the delay time categories in Table 4-1. This value is then multiplied by the number of passengers who would be affected taken from the interface page.

Table 4-1: Passenger Delay Costs (University of Westminster Transport Studies Group, 2008b)

Range from (min)	Range to (min)	Passenger Cost ($)
1	15	0.20
16	30	0.54
31	45	0.95
46	60	1.34
61	75	1.67
76	90	1.86
91	119	2.21
120	179	2.63
180	239	2.97
240	299	3.05
300	1000	3.60

ADVANCED MODEL

There are three types of passenger delay costs, which need to be taken into account as shown in Figure 4-2 . The simplest calculation is for those passengers not connecting to other flights. These passengers will be owed compensation (depending on the country in which the flight arrives) if the flight is later than a defined period e.g. 3 hours. Connecting passengers will need to be rebooked onto other flights if they miss them owing to delay of the original flight, as well as any compensation if their final flight arrives after the defined period.

The third does not concern passengers of the original flight, but the passengers on the succeeding flight by the same aircraft. In this case help and care costs i.e. meal vouchers, phone cards etc. are required to be paid if the aircraft is late departing. These are again only payable after a certain period of time and depend in part on the minimum time that the aircraft can be turned around in. These costs are not included in the subsequent flights delay costs as they are essentially already fixed having been paid out to passengers before the flight. For a delay of this length it is very unlikely that the costs can be recovered as there is only a limited difference in flight time between the lowest and highest speeds of the aircraft.

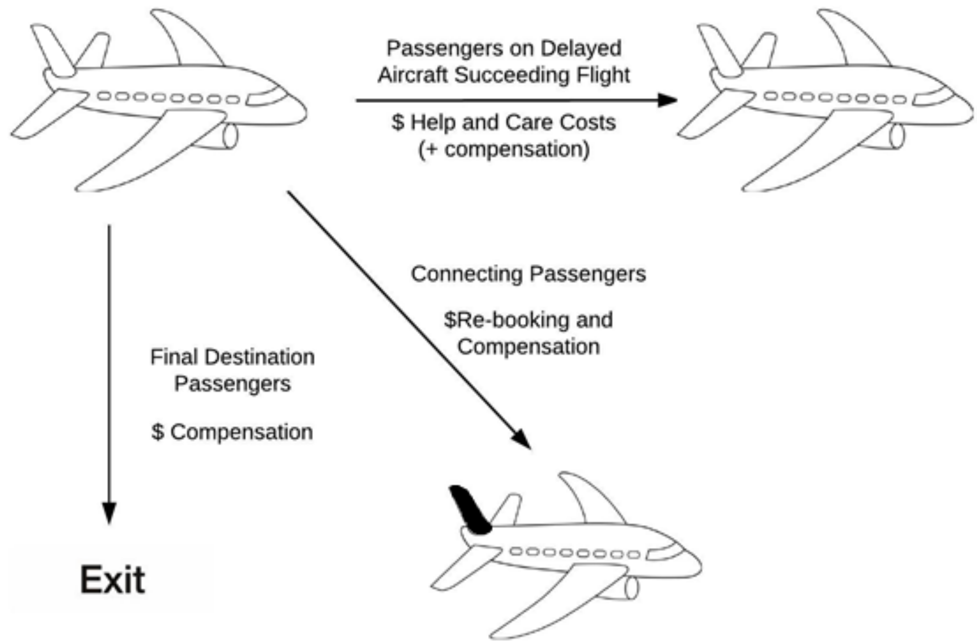

Figure 4-2: The three types of passenger delay costs considered in the OCI model

For care costs the minimum turnaround time for the aircraft is subtracted from the actual time between the two flights (if there is a difference) and this is taken from the overall delay time. The new departure time is calculated from this delay and compared with the original delay time. If a delay time threshold is crossed for compensation, the care costs are multiplied by the number of passengers on that next flight. Accommodation is also included in the care cost if a night time threshold is reached. Equations 4-3 and 4-4 demonstrate the process in the model to determine if care and help costs need to be paid and if so by how much, using IF functions.

$$A = IF((DP_S + (DP_S - (I_S - I_{MIN})) > NT, "Yes", "No") \qquad [4\text{-}3]$$

$$TC_{AH} = IF(A="Yes",(C_A+C_H)*P,IF(D_R>D_T, C_H*P,0)) \qquad [4\text{-}4]$$

Where:

A = Overnight accommodation required

DP_S = New departure time

I_S = Scheduled interval between flights

I_{MIN} = Minimum interval between flights i.e. fastest turnaround of the aircraft

NT = Night time threshold time

TC_{AH} = Total cost of help, care and accommodation

C_A = Cost of overnight accommodation

C_H = Cost of care and help

P = Number of passengers

D_R = Remaining delay after turnaround of aircraft

D_T = Care and help delay time threshold

C_H = Cost of care and help

Rebooking passengers is slightly more complicated. Firstly it is calculated as to whether passengers will miss their connecting flights given the information inputted on the interface page by the airline. The departure time for the connecting flight is taken from the flight information page and compared to the expected arrival time of the original aircraft given the expected delay. This gives the available transfer time, which is compared against the minimum transfer time required by the passengers. Whether the flight will be missed or not can then be determined by the following IF function (Equation 4-5).

$$MF=IF(((DP_C-AR_O)-I_S)>0, No, Yes) \qquad [4\text{-}5]$$

Where:

MF = Missed Flight

DP_C = Scheduled departure time for connecting flight

AR_O = Arrival time of original flight

I_S = Scheduled interval between two flights

If the output is “no”, then no costs are incurred, if the output is “yes” then the same process is undertaken for the next available flight and so on. If a flight has to be rebooked, it is first determined whether the flight is operated by the same airline as the original airline by searching for the identifier for that airline in the flight code, as this is likely to affect the rebooking cost. If it is a flight operated by another airline then normal rebooking costs depending on the class of passenger are multiplied by the number of passengers in that class.

Flight Data

Flight data is calculated from Piano-X as in the methodology described in Chapter 3. Using the number of passengers, cargo weight and the distance of the flight, a range of speeds for the flight in questions can be calculated. Firstly the MRC of the flight is calculated from the economy speed setting in Piano-X. This gives an output displaying flight time, fuel use and emissions of the flight. Mach numbers at 0.0005 increments are then inputted into Piano-X starting from the MRC up to the maximum speed the aircraft is able to fly, with every flight time, fuel use and emissions value taken for the individual speeds (Figure 4-3).

	A	B	C	D	E	F	G	H	I
1	**Flight Data**								
2			Schedule	Wind Speed					
3	**CX251**	HKG-LHR	**725**	**0**	Cost Index 1	**11**			
4	Mach	Block Fuel	Block Time	CO2	NOx	HC	CO	Cost Function 1	Total Cost
5	0.8200	89545	725	282961	1776.3	13	269.1	0.0583	17.5938
6	0.8205	89545	725	282961	1776.4	13	269.1	0.0582	17.5938
7	0.8210	89545	724	282963	1777.2	13	269	0.0582	17.5917
8	0.8215	89507	724	282843	1777	13.11	269.7	0.0581	17.5849
9	0.8220	89511	724	282854	1777.8	13.11	269.6	0.0581	17.5856
10	0.8225	89515	723	282869	1778.9	13.11	269.5	0.0581	17.5843
11	0.8230	89521	723	282887	1779.6	13.11	269.4	0.0580	17.5854
12	0.8235	89529	722	282911	1780.5	13.1	269.3	0.0580	17.5848
13	0.8240	89538	722	282940	1781.5	13.1	269.1	0.0580	17.5864
14	0.8245	89548	722	282972	1782.6	13.1	269	0.0579	17.5882
15	0.8250	89560	721	283011	1783.6	13.1	268.9	0.0579	17.5884
16	0.8255	89574	721	283053	1784.7	13.1	268.8	0.0579	17.5909
17	0.8260	89589	721	283101	1785.9	13.1	268.7	0.0578	17.5936
18	0.8265	89605	720	283153	1787.1	13.1	268.5	0.0578	17.5944
19	0.8270	89623	720	283210	1788.4	13.1	268.4	0.0578	17.5977
20	0.8275	**89644**	**719**	**283276**	**1789.7**	**13.1**	**268.3**	0.0578	17.5994

Figure 4-3: Flight Data for OCI Model

Initial Cost Index Calculation

The initial CI calculation (CI-1) takes the form of the traditional CI calculation using data previously calculated in the preceding databases (Equation 4-6).

$$CI=\frac{L_C+M_C}{F_C} \qquad [4\text{-}6]$$

Where:

CI = Cost Index (kg/min)

L_C = Labour Costs (\$/min)

M_C = Maintenance Costs (\$/min)

F_C = Fuel Costs (\$/kg)

Once the CI is found it is used to find the Cost Function (Cf) for each Mach number calculated by using Equation 4-7. The Mach number for which the lowest Cf is found i.e. where direct operating costs are minimised, is the desired flight profile that results from the calculated CI, giving the flight time needed for further calculations.

$$CF=\frac{ff+CI}{Vg} \qquad [4\text{-}7]$$

Where:

ff = fuel flow in kg/min

CI = in kg/min

Vg = Ground Speed which is the Mach (including addition of wind speed) multiplied by the speed of sound at altitude.

Final Cost Index Calculation

The final part of the model is the optimisation of the CI. The flight time from the use of the initially calculated CI (CI-1) is compared with the scheduled time for the aircraft, including any delay. If the flight time fits the schedule then the OCI model automatically registers this as the optimum CI for the flight.

If this is not the case then there are three different recalculation methods as follows:

CI-2 A new CI is calculated if the flight time from CI-1 does not fit the schedule representing the closest flight parameters that does meet schedule time.

CI-3 A recalculated CI taking into account delay, if present. This calculates any passenger costs and overtime for crew or maintenance.

CI-4 If delay is present this recalculates the CI to make up as much of the delay as possible, regardless of the total cost.

For the original CI (CI-1) flight the cost of labour, maintenance and fuel are combined. Crew overtime costs are calculated by taking the hours available and comparing them to the actual time of the flight. If this number comes out positive i.e. more time than the crew have available then the amount of overtime for the month is calculated for each crew member. There are three categories for this taken from discussion with airlines: 84-90 hours at 1.5 times salary, 90-100 hours at 2.5 times salary and over 100 hours at 3.5 times salary (although this may vary depending on the airline).

For maintenance, the contracted hours or extra hours affecting flight maintenance schedules are also calculated in a similar way. An exceedance of hours resulting in any penalty payments will also be added to the cost. Passenger delay costs will also need to be added to the total flight cost, as described previously i.e. compensation, help and care and the rebooking of passengers.

The first recalculation (CI-2) is used in the case when there is no delay. If the flight time from CI-1 is higher than scheduled time then the flight time will be adjusted to correspond to the schedule time of the flight. The corresponding values for fuel use, Mach speed and emissions are the found against the new flight time. As the model is no longer working from actual flight costs, the CI has to be found from creating an equation from the relationship between cost function and Mach speed. To do this a range of possible CI values are used to calculate the cost function for the flight data in question, in the same as described previously with Equation 4-7.

The third CI value (CI-3) represents the case where a flight delay is present. A new CI is calculated taking into all the costs of CI-1 but with the addition of delay costs. For small delays this consists of extra crew and maintenance costs, but for more significant delays passenger costs are also included. This gives an indication of how much of the delay can be recovered within the flight time, whilst still considering the increased costs of fuel. CI-4 on the other hand, does not take fuel costs into account and therefore, recovers as much delay as possible within the range of speeds possible for the aircraft. For longer delays, it may not be possible to recover all delay time in flight and therefore delay costs must be applied to the time that cannot be recovered. The purpose of CI-4 is to demonstrate the penalty for not including fuel costs in the calculation as compared to CI-3 to improve delay recovery management.

Once these total costs for the different CI values have been calculated the lowest total cost is found and this is the CI that is displayed to the user on the interface page, along with the flight characteristics e.g. fuel use, emissions, flight time etc.

4.3 Inputs

Inputs were used in the model for its development based on a base case in the industry using current data and practices. The following inputs were used in the model.

4.3.1 Flight Data – Interface Page

- Flight Number

The example flight corresponded to a year's worth of flight data provided by Airline X as described in Chapter 3. It is a daily night flight from Hong Kong to London Heathrow.

- Aircraft Model

The Boeing 777-300ER was chosen as it is the aircraft model corresponding with the flight data from Airline X.

- Average Wind Speed

Default is taken as zero wind speed but changed in the scenario analysis in Chapter 5.

- Fuel Price

Taken as fuel price as of 31 July 2015 from IATA fuel price analysis for Asia and Oceania, corresponding to $62/bbl or $0.5/kg (2015b).

- Cargo Weight

Weight of maximum of 44 LD3 containers that the B777-300ER can carry (Boeing., 2015).

- Crew Members

Minimum legal requirement needed for B777-300ER with 1 crew member per 50 seats in economy class plus additional staff for 3-class configuration (University of Westminster Transport Studies Group, 2008a).

- Number of Passengers (PAX)

Taken as load factor of 80% of total capacity of 386 passengers for the B777-300ER 3-class configuration (Boeing., 2015).

- Delay

Default setting is the average delay taken from CAA statistics for 2014 for the airline's flights arriving at Heathrow (CAA, 2014).

- Connecting PAX

Three example connections are used, to Manchester, Oslo and Edinburgh. Two flights to Manchester are considered, both of which are codeshares with another airline and with the Oslo and Edinburgh flights being operated by other airlines (Table 4-1). Reliable Data is not available on the number of connecting passengers to these flights so theoretical numbers are used for each class of passenger.

4.3.1.1 Crew Costs

Standard crew costs were used for basic salary and duty pay depending on job level for both flight and cabin crew obtained from Airline X. A schedule of flights was based on Hong Kong Flight Time Legislation for the avoidance of fatigue in air crews (Civil Aviation Department Hong Kong, 2013) and information gained from interviews with airline professionals. All scheduled flights for the B777-300ER for the airline were recorded and a schedule of flights could then be determined based on one long-haul round trip (e.g. London-Hong Kong) per month. This allowed the number of hours available for the current flight to be determined.

Table 4-2: Example flight connections, which arrives at 05:40 with next available flight, also presented if original connection missed.

Destination	Departure Time	Next Available
Manchester	08:25	10:15
Manchester	10:15	12:00
Oslo	07:55	10:20
Edinburgh	09:35	11:40

4.3.1.2 Maintenance

Maintenance costs for a two engine wide-body (i.e. B777-300ER) were obtained from IATA data in dollars per hour (IATA, 2014a). Methodology from the University of Westminster's Transport Studies Group (2008c) for calculation of marginal maintenance minutes was then used to find the maintenance costs dependent solely on flight time rather than flight cycle. This involved the removal of a 40% maintenance burden. The remaining cost was divided into airframe/components and powerplant with a 65% and 35% share respectively. From these remaining costs the marginal minute cost is found by removing a further 50% and 60% from the airframe/components and powerplant cost respectively.

4.3.1.3 Fuel Costs

The spot price of fuel is taken from the input on the interface page as described in Section 4.3.1. The fuel hedge for the year 2015 for the Airline X were taken from reports from the finance director of the carrier, which includes a 61% fuel hedge at $95/bbl. A carbon price is not entered at this point, but will form part of scenarios analysis in Chapter 5.

4.3.1.4 Delay Costs

Compensation costs are obtained for the EU from the Civil Aviation Authority (2015) as described in Chapter 2 and help and care costs are obtained from the University of Westminster's Transport Studies Group (2008b). Rebooking costs are variable and will depend on the specific flight and the day. Therefore, a standard cost of $150 is used for economy class passengers, $200 for business class passengers and $300 for first class passengers for all connecting flights.

4.4 Assumptions and Uncertainties

The OCI model has been created with the best available data and information; however there are certain assumptions and uncertainties that may require attention for real world use. The first area where a number of assumptions had to be made was with crew costs. Whilst general salary information is available, information regarding the structure of pay for flight and cabin crew is not readily available. The model at present only uses duty pay in the initial CI calculation but there is likely to be a variety of time dependent pay depending on the individual airline. Crew schedules also had to be estimated, but again this is something in reality that airlines should easily know.

Similarly with maintenance different airlines carry out maintenance in different ways and details about maintenance contracts are not readily available. The presence of these assumptions and uncertainties have been dealt with by providing a flexible framework for the model, in which airlines are easily able to adapt certain elements of the calculation. Other areas where estimations or educated guesses had to be applied included the destinations and numbers of connecting passengers and the costs of rebooking. Again this is something that can be easily adapted by airlines rather than an inherent problem with the model itself.

One of the more inherent uncertainties with the model at present is the use of Cost Function (Cf) values. In theory CI values should relate to a specific Cf and therefore individual Mach speeds. This is how the model was originally set up. However, when analysis was taking place using different scenarios, it was noted that even though CI values were changing, Mach speeds and the associated data was not. After investigation it was found that small changes in CI values were not enough to move to the next Cf value. Although piano-X flight profiles were created for Mach speed increments of M0.0005 it appears that this was still too large an increment that Cf values were too far apart. To rectify this, the equation for the relationship between Cf and Mach was used instead to find the correct Mach speed for a specific Cf value.

This problem may also be rectified in real life use, as discussed in the next section, by airlines using their own flight data, which may provide a better level of detail. However, this may also be an underlying issue with the use of Cf values in the flight management computer and will therefore require further research.

4.5 Application in Airlines and Further Developments of the OCI Model

The aim of creating the OCI model is to make an accessible and transparent model for the calculation of optimal CI for airlines. Excel is deliberately used for this purpose as it creates a more transparent model with the steps involved in calculation easy to follow. By seeing that these kinds of calculations can be done in this way may help to convince airlines that optimising the CI is something that they can easily incorporate into their flight planning systems. The use of Excel also makes the model easily adaptable by airlines. The setup of the model means that on a day-to-day basis airline operations would only need to use the interface page. However, adjustments to other parts of the model would need to be made occasionally, such as the amount of fuel hedged and at what price, additional connecting services, additional crew etc., although this is relatively easy to do.

Whilst the model effectively addresses the problems that exist with cumulative crew costs, there are some costs that the airline may still struggle to account for. For example, maintenance costs are particularly problematic. Although the model does address the issue of maintenance contracts, the initial maintenance costs may still not be accurately known. It is suggested that if maintenance costs cannot be determined by the airline, a good estimation to use would be the costs for A and C checks as suggested by the University of Westminster Transport Studies Group [13].

Delay costs represent one of the trickiest parts of the model, as it is so changeable even throughout the flight. Delay management is already a part of some airline's decision process. The OCI model is flexible enough to accommodate an airlines own system of accounting for delay if necessary, with their cost of delay replacing the models calculation in the final CI calculation page. The only caveat with this is ensuring that airlines delay models actually take the balance of costs into account, with extra fuel costs being considered as well as time dependent costs. This model is designed for pre-flight calculation of CI and therefore adaption to the model would be needed for in-flight changes in CI to be made for en-route delay.

There is also the option of airlines using a basic version of the OCI model, which has the same features, but with a slimmed down delay cost calculation. These delay costs are taken from the University of Westminster Transport Studies Group (2008b) who have done extensive work in this area and include pre-set values for different delay categories (e.g. 1-15 minutes, 16-30 minutes etc.). This means that airlines do not need to include the connecting flights of passengers, which may be more time consuming. However, this method should be used with caution as these costs are not airline specific and therefore are only provide a rough estimate compared to the advanced OCI model.

Whilst this model does provide a significant improvement on the current system of CI calculation, there are still areas that could be improved upon. Firstly the Piano-X calculations are time consuming as each Mach number has to be generated individually. This could be solved by using average passenger numbers and cargo loads for the flight in question. However, it should be noted that Piano-X is free software whereas most airlines have more sophisticated flight analysis software at their disposal. Therefore, this could be integrated into the system to optimise calculations.

Another issue is the amount of data potentially needing to be held in the spreadsheet for flights, crew members and aircraft. Multiple copies of the model can be created for different flights, which may overcome the problem. However, more powerful computing software may be needed in the future to accommodate data demands. This will ultimately depend on the individual airline using the model.

Even though these issues need to be addressed, it should be noted that if the assertion by Burrows et al. (2001) that “relatively crude approaches are likely to be cost effective” is correct then the model still has significant value even when inputs may not be 100% accurately known by the airline e.g. good estimation of maintenance costs would be sufficient. The impact of individual factors on the CI is examined in the next chapter.

Going forward the model will also be used as part of on-going research into the effects of policy on flights costs and emissions. This adds additional value to the OCI model, making it not just of use to airlines but also to policy makers and airline authorities.

4.6 Summary

This chapter has outlined the creation of the OCI model for airlines to more effectively calculate their optimum CI values for individual flights. At present airlines tend to use average values for an aircraft and CI calculations are not route and flight specific. There is evidence that a key reason for this is that accounting for the various intricacies, particularly concerning time-dependent costs, in one equation does not account for more complex nature of these costs. The OCI model does not try to account for all costs within one equation but instead performs subsequent calculations to ensure all costs are accounted for and therefore a minimum cost solution is found.

The model is created in Excel to provide transparency for users to understand the method for optimum CI calculation and also to provide flexibility for changes specific to individual airlines to take place. It is believed that with some addition of airline specific data this model could easily and effectively be used on a day-to-day basis by airline flight dispatch teams to provide an optimum CI value for each and every flight. However, although using this model can help reduce emissions by optimising CI in the first instance, in the future there is no guarantee that CI values will remain at the same values that result in lower carbon emissions than at present. Therefore, the following chapter explores where optimum CI values may lie in the future based through scenario analysis, and the effect that this will have on CO_2 emissions.

Chapter 5 Scenario Analysis with OCI Model

5.1 Introduction

The previous chapter described the creation and set up of the OCI model. This chapter aims to demonstrate how this model can be used to assess the impact of different costs, future events and policy decisions on CO_2 and costs of the flight. Three scenarios have been created to represent these impacts on the future of the industry as well as a sensitivity analysis being undertaken for all of the individual factors. The results of this are discussed in the context of future research and policy requirements for mitigation of CO_2 emissions from flights.

5.1 Future Impacts on CI

5.1.1 Change in Jet Fuel Prices

There will inevitably be a change in jet fuel price over time. As well as the general volatility that has been seen, there has also been an upward trend in fuel prices over the long term. Ultimately, reserves will affect the price of oil, but at present political and technological impacts can have an equal, if not more important impact on prices.

Projections for future crude oil prices were taken from Department of Energy and Climate Change (DECC, 2014a), which provides three scenarios until 2030 (Figure 5-1). The low scenario represents a situation in which unconventional oil remains economic; the central fuel scenario is based on DECC's long term forecast model, checked against the Energy Information Agency (EIA) and the International Energy Agency (IEA) oil price scenarios; whilst the high scenario represents a zero global supply growth for oil post 2030. As these prices are for crude oil, the application of an average crack spread of 24% was added to the values to represent jet fuel prices. The crack spread is dependent on the cost of refining crude oil to jet fuel, which is likely to change over time, but owing to uncertainty over the future values, this study uses the average margin since 1990 (IATA, 2008).

Looking to the future (Nygren et al., 2009) have examined the potential for future aviation fuel demand to be met, which will have a significant impact on the price of fuel. Three scenarios are presented:

A. Traffic will continue to grow according to industry forecasts and average fuel consumption for the world aviation fleet will remain as it is today. Fuel consumption will increase at the same rate as the rise in traffic.

B. Traffic will keep growing according to the industry forecast but the average fuel consumption for the world of aviation fleet will go down by 50% compared to 2005 by the year 2020. A decrease of 1% per year from 2020 to the year 2026 is assumed.

C. Traffic will keep growing according to industry forecasts and average fuel consumption for the world aviation fleet will follow a curve extrapolated from the average fuel consumption of the years 1987 to 2007.

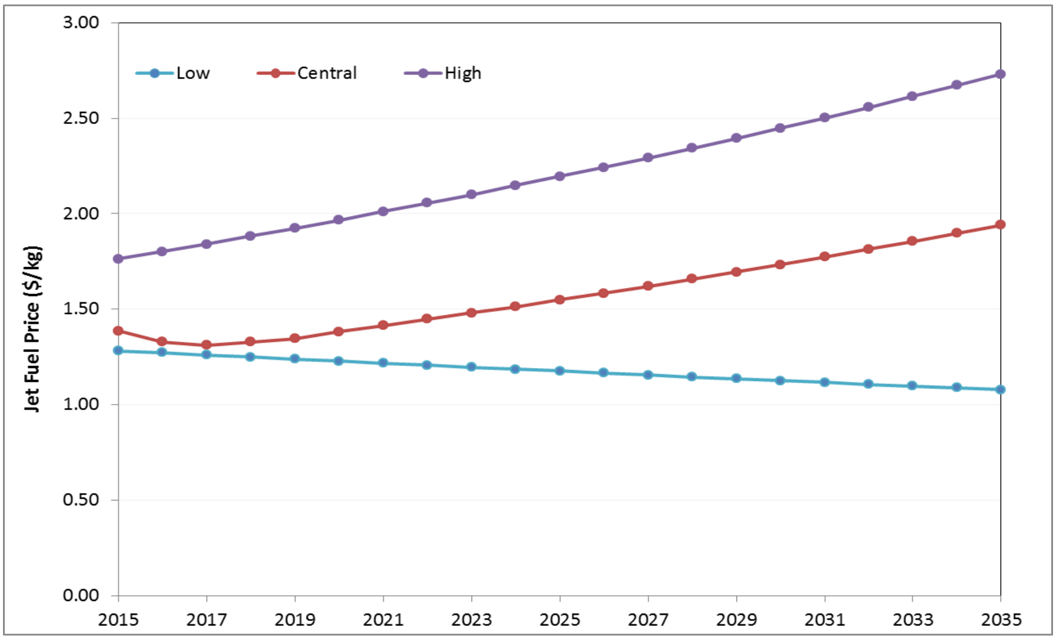

Figure 5-1: Jet fuel price projections to 2035 taken from DECC (2014a) crude oil price projections with a 24% crack spread.

For each of these three scenarios, three different crude oil production alternatives are used based on an increase in production from 82.3Mb/d in 2007 to 101.3Mb/d in 2026; a decrease to 61.5Mb/d in 2026; and between 66Mb/d and 72Mb/d in 2026 based on production from giant oil fields and unconventional production of oil.

Nygren et al. (2009) find that with a scenario of 5% demand growth and aviation fuel production at 6.3% of total crude oil production, demand exceeds supply enormously in the three supply scenarios. Even if 10% biofuels were used by 2017 and following historic trends this would not take consumption down to the BAU production scenario. Given current rates of biofuel production suitable for aviation compared to what is needed, it is very unlikely that this percentage could be reached in this time period.

These results strongly suggest that jet fuel prices will increase into the future. However, volatility is set to play a key role in short-term jet fuel prices, as seen at the beginning of 2015 with the lowering of prices. The longer-term prices will also depend on the emergence of new unconventional oil sources. However, it is important to note that there are some questionable assumptions made in this study, for example with a 50% reduction in fuel consumption in scenario B. However, even with this decrease in fuel consumption demand is still not met by supply, therefore this strengthens the argument that jet fuel prices will increase in the future.

The IEA (2015a) believe that whilst there may be ample physical oil resources for the foreseeable future, future prices will depend on the rate that new supplies can be developed at and the break-even prices of these supplies. Global oil supplies are also dependent of production policy of OPEC, which can be uncertain. A factor that may cause peak oil to be reached ahead of time is a continuation of sustained high prices and energy policies to provide better end use efficiency, as well as diversification of energy supplies.

An opportunity that the oil industry had hoped would provide a vast resource of oil was exploration in the Arctic. However, as of October 2015 Shell has given up its bid to find oil in the Alaskan Arctic, after a $7 billion exploration of the area failed to find more than marginal oil reserves. However, it should be noted that they still plan to explore other areas of the Arctic (Coghlan, 2015).

5.1.2 Efficiency Improvements

It is anticipated that future fuel use on a flight-by-flight basis will reduce owing to incremental improvements in fuel efficiency (although on a system wide basis, fuel reduction from these improvements are expected to be dwarfed by the increase in demand). These efficiency improvements were discussed in Chapter 2.

Whilst there are a range of estimates for the efficiency improvements that can be made, there is a general consensus that this value is likely to be around 1%. Efficiency measures for this analysis were taken from the range provided by the Committee on Climate Change (2009) of between 0.8% improvement per year and 1.5% improvement per year, with amid-value of 1.2%.

5.1.3 Introduction of Alternative Fuels

Finding an alternative fuel to kerosene is the only way that aviation can dramatically reduce its carbon emissions. However, finding this alternative is proving a challenge. Unlike other sectors, such as road transport, which can make use of electric vehicles, there are limited options for aircraft. The options for alternative fuels were considered in Chapter 2.

Biofuels are now certified for use in commercial aviation in 50% blends with jet fuel. This study uses scenarios based on Biomass-to-Liquid (BtL) fuels from energy crops, as this is one of the better-developed routes for conversion of biomass to jet fuel. Bauen et al. (2009) do provide one of the most thorough analyses of possible future prices. It is assumed that airlines will only use biofuels when they are price competitive with conventional jet fuel. Prices for aviation biofuels are still very difficult to predict. Prices for this analysis were taken from Bauen et al. (2009) and the International Energy Agency (IEA, 2008) with a high price of $1.2/kg in 2030 to a low price of $0.6/kg in 2050 assuming their development and use reduce the price.

Three scenarios are used for this study based on the prices for BtL in 2030 of a 10%, 30% and 50% biofuel blend. The emission factor of 0.35 $kgCO_2/kg_{fuel}$ is also taken from Bauen et al. (2009) for analysis of CO_2 emissions savings. This represents lifecycle emissions but excludes land use change. This is in contrast to the emissions factor for jet fuel, which is only based on direct combustion of the fuel. Therefore, emissions savings could be higher if this was also taken into account.

5.1.4 Introduction of a Market-based Mechanism for Carbon Reductions

As mentioned in Chapter 2, it is planned that by 2020 there will be a global market-based measure (MBM) implemented by ICAO. It is unclear in which form the mechanism will take but for the sake of future analysis a carbon price is added to the CI calculation to represent this, as all the schemes, will have a cost per tonne attached to them. It is hard to predict what the carbon price will be in the future, as previous experience with schemes such as the EUETS have been hampered by difficulties with the set-up of the system. It is hoped in order to create a real impact carbon prices will rise to a suitable level with more experience of international emissions trading schemes. ICAO (2013b) anticipate that by 2036 the implementation of a MBM will result in a decrease in 12% CO_2 emissions, an 18% decrease in traffic demand and a 6.9% increase in operating costs.

This analysis uses carbon price projections from the DECC (2014b) for analysis of the impacts (Figure 5-2). These were chosen as projections for fuel prices are also taken from DECC and these are some of the only predictions available with the aim of use for policy appraisal. These projections are divided into three scenarios:

- Central scenario – short term traded values are estimated using market-based approach based on averaging daily settlement prices of end of year European Union Allowance (EUA) futures contracts of different periods over three months.
- High scenario – short-term traded carbon values under this scenario are devised using the DECC Carbon Price Model (DCPM). This estimates EUA prices for a given year based on demand and supply of abatement over a number of years into the future. It is based on assumptions of higher economic growth, low prices of coal relative to gas and a tighter EU ETS cap.
- Low Scenario – short-term traded carbon values are also derived from the DCPM and based on assumptions of slower economic growth, high coal prices relative to gas and no tightening of the current EU ETS cap trajectory.

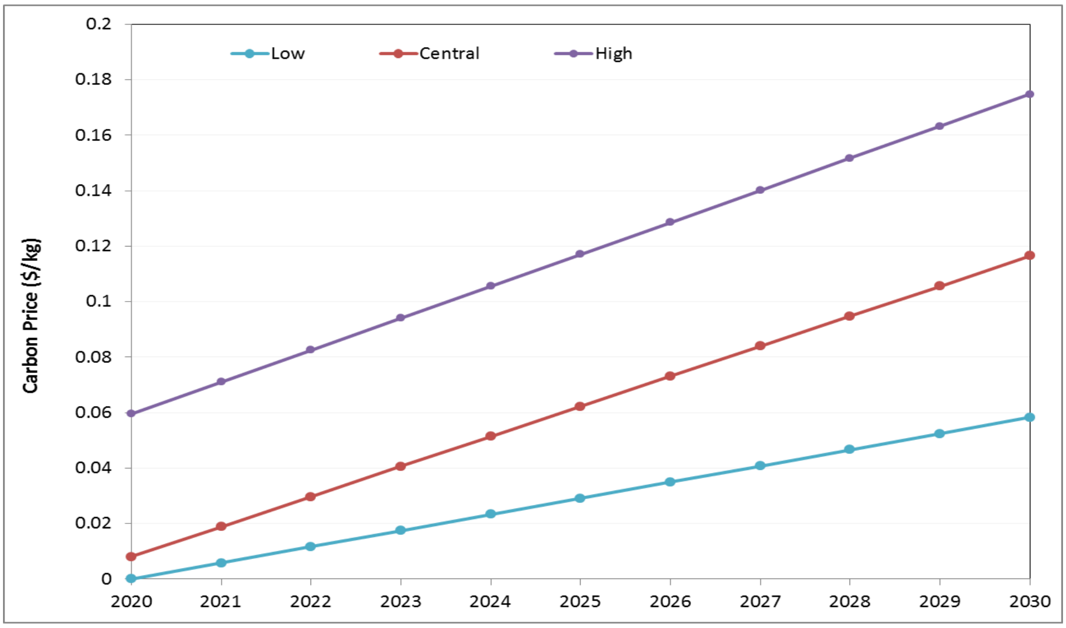

Figure 5-2: Carbon Price Projections to 2030 (DECC, 2014b).

5.1.5 Capacity Constraints and Climate Change Impacts

One of the key issues facing the aviation industry is how to continue with growth when the capacity of both airways and airports is becoming increasingly constrained. Some of the worlds most congested airports, such as London Heathrow, New York’s JFK, Hong Kong and

Frankfurt, the scheduled demand often is close to, and at certain points in the day exceeds, available runway capacity. For these airports this occurs even when there is good weather, for other airports these problems occur on days when weather conditions are suboptimal. This ultimately leads to significant problems regarding reliability and delays (Barnhart et al., 2012).

The costs that can result for airlines are difficult to calculate, but Ball (2010) estimate that the costs to US airlines was $8.3 billion in 2007, with the cost to passengers at $16.7 billion. These costs will undoubtedly rise with increasing demand. As of 2005, European Airlines are also responsible for increased passenger costs (unless the delay is out of the airlines control e.g. bad weather), having to pay compensation to those delayed by more than three hours (European Parliament, 2004).

Gelhausen (2013) analysed airport capacity constraints for a sample of 177 airports with traffic volumes exceeding 70,000 aircraft movements in 2008. Their results show that the majority of airports did not suffer from capacity constraints in 2008. However, it is stated that the situation is likely to deteriorate in the future with the number of constrained airports growing rapidly. By 2016 it is estimated that about 70% of flights to and from the analysed airports will take off and land at capacity constrained airports. Even with means of enhancing capacity at a number of airports, particularly those in Europe and the US, it probably will not be sufficient to keep pace with growing demand.

Inefficiency also arises because of problems with aircraft routing. A common cause for indirect flight paths is diversion around restricted airspace. An example of this is in the Pearl River Delta region in Southern China. This area consists of five airports in close proximity, three of which are facing serious capacity constraints. The area is difficult to navigate owing to the existence of three airspace navigation service providers that lack common integration. One of the major issues is the presence of the "invisible wall" between Zhuhai and Hong Kong airspaces, which aircraft have to cross at a height of 15,000ft. This results in aircraft leaving Hong Kong International Airport circling to gain sufficient height to cross the boundary. Cathay Pacific has estimated that this situation has resulted in fuel wastage of nearly 100 million kilograms and 531,000 minutes of flight time per year (Law et al., 2008).

Extended flight paths can also result from the cost of airspace. Europe has experienced this problem with vastly varying airspace charges according to 67 national boundaries. The

Single European Sky programme has recognised that a common charging scheme is essential if Europe is to have an integrated air traffic management system (Eurocontrol, 2014). Mihetec et al. (2011) give an indication that 56,000 tonnes of CO_2 savings could result from reducing route extensions in Europe. In 2009 the average route extension was 47.6km per flight, with 32.3km attributed to the inefficiency of the en-route network and 15.3km attributed to interfaces with the terminal area. In total a flight distance of 1,619,980NM could have been saved in 2010.

Both restricted airspace and over-flight costs can even be used as a political tool, a situation currently seen with Russia. There has been an on-going battle between European airlines and Russia over airspace usage charges, and recently Russia has now threatened to close its airspace completely to western airlines. This is in protest to sanctions on the country from the EU over the crisis in Ukraine. This would add significantly to airline costs and flight time as over-flight of Siberia is by far the quickest way to access Asia and Australia (Gander, 2014). Addressing political issues that affect routing will be key to gaining significant reductions in emissions without sacrificing flight times. Whilst some of these issues have been tackled with schemes such as the Single European Sky and NextGen in the US, there are is still a lack of common integration and Asia particularly remains a problem area that needs to be focused on.

There are a number of measures that can be taken to try and counteract the issues from congestion and capacity constraints. To start with there are measures which can be taken concerning infrastructure. The obvious option here is to build more runways at airports. However, this is not an option for many capacity constrained airports owing to interrelated reasons such as costs, environmental impact, land availability, lengthy approval processes and political feasibility (Peterson et al., 2013).

Another option would be to improve the existing air traffic management system, with improvements in communication, navigation and surveillance technologies being an important part of this. Air traffic flow management has become important in avoiding facility overload and reducing congestion at airports with research spanning the last 20 years, producing more sophisticated models for application of at individual airport, en-route and system wide. Large-scale programmes have guided improvements in air traffic management, namely SESAR in Europe and NextGen in the United States. However, infrastructure investments in this area can be costly e.g. NextGen has been estimated to cost between $15 and $22 billion between 2005 and 2025. However, this must be balanced with the benefits from reducing delay, with a 10% reduction increasing US net welfare by $17.6 billion and a more ambitious 30% reduction increasing net welfare by $38.5 billion (Barnhart et al., 2012, Peterson et al., 2013).

A third option is congestion pricing by imposing fees on aircraft operators or travellers to reduce the demand for air travel during peak periods of demand. A similar system already operates at some airports where peak air navigation charges are levied. However, this relies on the willingness of travellers to choose off-peak flights and may be relatively inelastic if flight time takes preference (Peterson et al., 2013).

A fourth option would be more strategic planning. This could include more transport system coordination and provision of high-speed rail routes making airports located considerable distance form cities accessible and relieve congested airports near cities by providing alternatives to air travel for distances of less than 800km; increasing capacity per slot by using larger aircraft, efficiently distributing demand throughout the day; and increasing operations at under-scheduled airports (Barnhart et al., 2012, Peterson et al., 2013). However, this would rely heavily on stakeholder cooperation to achieve.

A complicating factor in future capacity constraints may well be the uncertainty in the impact that climate change will have on the aviation system. It is anticipated that climate change will lead to more extreme weather events in the future, which can significantly impact delay in the system.

This is something that aviation authorities are beginning to take more seriously and ICAO include it in their Environmental Strategy (2013a). A study by Koetse and Rietveld (2009) reveals the impact that this could have on San Francisco Airport, where delays due to wind, rainstorms and poor visibility could be significant. Cancellations per day could increase by a factor of two to three when bad weather is experienced in the morning and a factor of three to four when there is bad weather all day, with similar figures for delay.

5.1.6 Change in Labour Costs

Labour costs have historically represented the biggest cost burden for airlines. In some areas of the world fuel costs have now surpassed labour as the largest cost but it still remains a key concern for airlines (IATA, 2010). Crew labour costs peaked in 2000 before seeing some improvement. Airlines made an effort to reduce their costs after the financial problems seen in the industry post 9/11. In North America, large scale restructuring from 2001 resulted in the total share of labour costs of total operating costs decreasing from 36.3% to 21.5% (this is partly reflected by the rise in fuel prices in this period as well). In Europe the reductions were less at 27.2% to 24.8% (partly because fuel cost played less of a role with more hedging strategies taken by European airlines during this time). In Asia there was also a drop in labour costs, albeit from a lower base of 17.2% to 14.7% (IATA, 2010).

Whilst in the US where airlines have come under court mandated labour cost reductions in the past years, European airlines show evidence that pay is still quite high compared to equivalent jobs outside the industry (IATA, 2013). This suggests that airlines in these regions may turn to further reductions in labour costs in the future to guard against rising costs.

Some of the ways in which airlines have attempted to reduce labour costs were discussed in Chapter 2. These included reorganisation of terms and conditions of employment with a freeze of wages, reduced staff numbers and/or agreeing higher workloads with existing staff and hiring staff in countries where wages are lower. It is anticipated that airlines will continue to pursue such measures in the future. However, it is likely that these efforts will result in a plateau of costs as measures are exhausted.

Even within the same regions of the world between the same types of airline there can be substantial differences in costs. An example of this is given by Lange et al. (2015), looking at the differences between British Airways (BA) and Lufthansa (LH). They are both national flag carriers, lead international alliances and do not receive subsidies from airports. Both airlines have attempted to emulate some of the elements of low cost carriers but to varying degrees. The result has been that BA has decreased labour costs and costs per employee to 30% lower than at LH. There is one reason that stands out as being the cause for this and that is the involvement of the employee unions. Whilst one of the biggest strikes for BA in the last five years by cabin crew resulted in the breakdown of communications with their union and resulted in BA saving £60 million annually, in 2012 LH's new CEO Christoph Franz tried to aggressively reduce labour costs but underestimated the unions and ended up actually increasing salaries by 4.6%, in exchange for the union accepting lower wages for new recruits.

There has also been increasing input by governments to tackle some of the loopholes that airlines are trying to use to reduce their labour costs further. For example, one of these concerns is related to the emergence of the so-called “flag of convenience” airlines. This included Norwegian Air International who acquired an Irish Air Operations Certificate (AOC) in order to operate its long-haul trans-Atlantic routes with aircrews of convenience i.e. hired by agencies in Asia; something that the Norwegian Government had rejected. It is though this could lead to a reduction in airfares of 50%. However, the airline also required a permit from the US, to fly its routes to the US but this was denied after an intense debate about the airlines supposed social dumping (CAPA, 2014).

From the evidence it is anticipated that some airlines will be able to continue to reduce their labour costs in the short to medium term whilst others will struggle to further reduce their labour costs. In this analysis we assume that trends averaging a 2-3% per year change in labour costs based on past trends recorded by IATA (2010).

5.1.7 Change in Maintenance Costs

There are a number of strategies to reduce the cost of maintenance by airlines. These include fleet harmonisation; reduction in average fleet age; optimisation of maintenance activities; and joint purchasing of some work (IATA, 2013b). However, the age of the aircraft is still one of the key areas where costs can increase. Ageing aircraft require higher levels of non-routine maintenance. Figure 5-3 shows how the aircraft maintenance cycle is broken down into three phases. The first-run phase in the initial operating years is generally considered the first four to six years of operation when the structure, systems and components are new leading to the lowest maintenance costs. The mature-run period runs through the first maintenance cycle typically falling between the first heavy maintenance visit and the second. The ageing-run begins after the end of the first maintenance cycle when the effects of airframe age result in higher non-routine maintenance visits and continues to increase with time (Ackert, 2012).

One of the ways to decrease these costs is through the design of the aircraft. About 70-80% of commercial aircraft life costs can be attributed to the design stage, which in turn depends on the customer and manufacturer demand, safety protocols, physical and economic constraints etc. The current system designs experience a 40% or higher equipment false removal rate generally resulting from unclear and labour intensive test procedures. This is not helped as aircraft systems become more complex. Therefore work to improve the inherent reliability of aircraft is key to reducing costs as well as achieving an optimum maintenance plan. This will require the traditional thought process of failures being unavoidable and acceptable, to be rethought (PeriyarSelvam et al., 2013).

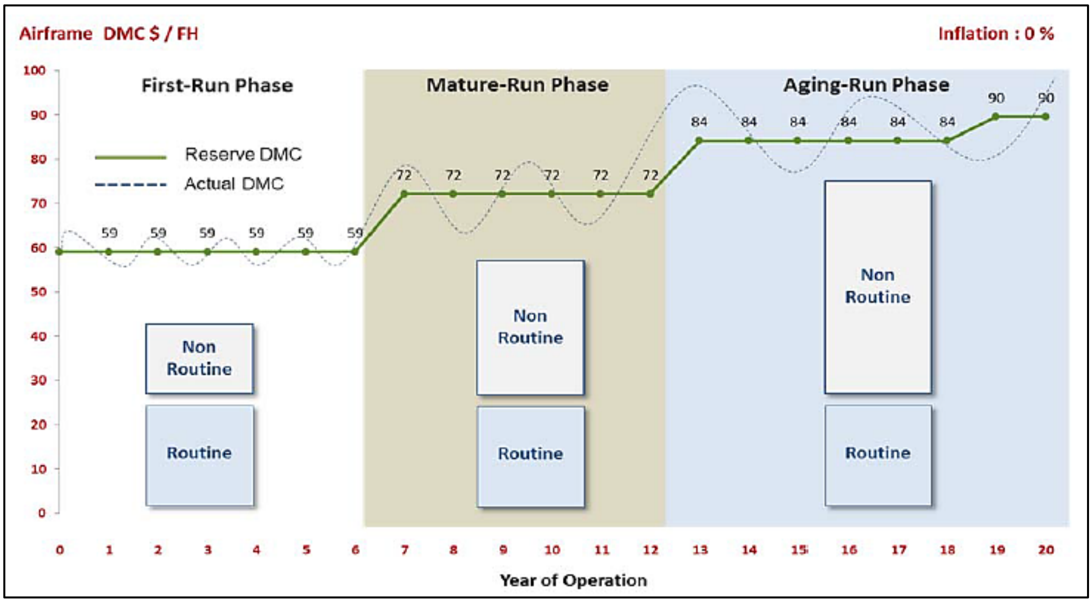

Figure 5-3: Example of Direct Maintenance Cost (DMC) with age of aircraft (Ackert, 2012)

In recent years maintenance costs have continued to rise, although the rate of increase appears to be slowing for the 26 airlines included in IATA's Airline Maintenance Cost Executive Commentary (2014a). Although costs are still increasing there are a number of reasons to suggest that maintenance costs will decrease in the future. E-enablement of aircraft is set to improve the communication to and from aircraft regarding maintenance issues, for example allowing for remote health monitoring of the aircraft. The use of electronic flight bags by pilots also means they are able to log faults whilst still in the air. Previously faults were recorded in paper logs, which were only received by maintenance crews on landing. By providing this information before the flight lands, this provides precious extra time for maintenance crews to understand the problem and source parts for repairs if necessary. Another promising prospect is the use of 3-D printing which, whilst not yet mature, could provide opportunities for manufacturing of repair parts at significantly lower costs (IATA, 2014a). It is unclear about how maintenance costs may change in the future therefore this analysis assumes a similar rate of change as seen in Figure 5-4 for maintenance costs of around 3-4% per year.

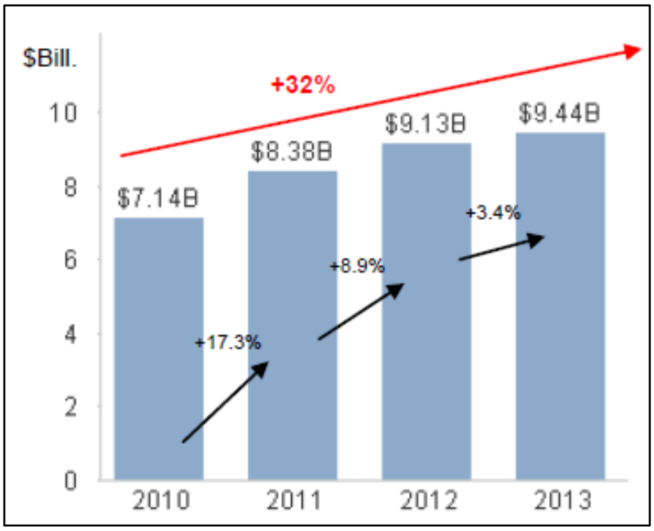

Figure 5-4: Evolution of airline maintenance costs for 26 benchmark airlines (IATA, 2014a)

5.2 Scenario Analysis

5.1.8 Adaptation of the OCI Model

To enable scenario analysis to take place small adaptions to the OCI model were made. Firstly, the input page has input cells for time-costs and carbon costs to speed up analysis. The input page also has a section for the input of per cent efficiency measures and per cent biofuel use. When there are no efficiency improvements or biofuels being used the model works in exactly the same way as described in Chapter 4. However, when efficiency measures are included, an extra step has been added to the analysis to reduce the fuel use by the per cent efficiency improvement and the resulting CO_2 emissions are calculated by multiplying fuel use by the emissions factor of 3.157. For biofuels it is slightly more complicated. The fuel use is unaltered but CO_2 emissions and costs do need to be altered. The cost of biofuel is accounted for before the scenario input to simplify the process as in Equation 5-1 and input as normal on the interface page.

$$\text{Fuel Price} = (\%\ \text{jet fuel} * \text{jet fuel price})+(\%\ \text{biofuel} * \text{biofuel price}) \qquad [5\text{-}1]$$

CO_2 is accounted for in a similar way using Equation 5-2 in the flight data worksheet. Biofuels are still assumed to have CO_2 emissions related to their use and the emissions index of 0.35kgCO_2/kg_{fuel} is taken from Bauen et al. (2009). If efficiency measures or biofuel percentages are entered then the fuel and CO_2 values will automatically be adjusted to appear in the outputs on the interface page, along with the other flight parameters.

$$CO_2=\left(\left(\text{Fuel use}*\left(\frac{100\text{-biofuel }\%}{100}\right)\right)*3.157\right)+\left(\left(\text{Fuel use}*\left(\frac{\text{biofuel }\%}{100}\right)\right)*0.35\right) \quad [5\text{-}2]$$

This version of the model could also be of use for airlines in future planning, as well as policy makers.

5.1.9 Description of Scenarios

There are four scenarios analysed working from a base year of 2015. The analysis is to the year of 2050, with 2020, 2025, 2030, 2035 and 2040 evaluated. The scenarios represent a mix of time and fuel cost changes, implementation of a carbon price, introduction of efficiency measures and biofuels, and delay associated with capacity constraints and weather conditions as summarised in Table 5-1.

5.1.9.1 Base Year – 2015

The base year used the initial model set-up described Chapter 4 to represent the current situation. The following values are used:

- Maintenance and labour costs held at $26/min to give a CI of 40 (this is a known CI value for this aircraft and this route).
- Spot jet fuel price at $0.5/kg, with fuel hedging of 61% at $0.74/kg
- Delay is at 15 minutes as explained in chapter 4.
- There are no efficiency measures or biofuels.
- No carbon price is applied
- Wind speed is zero.

Table 5-1: Summary of Scenario Conditions

	Pessimistic A	Pessimistic B	Likely	Optimistic
Time Costs	Increase 6% per annum	Increase 6% per annum	No Change	Decrease 6% per annum
Fuel Costs[1]	Low Fuel Cost	Central Fuel Costs	Central Fuel Costs	High Fuel Costs
Carbon Price[2]	None	None	Central Carbon Price	High Carbon Price
Efficiency Improvements[3]	0.8% per annum	0.8% per annum	1.2% per annum	1.5% per annum
Biofuels[3]	None	None	From 1% in 2030 to 15% 2050	From 5% in 2030 to 30% in 2050
Delay	High Delay (increasing to 240 minutes in 2050)	High Delay (increasing to 240 in 2050)	Medium Delay (Increasing to 180 in 2050)	Low Delay (Increasing to 60 minutes in 2030 then decreasing to 15 minutes in 2050)

[1]From DECC Projections (2014a) [2]From DECC Projections (2014b) [3]From CCC (2009)

5.1.9.2 Pessimistic-A

The Pessimistic-A scenario is based on the industry taking very little action to improve conditions in the future. It is driven by the low fuel price scenario, in which the cost of jet fuel decreases to 2050. With these low jet fuel prices there is little incentive to significantly improve efficiency that continues at a low level of 0.8% improvement per year. The use of biofuels is not incentivised, as prices cannot reach parity with the low jet fuel prices. Meanwhile congestion increases as few measures are taken for improvement, which leads to an increase in delay costs to 2050. This scenario also takes into account the inability for ICAO to implement a market-based measure into the sector resulting in no carbon price being applied. Time costs are also not improved and instead increase at 6% a year.

5.1.9.3 Pessimistic-B

This scenario is the same as Pessimistic-A but the difference is that central fuel costs are used instead of low fuel costs. This represents a scenario where rather than inaction being motivated by low fuel prices, it is a lack of political will and stakeholder cooperation.

5.1.9.4 Likely

This scenario is based on central scenarios to represent the most likely situation to 2050. Central fuel costs are used which see a rise to 2050. This, combined with the central carbon price encourages increased uptake of efficiency measures of 1.2% per year and a small amount of biofuels reaching 15% in 2050. This scenario suggests that airlines take preventative measures to avoid rising time-dependent costs, but are unable to reduce them further overall. For example, maintenance costs may reduce but this may be offset by a rise in labour costs as airlines reach maximum productivity in this area. This scenario assumes that there is an introduction of a MBM with central carbon prices. It also assumes that some measures are taken to reduce capacity issues resulting in a slower increase in delay than the pessimistic scenario.

5.1.9.5 Optimistic

The Optimistic scenario represents a situation in which the industry makes a significant effort to solve the future issues it faces. It is assumed that this would be stimulated by the presence of high fuel and carbon costs. This results in a higher push for efficiency at 1.5% improvement per year until 2050 and increased biofuel penetration resulting in 30% use in 2050. Efforts are also made to decrease time costs, particularly regarding maintenance with a reduction of 6% per year. Finally a substantial effort is made to reduce congestion and guard against risks to system disturbance. Therefore after an initial increase in delay, as these issues are resolved delay eventually reduces to 2015 levels.

5.1.10 Scenario Results

Full scenario results are available in the appendix. Initially all the scenarios show a general decrease in CI until 2030, except Pessimistic-A, which shows an increase (Figure 5-5). However, between 2030 and 2035 the two pessimistic scenarios show sharp increases in CI. This is a result of the delay threshold of three hours being passed in these scenarios, resulting in higher costs pushing the CI values up. The Pessimistic-A scenario then continues to increase in optimum CI value to 282 in 2050, as jet fuel prices continue to decrease, whilst the Pessimistic-B scenario starts to decrease again as fuel prices continue to increase, resulting in CI=113 in 2050. The Likely scenario and Optimistic scenarios only decrease slightly in optimum CI as a further decrease is curtailed by lower biofuel prices, with a higher percentage of biofuel use implemented after 2030. Whilst the Optimistic scenario finally plateaus at a CI of 5 in 2050, the Likely scenario sees a sharp increase in CI value between 2040 and 2050 to CI=85. This is again owing to the 3-hour passenger delay compensation being crossed at this point.

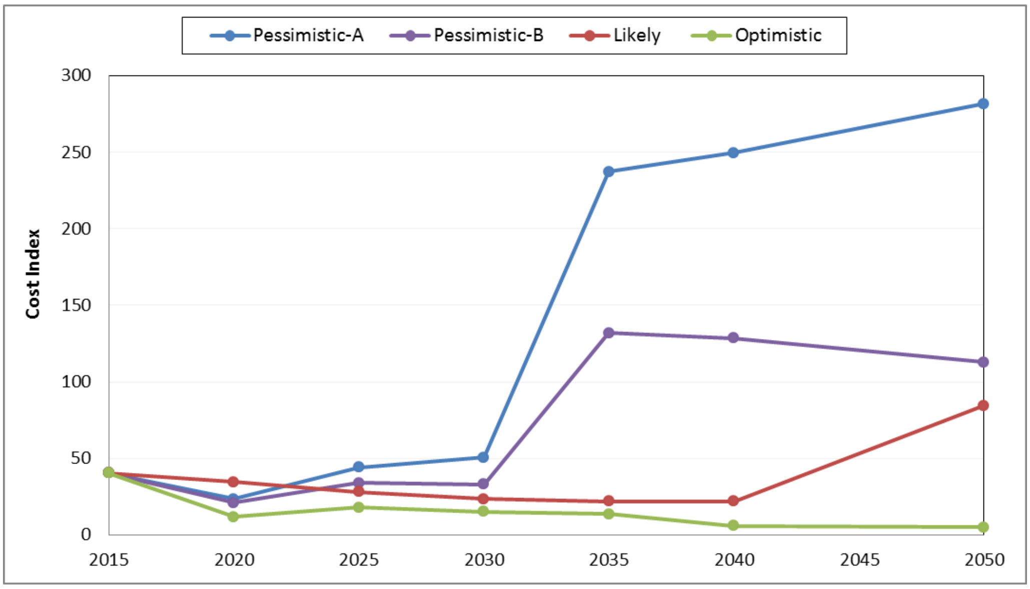

Figure 5-5: Change in CI for Four Scenarios from 2015 to 2050

The use of fuel decreases overall for all scenarios (Figure 5-6). This is expected in the Pessimistic-B, Likely and Optimistic scenarios owing to decreasing optimum CI values to 2050. However, even though CI values increase to 2050 in the Pessimistic-A scenario, fuel use does decrease slightly owing to a 0.8% per year improvement in efficiency of the aircraft. The decrease in fuel use for the pessimistic scenario reaches a total of 3% and 4% in 2050 from 2015, compared with 7% and 9% for the Likely and Optimistic scenarios respectively. These decreases can be entirely attributed to the improvement in the efficiency of aircraft. It should be noted that the use of biofuels in these scenarios does not affect the overall fuel use, only the resulting CO_2 emissions. However, there is a slight increase in fuel use for the Pessimistic scenarios between 2030 and 2035 as the CI increases sharply to account for delay costs. However, as the CI is there to balance out these costs, this increase is only small.

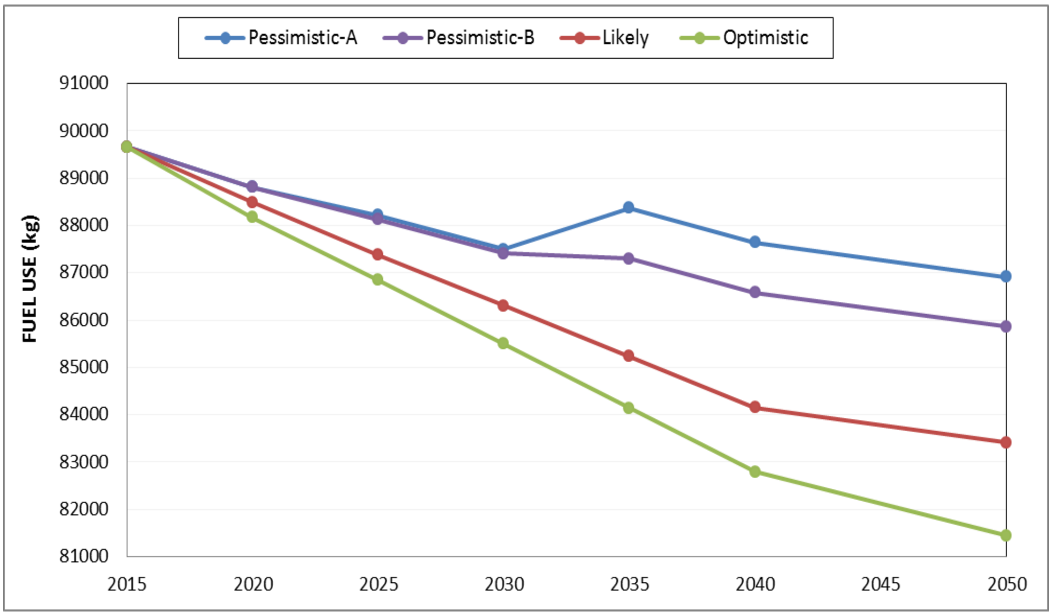

Figure 5-6: Change in Fuel Use for Four Scenarios from 2015 to 2050

The change in total CI related operating cost is generally linear in reflection that the CI is doing its job in balancing costs between fuel and time costs (Figure 5-7). If the CI was not optimised correctly there would be sharp spikes in price for the Pessimistic and Likely scenarios as seen in Figure 5-9 on page 100 but this is curtailed by the increase in CI. The Optimistic scenario shows the highest costs until 2050. As time-dependent costs are decreasing during this time, this indicates that the high fuel and carbon prices are having the most significant effect on total costs. The Pessimistic-B and Likely scenarios follow a similar trend albeit at a lower total cost. They are close in total costs as they both use the same fuel costs, although the Likely scenario moves closer to the pessimistic B scenario by 2040 due to the addition of lower biofuel prices. The Pessimistic-A scenario shows a decrease in total costs as even though time-dependent costs are increasing, fuel costs clearly outweigh this to cause an overall decrease in total costs.

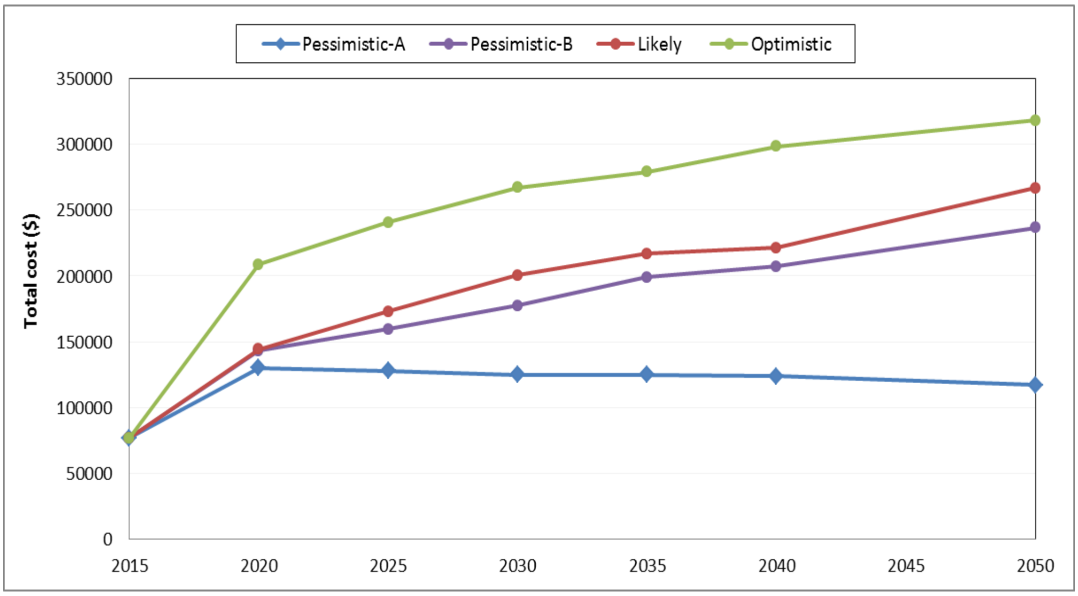

Figure 5-7: Change in Total Cost for Four Scenarios from 2015 to 2050

In terms of the effect that these scenarios have on flight time (Figure 5-8) there is a significant variation between scenarios. The two pessimistic scenarios see a sharp drop in flight time after 2030 owing to the increase in CI values, before plateauing. The Pessimistic-A scenario decreases the most by 15 minutes between 2015 and 2050. In general the Optimistic scenario shows a rise in flight time as CI decreases by five minutes between 2015 and 2050. For the Likely scenario the flight time initially increases by three minutes to 2040, but owing to the increase in CI because of delay costs, the flight time then decreases by ten minutes to 2050.

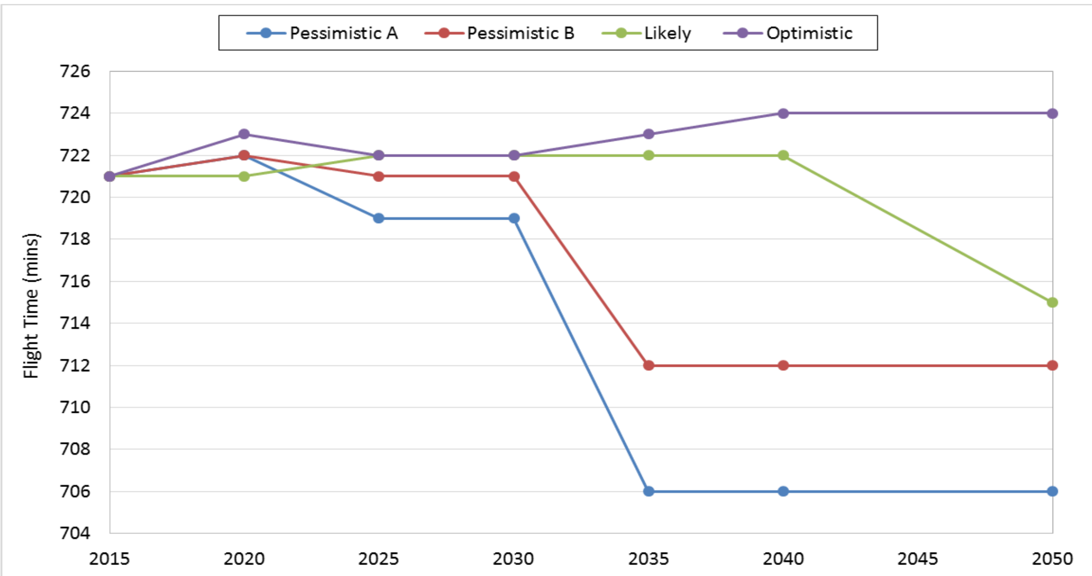

Figure 5-8: Change in Flight Time for Four Scenarios from 2015 to 2050

CO_2 emissions for the Pessimistic scenarios show a decrease at the same rate of fuel use of 3% and 4% respectively by 2050. However, the Likely and Optimistic scenarios see a much higher decrease compared to that of fuel use at 15% and 33% respectively. The reason for such a significant decrease is the use of biofuels in these scenarios after 2025, at 15% and 30% respectively in 2050. However, not all of this decrease is the result of biofuels, which are not assumed to be completely emissions free. As already apparent efficiency improvements caused a decrease in fuel use, which is directly proportional to CO_2 emissions and a smaller proportion is the result of the decrease in optimum CI caused by the increase in fuel costs and decrease in time-dependent costs. For one journey on this route and with this aircraft model the best-case scenario would be a saving of 95 tonnes of CO_2 between 2015 and 2050 (Optimistic scenario) and 14 tonnes of CO_2 in the worst-case (Pessimistic scenario). Overall results for these scenarios are summarised in Table 5-2.

Table 5-2: Summary of Scenario Results - Change between 2015 and 2050

	Cost Index	**Fuel Use (kg)**	**Flight Time (min)**	**CO_2 (kg)**	**Total Cost ($)**
Pessimistic A	+ 241	- 2648 (-3%)	- 15 (-2%)	- 8,360 (-3%)	+40,204 (+52%)
Pessimistic B	+ 72	- 3803 (-4%)	- 7 (-1%)	- 12,006 (-4%)	+159,549 (207%)
Likely	+ 44	- 6248 (-7%)	- 4 (-0.6%)	- 43,140 (-15%)	+189,880 (+246%)
Optimistic	- 33	- 8213 (-9%)	+ 5 (-0.7%)	- 94,516(-33%)	+241,208 (+313%)

5.2 Sensitivity Analysis for Individual Inputs

Table 5-3 shows the results of a 10% increase in inputs to the OCI model on the key outputs. It is evident that fuel price, time costs and carbon price all have a very similar impact on all the outputs. The only slight variation is in flight time where time costs have a slightly higher impact in decreasing flight time, although all results are fairly negligible. Efficiency improvements have the greatest impact. It is expected that a 10% increase in efficiency would have the same impact on reducing fuel use and $CO_{2,}$ but there is also a 7.6% decrease in total costs as a result. One of the key advantages of using efficiency measures is that flight time remains unaffected.

Biofuel use does not have an impact on total costs, fuel use and flight time. This is because of the fact that in this case the same price is used for jet fuel and biofuels. Although biofuels may be beneficial in the future in providing lower fuel prices than jet fuel, their main advantage is a decrease in CO_2 emissions. A 10% increase in their use results in an 8.9% decrease in CO_2 emissions as they do still have a small amount of emissions associated with them. Delay represents a similar story in the case of the OCI model. As the CI balances extra delay, increasing it by 10% has no or very little impact.

Table 5-3: Sensitivity Analysis for Key Inputs with a 10% increase from the base case of CI=40

Outputs / Inputs	CI	Total Cost	Fuel Use	Flight Time	CO_2 Emissions
Fuel Price	39	+ 2.2%	0	0	0
Time Costs	44	+ 2.5%	+ 0.09%	- 0.3%	- 0.09%
Carbon Price	40	+ 0.4 %	0	0	0
Efficiency	40	- 7.6%	- 10%	0	- 10%
Biofuel Use*	40	0	0	0	- 8.9%
Delay	40	+ 0.05%	0	0	0

*Biofuel price at parity with jet fuel price

As CI is not linear the sensitivity of results depends on the base CI that is used. As discussed in Chapter 3 the higher the CI the greater effect changing it can have on outputs. Table 5-4 shows the same analysis as previously undertaken but with a base CI of 100. In this case, the impacts on fuel use, flight time and emissions are still small, although higher than for CI=40. However, this time the impact on total costs is more noticeable, with fuel price having the greatest impact, followed by time costs and carbon price. Interestingly efficiency improvements have less of an impact on total costs, as does delay.

In the sensitivity analysis the 10% increase in delay time was conducted from a low base of 15 minutes, therefore a 10% increase had very little impact. However, delay costs associated with passenger compensation and care/help costs are unique in that specific delay time thresholds trigger them. In the case of long-haul flights this is at three and five hours. It is evident from Figure 5-9 that the impact of these thresholds being passed is significant. When there is any delay the alternate optimum CI is always favoured, although the difference between this and the normal CI is marginal. However it is clear that once the three-hour threshold is passed, costs are kept to a minimum by taking account of this extra delay, opposed to using the normal CI that would cause total costs to spike dramatically.

Table 5-4: Sensitivity Analysis for Key Inputs with a 10% increase from the base case of CI=100

Inputs \ Outputs	CI	Total Cost	Fuel Use	Flight Time	CO_2 Emissions
Fuel Price	90	+ 5.5%	- 0.1%	+ 0.14%	- 0.1%
Time Costs	110	+ 4.5%	+ 0.2%	- 0.28%	+ 0.2%
Carbon Price	99	+ 0.14 %	0	0	0
Efficiency	100	- 5.6%	- 10%	0	- 10%
Biofuel Use*	100	0	0	0	- 8.9%
Delay	100	+ 0.1%	0	0	0

However, it is very important to note that accounting for extra passenger delay costs does not mean trying to recover all the delay time. This is also represented in Figure 5-9, showing that the total costs are still higher than optimum CI and are still subject to the same thresholds as the normal CI value. This is because this strategy of recovering delay does not include the additional costs of fuel that result from such a substantial increase in speed caused by the significant increase in CI.

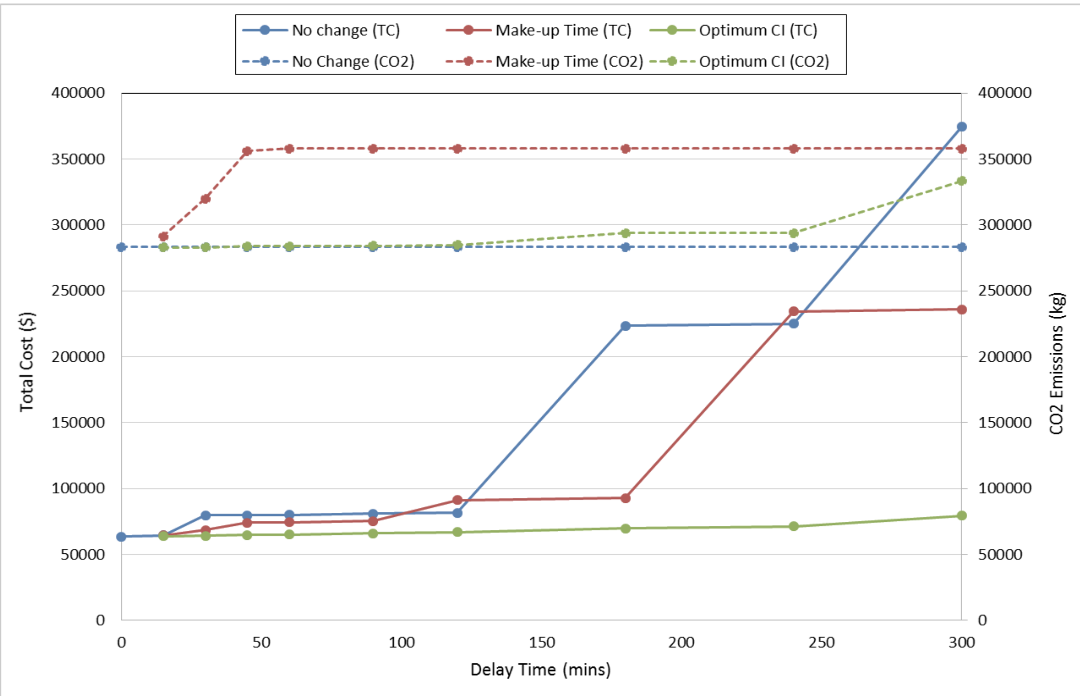

Figure 5-9: Impact of delay time on total costs and change in CO_2 emissions (TC=Total Cost)

However, there is also another complicating factor: the impact on CO_2 emissions. In contrast to total costs, the best scenario would be the one where the normal CI value is used. The optimum CI still performs well compared to the normal CI until delay reaches around 120 minutes when CO_2 emissions start to increase. By far the worst scenario for CO_2 is the one where all delay time is recovered. This is partly to do with the fact that at present the emission of CO_2 are not priced and therefore in the CI equation it currently has no value. If a carbon price was to be added then this could change the situation. However the highest carbon price projected by DECC in 2050 is $124/t. Even with only a 15-minute delay a carbon price double this would be needed to stop the CI from increasing. As delay gets higher this number increases dramatically. At only 45 minutes the price needed would be $11,000/t, at 180 minutes $35,000/t and at 300 minutes $100,000/t. These latter prices for carbon are very unrealistic; therefore this highlights the need to reduce delay in order to reduce carbon emissions as well.

5.2.1 Wind Speed

A factor, which has not yet been mentioned in any detail, is the impact of wind speed on the CI. As discussed in Chapter 4, wind speed has a strong impact on the flight time and fuel use of a flight. This factor is usually accounted for by the FMS prior to departure so is not included in the original CI equation calculated by flight dispatch. However, as it can have a significant effect on flight time it is important to understand the effect that it may have on the overall flight. Figure 5-10 shows the impact of increasing head- and tailwinds for the flight in question. Headwinds have the most significant effect on the flight compared to tailwinds and it is notable that the impact of fuel use and flight time is not of the same magnitude. If a headwind reaches 200kt then the flight time will have to be decreased by 0.8% to compensate for this, but will only increase fuel by 0.4%. Conversely, when there is a tailwind the aircraft can afford to fly faster, decreasing flight time by 0.4% and resulting in a fuel decrease of 0.1%.

Changes in wind speed between -50kt and +50kt only have a negligible effect on the CI of a flight. With the average for the route analysed being -26kt, wind speed is deemed not to have an important impact. However, this does become important for routes affected by strong jet streams. In recent years jet streams have reached speeds of up to 200kt and therefore care needs to be taken calculating optimum CI values for these routes. However, crosswinds are also an important issue, particularly on routes between Asia and Europe.

They are not included in this analysis as reliable data is not available but should be considered by airlines.

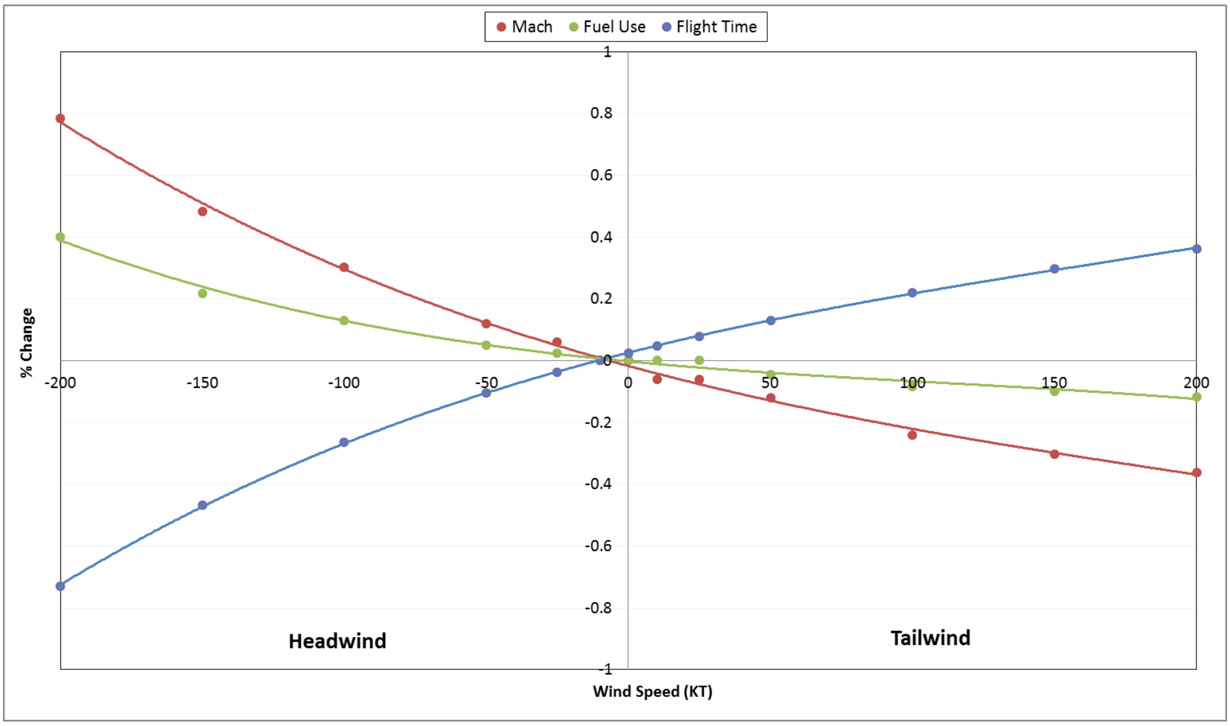

Figure 5-10: Per cent change in flight parameters with changing wind speed

5.3 Uncertainties

There is a lot of inherent uncertainty in creating scenarios that represent the situation in the industry in 2050. There is very little data concerning how maintenance and labour costs will change in the future and past trends provide mixed indications. These will also be very airline specific. Whilst there is more information regarding future projections for carbon and oil prices, these can also be highly variable, as was seen with the unpredicted low oil prices at the beginning of 2015. In terms of carbon prices this can be even harder to predict as the market-based measure to be used in the aviation industry has not yet been decided upon. Biofuel development is still in its early stages to and will be hampered by problems such as the supply of feedstock and sustainability issues. The area where the most estimation had to be made was the amount of delay that can be expected in the future owing to a lack of data and this will also be extremely flight specific, with the extent of delay varying flight-by-flight. The best available data for the scenarios was used where possible, but these scenarios are aimed to provide more of an indication of the impact of how different situations could impact the industry in future and the areas in which more research and policy implementation is needed, rather than providing absolute values for CI in the future.

5.4 Discussion

Results of the scenario analysis show that the picture regarding CI will be very different from today. There is a general trend that CI values decrease. This demonstrates the importance of increasing fuel prices, as even with constant and decreasing time costs (not including passenger delay costs), the optimum CI value was reduced. The only scenario where this is not true is the Pessimistic-A scenario in which fuel prices decrease and as a result an increasing CI was seen. However, it seems unlikely that these fuel price decreases will be seen in the future, unless significant new reserves are found and/or unconventional oil sources can be recovered economically.

Although fuel costs clearly have a significant impact on the optimum CI value of a flight, the model does show slightly higher sensitivity to time-dependent costs. This is because only a 6% change in time costs was used compared to over 10% for fuel costs. Airline costs are very hard to predict, as they are very airline specific. Some airlines, particularly low cost airlines, are a lot more aggressive when it comes to cost savings in this area. It has already been discussed in this chapter how airlines have varied in the past regarding policies to reduce labour costs in particular. However, further efforts to reduce labour costs are becoming increasingly difficult to implement. This is particularly true for airlines that are trying to implement new policies, which come against strong opposition by aviation authorities.

Whilst airlines might struggle to reduce labour costs further, maintenance is an area that could show promise for cost reductions. Although aircraft design is becoming more complex, there are also new technologies becoming available to deal with this. Other advancements such as better aircraft design for maintenance and the use of 3D printers to produce aircraft parts could also significantly reduce costs, but how far these measures will be developed is still in question.

With the likelihood being that constraints will limit further labour cost reductions leading to a stagnation or even increase, and with maintenance costs showing a potential to decrease but uncertainty over the extent of the decrease, it is likely that time-dependent costs may remain at a similar level to what they are today. However, a component of time dependent costs that is likely to have an overriding impact on CI values in the future are those associated with passenger delay. Up until the threshold of three hours for delay compensation, delay costs for labour and maintenance only have a negligible impact on CI. However, once this threshold is crossed the impact is significant, with CI increasing dramatically in order to keep total costs to a minimum. This is not a favourable situation for fuel use or CO_2 and even though costs are kept to a minimum, there is still an overall increase.

It is very important to note the importance of recalculation of the CI in this situation. The situation in which the worst outcome is experienced is the one in which airlines try to deal with delay by making up as much of the delay time as possible. However, this ignores the increase in costs of fuel that result from increasing the speed of the aircraft, which in the case of this analysis are not outweighed by the costs of delay. The recalculated cost instead finds a balance between this situation and not changing the CI at all. As discussed previously, estimating the amount of delay, which might be regularly experienced by a flight in the future, is very difficult. This analysis shows the importance of avoiding these delay cost thresholds and highlights the need for additional research into this area in the future. This will include researching and implementing solutions to reduce capacity constraints and congestions and also undertaking more research into future events that might exacerbate the situation, such as climate change induced severe weather events and finding ways to guard the system against them.

At the other end of the spectrum, it was found that carbon pricing has very little impact on future CI values, total costs and CO_2. There is currently great hope that a market-based measure can significantly reduce carbon emissions from aviation. However, there are many uncertainties involved with this approach, not to mention whether success with other schemes can be transferred to such a unique area of aviation. The success of a cap-and-trade system is determined by four criteria: the prevailing cost of carbon; the number of carbon allowances allocated for free for airlines; the rate of 'price pass through' of the cost of carbon by airlines to customers; and any resulting change in demand by customers owing to increased ticket prices.

This analysis has shown that in terms of CI, the addition of a carbon price has very little impact. This is despite fairly high carbon prices being used compared to other industry predictions. As the Carbon Trust (2009) suggest adding a cost of carbon will be less effective than high kerosene prices. The price of carbon is particularly important in terms of the CI when delay is also present. However, it is very unlikely that the scale of carbon price will ever exist to counteract the extra costs of delay to ensure that there are no additional emissions, as prices in the range of \$11/kgCO_2 to \$100/kgCO_2 would be required to do this. To put this in perspective, even the highest projected carbon price in 2050 used here is only \$0.124/kgCO_2. However, the Carbon Trust (2009) also states that a carbon price could act as a "turbo-boost" on already volatile fuel price. PWC (2012) in their assessment believe that putting a price on carbon is unlikely to drive the required emissions reductions itself, with governments needing to offer airlines a practical way of growing their business, whilst freezing further emissions growth.

Linked to this is the use of biofuels in the industry. This analysis shows that the greatest impact on carbon emissions is the introduction of fuel efficiency measures and particularly the use of biofuels. This analysis was quite conservative in its assessment of the use of biofuels on an individual flight basis, with a maximum of 30% in 2050. However, this leads to a significant reduction in emissions, 3.7 times higher than what is achieved by efficiency measures and the change in CI alone.

Although there have been a number of successful test flights using biofuels, there are still significant challenges in meeting strict fuel quality standards and the feedstocks used. Only second and third generation biofuels are suitable, as conventional biofuels do not meet strict fuel quality standards, which still require significant development before they reach large scale commercial production. Other issues include sustainability concerns; lack of policy incentives and funding; lack of feedstocks; and new infrastructure requirements (Gegg et al., 2014, Upham et al., 2009). There are also mixed signals from governments regarding their support for the use of aviation biofuels. There is a lack of international consensus on how best to incentivise this option. As biofuel policy is needed in all regions where an airlines will operate, as well as where they will source them from, there is a need for a global approach (Airlines International, 2014).

Land area is one of the key issues with the use of biofuels and it puts their sustainability into question. Figure 5-11 shows the land area that would be needed to replace all jet fuel in 2003 when global consumption was about 720 million litres a day (light blue). It is clear that a vast area of land would be needed, taking up an area equivalent to Spain and Portugal. This could be reduced if productivity could be increased (dark blue and red areas). However, fuel consumption continues to grow. Therefore, if productivity is not increased then an even more significant area of land will be needed. However, it is important to look at this in relation to global food supply. It has been promised that biofuels for aviation will use marginal crops, which do not need to be grown on agricultural land (Vera-Morales and Schafer, 2009).

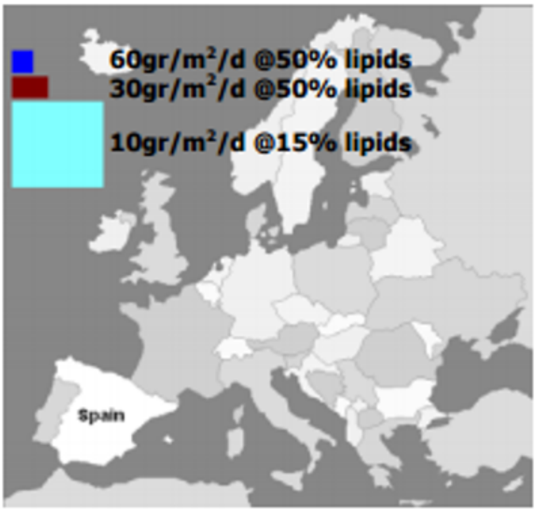

Figure 5-11: Land Requirements to supply the world consumption of jet fuel during 2003 with light blue area representing amount of land needed at current production levels (equivalent to Spain and Portugal) and the dark blue and red areas showing land requirements with increased production levels (Vera-Morales and Schafer, 2009)

However, there are only around 400Mha of marginal land currently available, with no indication of how accessible this land is. If biofuels were to replace the total jet fuel use of 2014 a land area of around 200Mha would be needed (FAO, 2011). With aviation demand due to grow at 5% per year, the amount of land is unlikely to be enough in the future. A more significant problem is likely to be that biofuels used for aviation may be worth more than food crops for farmers, and therefore the likelihood is that farmers will opt to grow biofuels on better quality agricultural land in the future. Without intervention by governments this would undoubtedly have an impact on food production. More research is needed in this area, particularly concerning using more efficient biofuel feedstocks such as algae, which requires significantly less land area.

There are two key results from this analysis which have provided important indications of where future policy and research needs to lie in order to reduce both future costs and ensure a reduction in carbon emissions: ensuring delay remains under passenger compensation thresholds and the effectiveness of carbon pricing on an individual flight basis.

The results of this analysis are contrary to the research of Lee et al. (2013), with their analysis ranking emissions trading as the most effective tool in CO_2 mitigation, followed by efficiency measures and then biofuels. However, it is hard to compare these studies as different parameters have been used and there is no indication of the carbon price used in their study. This highlights two key differences in using a system wide approach to analysis compared to the specific flight-by-flight analysis used here.

Firstly in the flight-by-flight analysis there is no account taken of offsetting, which is predicted to be a major part of airlines management of an emissions trading schemes. Secondly, it appears that most studies do not take account of the use of CI in their analyses. With the CI not demonstrating linear relationships it cannot be assumed that costs and CO_2 emissions will see the same changes without its consideration. This study has shown that the carbon price can be absorbed without a significant impact on overall flight parameters. For example, ICAO (2013b) estimates that a MBM will have an impact of a 6.9% increase in costs with a 12% reduction in CO_2 emissions, this analysis finds roughly the same increase in costs of 6% but less than 0.1% decrease in CO_2 emissions for a high carbon price. Therefore, CI needs to be considered in future research regarding the impact of MBMs on the industry.

This conclusion does not mean to undermine the use of system wide studies in evaluating the impacts of policies on the industry, as they remain a very valuable tool in the gauging overall impact, as well as taking into account factors which the CI cannot, such as the use of offsetting. Instead the conclusion of this analysis is that system wide and flight-by-by analysis, which takes into account of the detail of complex airline practices, should be used side-by-side in future research.

5.5 Summary

This chapter has demonstrated CI's dual purpose in being a mitigation measure for aviation-induced emissions and as a policy tool in evaluating future impacts on the industry. The scenario analysis has been intended to give an indication of the areas were future research and policy implementation is needed. It is clear that fuel costs will play a major role in deciding the future optimum CI values and evidence points towards this factor helping to reduce CO_2 emission to 2050. The two main areas that stand out as needing more research and policy attention are delay management and the application of carbon pricing to aviation. Delay costs had the most significant impact on the CI after the threshold limit of passenger compensation was met, with the assumption that delay will increase in the future without measures to manage congestion and permutations in the system. Contrary to this the application of carbon prices appears to have only a minor impact of CI values and resulting CO_2 emissions, suggesting that more needs to be done to encourage environmental sustainability in the industry. These issues will be further explored in the next chapter, along with other areas where the use of CI could be developed further.

Chapter 6 Further Work

6.1 Introduction

In previous chapters the CI concept has been evaluated and developed thoroughly within the scope of this thesis. However, there are many areas that still require further research. This includes further development of the OCI model and the practicalities of changing CI values, as well as further examination of more general climate mitigation issues in the industry, which have been highlighted by the analysis.

6.2 Developing the OCI Model

The OCI model created in this thesis has demonstrated that flights can be more optimally planned using CI, but further development with the airline industry is needed to ensure it works on an operational basis and provide more validation of the methodology. Chapter 4 described some basic adjustments that would need to be made, such as using more powerful software to deal with the volume of flight data required. It is likely that more adjustments would be needed for different business models, such as low cost and charter carriers. Although the model would essentially be the same, certain aspects may be slightly different, such as the proportion salary paid as duty pay and conditions of overtime.

An area where more work would be needed to adapt the model would be for freight aircraft. The model would have the same basic structure, but a key difference would be for crew pay, as cabin crew costs are eliminated. The main area for change would be with delay costs. These are likely to be reduced as passenger costs are no longer applicable, but there may be other delay costs associated with getting freight to its customers.

The most important aspect of developing the OCI model is working with airlines to maximise the positive impacts it has on their operations. This would require work with a variety of airlines as even those that appear to have the same business models, can vary significantly in their operations. Different airlines have different pay structures for their flight and cabin crews, some lease aircraft whilst others own, some manage their own maintenance and others outsource it and different airlines have different delay management strategies. All of these factors need to be taken into account when calculating the CI. Also some airlines may wish to include other costs, such as depreciation, into their CI calculation, which can be added to the OCI model. The model is designed to take all of these variables into account, however it would be up to the individual airline to supply the specific inputs for their operations.

Whilst in general there is a lack of research into the area of CI, there is even less information regarding how the CI value is actually used within the flight management system (FMS). This was an issue in the use of the model as small changes in CI values were not enough to change the cost function and therefore the speed of the flight. It was assumed that the FMS has a higher level of precision; therefore the OCI model was adjusted to account for this. However, this assumption may not be true and this could represent a fault in the system for the FMS using CI values to determine flight speed. With this is mind, more information regarding the way the FMS uses CI values would benefit the development of the OCI model.

6.3 Network Issues

In Chapter 2 it was demonstrated that many aircraft, thought to fly at roughly their LRC speed, actually fly higher than this speed for the majority of a flight. As the optimum CI values usually lie somewhere between the MRC and LRC of an aircraft, airlines optimising their CI values might find their aircraft are flying at considerably lower speed. For an aircraft in isolation this is not necessarily an issue, but on a network scale this could present an issue to the air traffic management systems. This is further complicated by the fact that some airlines may be taking steps to optimise their CI values, whilst others are not resulting in variety of different speeds amongst aircraft. Even when different airlines are optimising their CI values, differences in costs can result in different changes in speed relative to those previously used.

As discussed in Chapter Two, safety alerts have been triggered by the range of speeds in airspace between the same aircraft types, with a key reason being given as a lack of information regarding the CI based flight-planning process. A challenge can be presented to ATC when speeds can vary owing to CI by 10% and speed changes of 5% have to be reported to ATC, with the potential to increase controller workload and reduce capacity in the system (Rumler et al., 2010).

There is also anecdotal evidence that problems already exist with the presence of slower aircraft with aircraft either being held up or having to overtake. In this latter case there are questions of whether this results in more fuel being used than is saved by the slower aircraft. There is very little information available about this issue and therefore it requires more research attention.

A further issue is how CI will fit in with a future air traffic system that is based on new concepts, such as 4-D trajectories. The aim of using 4-D trajectories is to achieve synchronisation between the ground controls and aircraft, such that time prioritisation for arrivals at airports is initiated. The concept has been implemented in order to cope with capacity and safety. It works by ATC initiating a trajectory negotiation via datalink when the aircraft is around 40 minutes away from the destination airport. The aircraft FMC computes a reliable and achievable estimated time of arrival (ETA) window, which the arrival manager then uses this to compute a controlled time of arrival (CTA) (Korn and Kuenz, 2006, Mutuel et al., 2013).

The SESAR programme in Europe has been testing such a procedure with its I4-D concept cumulating in 2012. There were issues with the integration of CI with the 4-D concept and it was acknowledged that any required time of arrival would need to be extended to the full range of speed covered by the CI. In addition, where high CI values were being used in the test flight, applying the CTA resulted in decelerations, with the main remark by flight crews being that the lack of anticipation of large speed variations was disturbing (Mutuel et al., 2013).

The conclusion from SESAR was that CTA and ETA should be matched as much as possible. However, more work is needed to not only figure out how to accommodate CI within the 4-D trajectory concept, but to also understand how CI could help enable this concept to be a success. For example, optimisation of CI is likely to reduce speeds and therefore eliminate some of the issues with sudden decelerations.

6.4 Interaction of CI and Future Industry Impacts

This study has highlighted two key areas where more research is needed within the context of CI and the interaction with other impacts. The first is the issue of congestion and capacity constraints leading to delay in the system. This is already an issue in certain areas of the system and is quite visible. Therefore, there has already been a lot of research interest and development in this area, particularly with the SESAR programme in Europe and the NetGen programme in the US. However, there will be a need in the future to extend such programmes, particularly to Asia, which is seeing the greatest growth in air traffic demand worldwide (ICAO, 2013a). The implementation of technologies and procedures that will be needed for the reduction of congestion will also require a significant amount of stakeholder cooperation, which is discussed in the following section.

An area that is still significantly lacking in understanding is the implementation of a market-based measure to the industry. This is a time sensitive issue as ICAO are currently deciding what this measure should be with the view for implementation from 2020. There are mixed views on whether such a scheme can be successful in reducing emissions.

The benefits of using a MBM scheme to reduce emissions instead of a command and control mechanism include flexibility and financial incentives to guide the behaviour of airlines towards environmentally responsible activity. It is also deemed to be an important gap filler, as it is forecast that emissions reduction from technology and operational measures alone will not be enough to achieve carbon neutral growth from 2020 (ICAO, 2013).

Whilst studies such as Lee et al. (2013) have stated that a MBM will be the more effective at reducing emissions than other measures, this analysis has found that in terms of CI it will have little effect. If carbon prices are not high enough to change CI values then it is unlikely it will be enough in isolation to promote further efficiency improvements.

Lawson (2012) addresses this issue stating that the implementation of an MBM is likely to be ineffective owing to the technological "lock-in" experienced by the aviation industry. Aircraft appear to be reaching technological maturity, with the majority of efficiency measures having already been made. More radical innovations, such as new aircraft designs are too risky for airlines to invest in and new fuels, like biofuels, are still in the early stages of development with it being unclear whether technical, social and environmental issues with their use can be overcome.

Therefore, it is unlikely that an MBM would result in any significant reduction in emissions within the industry and airlines would instead rely on offsetting from other industries. Whilst this may not be seen as a problem by some, Lawson (2012) points out that this does not encourage the aviation industry to break out of a system where interdependencies lead to increases in demand for air services, with the need to further increase the sale of these services in order to remain profitable, with this being at odds with a lack of technological fixes.

It should be pointed out that by using CI for analysis, offsetting is not taken into account, which is where most of the emissions savings from a MBM are expected to come from. Carbon Market Watch (2013b) has highlighted why there are concerns over using offsetting in this way. Firstly, as already mentioned, it does not lead to emissions reductions in the aviation sector, therefore cannot deliver long term solutions. In addition, if offsets are of low quality then climate impacts might even be made worse. It is essential that emissions from offsets are real, permanent, additional and verified. However, the history with offsetting in other trading schemes does not offer a positive outlook for future schemes.

Sreekantha et al., (2014) highlight some of the issues that have been seen with the Clean Development Mechanism (CDM), which is one of the key providers of offset credits on the international compliance market. There are issues concerning the scope of the scheme, with only four countries (Brazil, China, India and the Republic of Korea) responsible for the majority of offset schemes, with highly uneven shares of projects, with the majority consisting of biomass energy and hydroelectric schemes. It was found that the CDM left to market forces did not comparably contribute to sustainable development.

Problems with additionality of projects is one of the key issues with offsetting i.e. there is no differentiation between projects achieving emissions savings to those that would achieve those emissions savings without the CDM. For example in China, new projects from CDM equalled 5.1GW of the 9GW saved in 2007, but previously 7.7GW had been achieved without the use of the CDM (Broderick, 2009).

Whilst there have also been a number of conspicuous CDM projects which are actually more harmful to the environment, such as iron smelting or landfill sites, a more pressing problem is the type of project that is allowed under the scheme. A popular CDM project involves land use changes, primarily with reforestation, but carbon biologically sequestered in soils could cause more climate damage as it is prone to release at a future date, as well as avoiding moving away from the use of fossil fuels and incentivising innovation in new technologies (Broderick, 2009).

This is not to say that an MBM does not have a place in the industry, but it is clear that more research and analysis is needed in order to provide a mechanism that is able to result in significant emissions reductions. In their report, PWC (2012) states that putting a price on carbon alone is unlikely to drive the sufficient emissions reductions and therefore there is a need for alternative or additional measures for emissions mitigation. As pointed out in this analysis it is unlikely that carbon pricing will be enough to stimulate the required development in alternative fuels. Therefore additional support is needed from governments in order for the technology to be scaled up and made economically viable for airlines.

PWC (2012) also state that there will need to be an investment in public goods through participants being brought together, as discussed in the next section, or by governments financing the investments needed. Other measures could also include the introduction of positive incentives or mandates to airlines.

6.5 Stakeholder Engagement

A key theme that has emerged from both examining the implementation of CI on a system wide basis and with the implementation of mitigation measures to reduce emissions, is the need for stakeholder cooperation. The aviation system is defined by its multi-stakeholder nature, which makes implementing system level changes difficult. Owing to the complexity in the system, as seen in Figure 6-1, the availability of a specific technology is not a sufficient condition to ensure implementation (Mozdzanowska et al., 2008).

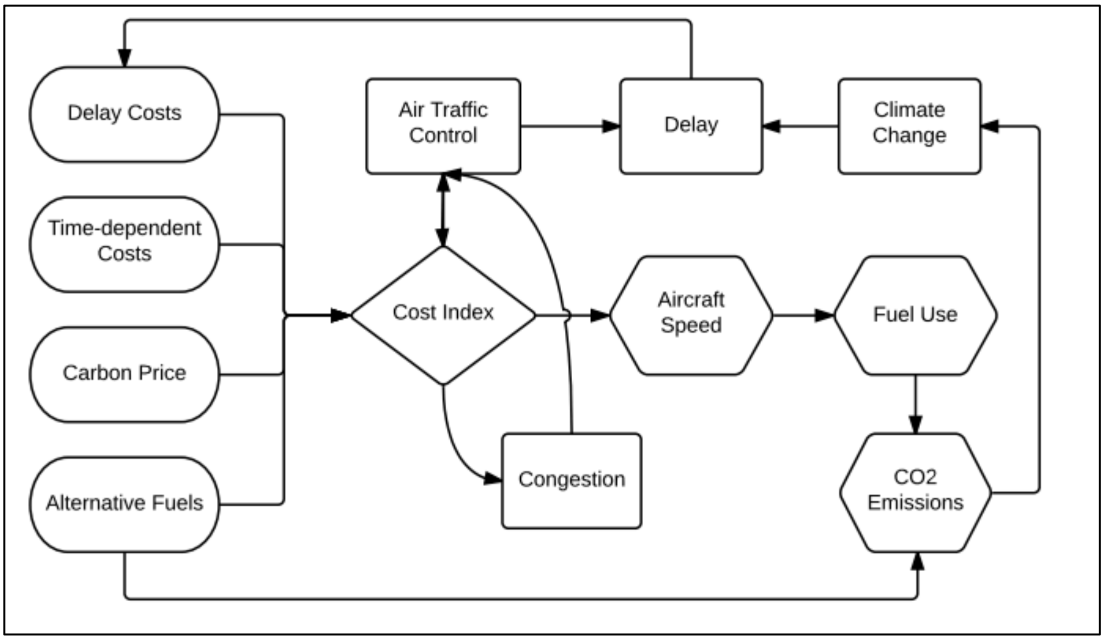

Figure 6-1: Interactions between CI and the Air Traffic System

Whilst one of the main draws for airlines in using CI is to optimise their flight operations and potentially reduce emissions is that it can be used independently from other airlines and ATC, as Kivits et al. (2010) state “technology is rarely stand-alone but almost always part of a technological system. Within the system, all components are interrelated”. As previously mentioned whilst individual airlines can implement their own CI values independently from one another, the ATM system is likely to be affected. Therefore it is in the interest of the aviation industry as a whole to develop the use of CI together to ensure the best outcome in terms of fuel use and CO_2 emissions.

For the optimisation of CI to be truly effective there is also a need for airlines to improve engagement within the airline itself, between their own departments. Evidence suggests from discussions with airline professionals and from studies, such as Burrows et al. (2001) and Airbus (Airbus, 1998) highlights that there is a lack of communication between flight operations and accounting departments. This means that the true cost components of CI are not known and needs to be a primary step in using CI effectively.

The development of CI would also benefit from the involvement of the pilots who are ultimately responsible for flying these CI determined flight speeds. There is a two-fold reason for the need to involve pilots. Firstly, every flight is different and so the implications on the environment of a flight is not standardised, even within airlines. Therefore, pilots can provide valuable information regarding how the CI could be optimised and the practicalities involved with this.

Secondly, there are reports showing that traditionally there is an adversarial relationship between managers and pilots with little communication and consensus over the direction of the business. In the past pilots have not understood initiatives to reduce fuel use from flights and this has led to them being uncooperative in implementation of fuel efficiency measures. It has been suggested that these initiatives could be more effective if pilots had more confidence in the reliability of the system and not just being provided with the bare facts (Harvey et al., 2012).

Further guidance for the implementation of measures to mitigate emissions more generally on a system wide basis could also be provided by analysis by Marais and Weigel (2006) who provide a framework for the levers needed and the amount of stakeholder engagement required. Figure 6-2 shows an example of this. For example, CI would fall into the category of a desirable technology that airlines would have an immediate incentive to invest in as it reduces costs, whilst other strategies to, for example, improve congestion would requires more policy interventions i.e. the blue and red boxes.

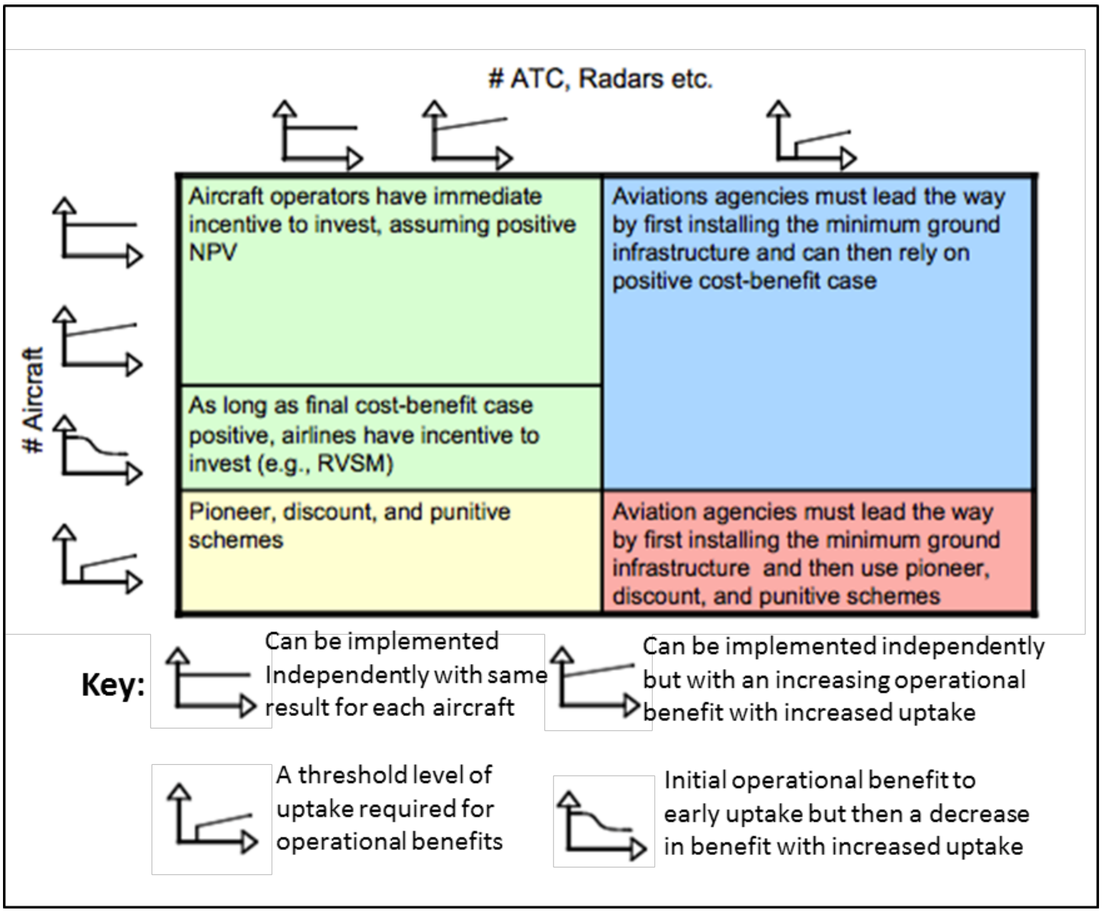

Figure 6-2: Leverage strategies according to network benefits (Marais and Weigel, 2006).

6.6 Summary

The use of the CI in optimising flight efficiencies, particularly in reducing CO_2 emissions seems very promising and this thesis has aimed to demonstrate a way in which its calculation can be carried out more effectively. To build on this there will need to be further research undertaken within the industry to ensure that the optimisation of CI can be done in an effective and practical way for airlines. Wider system impacts also need to be considered with the use of CI, as well as the interaction that CI has with wider climate mitigation measures. Further research is needed into these areas to ensure that there are net emissions reductions. To tie this all together there will need to be stakeholder engagement, not just within the industry and between policy makers, but also more communication in airlines as to the importance of CI and the need for accurate information for calculation. A key group for inclusion will be pilots, as they will ultimately be responsible for operating aircraft using optimised CI values.

Chapter 7 Summary and Conclusions

7.1 Introduction

The aim of this thesis was to explore how the use of CI could help airlines to reduce their CO_2 emissions. The CI is a valuable tool that determines the speeds of individual flights based on the condition that total costs should be minimised by balancing time-dependent and fuel costs.

It is evident that there is significant scope to optimise airline CI values. There is both anecdotal and evidence from the literature that it is not currently being used optimally by a large number of airlines, either through misuse or miscalculation. This thesis examined how to change this and optimise the CI with a novel calculation method.

7.2 CI's Role in Emissions Reductions

The analysis in Chapter Two showed that there is significant potential for CI to contribute to the basket of mitigation measures to help to achieve carbon neutral growth in the industry from 2020. Initially analysis examined the relationship between fuel use and flight time for a range of CI values for six different aircraft models, over distances from 1000NM to 6000NM. Results clearly showed that the greatest savings in emissions can be achieved with both higher distances and with larger aircraft, suggesting that the area to focus on initially should be long-haul flights.

It is a common expectation that aircraft fly around their LRC speed – the speed at which there is a sacrifice in fuel efficiency of around 1% for a faster flight time. However analysis undertaken, along with evidence from the literature suggests that aircraft are flying above this speed for the majority of the flight. As the optimum CI of a flight generally lies between the LRC speed and the MRC speed – the speed at which there is minimum fuel consumption – there is significant potential for emission reductions of at least 1% per flight, although highest theoretical saving could be as high as 12%.

To put this in context, compared to other measures, CI is a very strong candidate to add to the basket of mitigation measures to reduce CO_2 emissions in the short to medium term. Its value as a mitigation measure is added to by the fact that larger scale solutions, such as biofuels are expected to be slow to penetrate the industry. Other measures to be used alongside CI include improvements in engine and aerodynamic efficiencies, as well as better aircraft and airspace operations. The majority of these measures also only result in small savings of less than 5% by 2020 (ICAO, 2013), but used together there is a higher chance of stabilising emissions at 2020 levels.

7.3 The Creation of a New Model for CI Optimisation

With the significance of CI as a mitigation measure being realised, the next step was to find a way to enable its optimisation in airlines in an efficient, easy, transparent and cost effective way. To do this all the costs involved with the CI had to be analysed. It is clear from this analysis that the costs that complicated the calculation of the CI were primarily those that were time-dependent. The reason for this is because they have cumulative and threshold costs associated with them. For example, an extra minute of crew costs for one flight might not make a significant difference to the individual flight costs, but when considered cumulatively across all flights, might lead to the payment of overtime. Another issue arose when examining delay, in that these costs have threshold values, which if crossed result in a significant increase in time-dependent costs. Therefore the CI has to be recalculated to take this into account.

The decision was made to create an Optimised CI (OCI) model in which cumulative and threshold costs were dealt with separately, instead of trying to accommodate them in one calculation that would ultimately lead to incorrect values being used. Instead up to four different CI values are produced depending on the information provided for the flight by the airline i.e. the crew on-board, the number of connecting passengers, the amount of delay expected etc. The four CI values represent the following:

CI-1 The initial CI value calculated from the per-minute time-dependent costs and the fuel costs per kilogram for that flight.

CI-2 A new CI is calculated if the flight time from CI-1 does not fit the schedule representing the closest flight parameters that does meet schedule time.

CI-3 A recalculated CI taking into account delay, if present. This calculates any passenger costs and overtime for crew or maintenance.

CI-4 If delay is present this recalculates the CI to make up as much of the delay as possible, regardless of the total cost.

Once these four CI values are calculated, the one with the lowest total cost is presented as the optimum CI value to the airline. The model provides transparency to airlines over how these costs are calculated and provides a model, which with a few alterations to deal with their own aircraft data, could provide a simple calculation method for CI that could be conduction for every flight. This would be a significant improvement to the current situation of airlines using average values across the same aircraft model, regardless of individual routes, flight conditions and the age of the individual aircraft.

7.4 The Interaction of CI and the Future Aviation System

Using the OCI model to test different scenarios has a two-fold purpose. Firstly, it can help to further understand the model and how CI affects flights. Secondly, if airlines realise the value of optimising their CI values, then CO_2 savings will reach a plateau eventually. Whilst the OCI model would continue to be used in flight planning as flight parameters continue to change, added value from the model is created by the insights that it can provide in how future impacts on the industry can affect the CI and resulting flight parameters.

Future impacts include changes in fuel prices, the introduction of alternative fuels, the introduction of a market-based measure to reduce CO_2 emissions, improvement in aircraft efficiency and changes in time-dependent costs, as well changes in delay caused by congestion and extreme weather. In addition to changing values being applied to the OCI independently for each measure, four future scenarios were created to provide an indication of changes up until 2050.

It is clear from results that fuel costs play a very important role in determining the CI as they are predicted to vary more than normal time-dependent costs in these scenarios. However, the most significant impact came from delay costs when passenger compensation cost thresholds were passed. This resulted in an increase in CI and CO_2 emissions, although increases in total costs were curtailed by the recalculation of the CI. On the other hand, the addition of a carbon price to the fuel side of the equation had very little impact on CO_2 emissions, although costs increased more significantly. This result was seen even when high carbon prices were applied. Therefore, the issue of an increase in delay, most likely owing to increased congestion and extreme weather events, and the apparent inadequacy of a carbon price to reduce emissions, present themselves as key areas where further research is required.

7.5 Further Research and Policy Developments

Building on this research there are a number of areas where further improvements can be made and there are areas where further research is needed. The OCI model requires further development within the industry to ensure that it is effective and practical to use on a day-to-day basis by flight planning departments. This involves smaller changes, such as inputting an airlines own data into the model, to more significant changes, such as adapting the model to accommodate freight operations.

Another key area is to examine the wider system impacts, which may result from the introduction of more optimised CI values, as well as the integration of the use of CI into future ATC changes, such as the introduction of 4-D trajectories. Whilst the CI may be problematic in some areas of ATC, particularly initially if different airlines are flying a wide variety of speeds, ultimately its use may be useful in reducing the impacts of schemes such a 4-D trajectories.

The final two areas of improvement concern not only CI, but also climate change mitigation in general within airlines and the industry. It is suggested that further research is needed in the two areas highlighted in Chapter 5 – issues with congestion and extreme weather events and the implementation of a market-based measure to the industry. Concerning the latter issue there is particular concern that the measure will not provide sufficient reductions in emissions and therefore alternative measures also need to be considered.

Finally it is evident that a significant amount of stakeholder engagement and cooperation will be needed in order to ensure that real emissions savings are made and that CI implementation is effective. This will need to start within airlines to ensure that all necessary departments value the importance of CI, particularly between operations and accounting departments to make sure that the costs associated with CI are known and are accurate. It is also important to inform pilots of practices involving CI, as they will ultimately be in charge of flights determined by the calculated CI values and can provide important information to help in the development of CI. Further stakeholder cooperation in the industry in general, as well as with other policy makers, is also important to understand the practicalities and impact involved with the policies and research needs on the industry.

7.6 Key Recommendations

Based on the above conclusions there are five key recommendations to further develop CI.

- CI should be seriously considered as a mitigation measure for reducing CO_2 emissions, as well as having other benefits such as minimising costs, in order for the industry to enable its optimisation.
- The OCI model should be further developed with the industry to provide a practical way of airlines to effectively calculate CI values on a flight-by-flight basis.
- The use of CI should be considered as an additional tool in calculating future impacts on the industry.
- Policy concerning climate change mitigation for aviation needs to consider a variety of measures, including but not limited to, market-based measures.
- Stakeholder cooperation is a needed in order to maximise the benefits of CI and climate mitigation in general, both within airlines and the industry as a whole.

7.7 Overall Conclusions

The CI is a valuable tool to airlines and it shows significant promise as a tool to help reduce CO_2 emissions. Optimisation of CI also benefits airlines by minimising costs for individual flights. This research has found that savings of at least 1% in fuel use and CO_2 emissions are possible by optimising CI on a flight-by-flight basis.

Whilst the tool has been available for over three decades, airlines have struggled to incorporate accurate costs into their calculations. In the past this may not have been seen as an issue as airlines fuel costs were significantly lower than they are today. However, with rising jet fuel prices and the threat of a carbon price being applied to their fuel use, airlines are now taking notice of the importance of optimising CI. One of the key issues is the presence of cumulative costs, which depend on more than one flight and delay costs. Airlines also tend to use the same CI value for extended periods of time and use average values across the same aircraft models. By separating out these costs and performing multiple CI calculations, it has been shown that the OCI model created in this thesis provides a more practical way to calculate CI and provide individual values for each flight.

By finding the minimum cost from a variety of CI values, the OCI model provides the best solution given the flight parameters provided by the airline.

The OCI model also has a dual purpose as it can also be used to test future scenarios for airlines and the aviation industry as a whole. The analysis undertaken in this thesis shows that there is significant scope for change in CI values in the future, which could substantially change CO_2 emissions. Two factors arose from this analysis as needing further attention, both for opposite reasons. Firstly delay has a negative impact on CO_2 savings as it forces CI values to rise dramatically. However, addition of a carbon price aimed to reduce emissions does not have a significant effect on emissions. It is strongly recommended that alternative policies to reduce emissions within the industry are also considered.

As well as further research in these areas, further work will be required in order to develop CI further, particularly in terms of stakeholder engagement and network issues. However, none of this further work is insurmountable and evidence suggests that CI has the potential to provide significant benefits in the future and not just in terms of reducing emissions.

The major benefit of CI is that it is already available in most commercial aircraft's flight management systems and it would be relatively cheap and easy to implement by individual airlines. With the target of ICAO (2013) to achieve carbon neutral growth from 2020 and with evidence that immediate measures are needed to prevent the worst effects of climate change, the optimisation of CI should be considered as a key measure to help with mitigation of climate change impacts. Whilst airlines are beginning to see the value of CI and looking to optimise their values, an effort by the industry as a whole is needed in order to realise CI's full potential.

References

ACKERT, S. 2012. Basics of Aircraft Maintenance Reserve Development and Management. *Aircraft Monitor*.

AIR TRANSPORT DEPARTMENT CRANFIELD UNIVERSITY. 2010. *Fuel and air transport: A report for the European Commission* [Online]. Available: ec.europa.eu/transport/modes /air/doc/fuel_report_final.pdf. [Accessed 14/08/2014.

AIRBUS 1998. Getting to grips with the cost index Blagnac Cedex, France Flight Operations Support & Line Assistance

AIRLINES INTERNATIONAL. 2014. *Biofuels in Aviation: The Dilemma* [Online]. Available: http://airlines.iata.org/analysis/biofuels-in-aviation-the-dilemma.

ÅKERMAN, J. 2005. Sustainable air transport—on track in 2050. *Transportation Research Part D: Transport and Environment,* 10**,** 111-126.

AKTURK, M. S., ATAMTURK, A. & GUREL, S. 2014. Aircraft Rescheduling with Cruise Speed Control *Operations Research* 62**,** 829-845.

ATAG 2010. Beginner's Guide to Aviation Efficiency Geneva Air Transport Action Group

BALL, M., BARNHART, C., DRESNER, M., HANSEN, M., NEELS, K., ODONI, A., PETERSON, E., SHERRY, L., TRANI, A. & ZOU, B. 2010. Total Delay Impact Study - A comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States.

BARNHART, C., FEARING, D., ODONI, A. & VAZE, V. 2012. Demand and capacity management in air transportation. *European Journal of Transport Logistics* 1**,** 135-155.

BAUEN, A., HOWES, J., BERTUCCIOLI, L. & CHUDZIAK, C. 2009. Review of the potential for biofuels in aviation for CCC. London: E4 Tech.

BAZARGAN, M. 2010. *Airline Operations and Scheduling 2nd Edition,* Farnham, UK, Ashgate

BOEING. 2015. *Current Products & Services* [Online]. Available: http://www.boeing.com/commercial/ [Accessed 11/05/2015.

BRODERICK, J. 2009. Voluntary Carbon Offsetting for Air Travel *In:* GOSSLING, S. & UPHAM, P. (eds.) *Climate Change and Aviation: Issues, Challenges and Solutions* London earthscan.

BURROWS, G., BROWN, C. A., THOM, T. W., KING, J. M. C. & FREARSON, J. 2001. Real-time cost management of aircraft operations. *Management Accounting Research,* 12**,** 281-298.

CAA 2014. Punctuality Statistics London.

CAPA. 2014. *Norwegian Air Shuttle's long-haul business model. "Flag of convenience" or fair competition?* [Online]. Centre for Aviation Available: http://centreforaviation.com/analysis/norwegian-air-shuttles-long-haul-business-model-flag-of-convenience-or-fair-competition-146928 [Accessed 09/09/2015.

CARBON MARKET WATCH 2013a. Turbulence Ahead: Market Based Measures to Reduce Aviation Emissions Brussels.

CARBON MARKET WATCH 2013b. Turbulence Ahead: Market Based Measures to Reduce Avition Emissions Brussels.

CARBON TRUST 2009. Fasten your seatbelt: Airlines and cap-and-trade. London.

CIVIL AVIATION AUTHORITY. 2015. *Delays and Cancellations* [Online]. Available: http://www.caa.co.uk/default.aspx?catid=2226&pageid=15601.

CIVIL AVIATION DEPARTMENT HONG KONG 2013. CAD 371 (2nd Edition) The Avoidance of Fatigue in Aircrews Hong Kong

CME GROUP 2013. Introduction to Crack Spreads Chicago.

COGHLAN, A. 2015. Shell quits Alaska, stays in Arctic. *New Scientist,* 228**,** 7.

COMMITTEE ON CLIMATE CHANGE 2009. Meeting the UK aviation target - options for reducing emissions to 2050. . London

COOK, A., TANNER, G., WILLIAMS, V. & MEISE, G. 2009. Dynamic cost indexing - Managing airline delay cost *Journal of Air Transport Management,* 15**,** 26-35.

DALEY, B. 2010. *Air Transport and the Environment* Farnham, Surrey Ashgate Publishing Ltd.

DECC 2014a. DECC fossil fuel price projections 2013. London: Department for Energy and Climate Change

DECC 2014b. Updated short-term traded carbon values used for UK public policy appraisal London: Department of Energy and Climate Change.

DEJONGE, M. K. & SYBLON, W. H. 1984. Application of Cost Index to Fleet Hub Operation *American Control Conference* San Diego, USA: IEEE.

DELGADO, L. & PRATS, X. 2009. Fuel consumption assessment for speed variation concepts during the cruise phase *Conference of air traffic management economics* Belgrade

DERWENT, R. G., COLLINS, W. J., JOHNSON, C. E. & STEVENSON, D. S. 2001. Transient Behaviour of Tropospheric Ozone Precursors in a Global 3-D CTM and Their Indirect Greenhouse Effects. *Climatic Change,* 49**,** 463-487.

DOGANIS, R. 2002. *Flying Off Course, The Economics of International Airlines,* London Routledge.

EUROCONTROL 2007-2008. CARE-INO III - Dynamic Cost Indexing

EUROCONTROL. 2014. *Full Integration with Single European Sky* [Online]. Available: https://www.eurocontrol.int/articles/full-integration-single-european-sky [Accessed 09/11/2014.

EUROPEAN COMMISSION. 2013. *Stricter EU rules on aircraft fatigue* [Online]. Available: http://ec.europa.eu/ireland/press_office/news_of_the_day/stricter-eu-rules-on-aircrew-fatigue_en.htm [Accessed 21/07/2014.

EUROPEAN PARLIAMENT 2004. Establishing common rules on compensation and assistance to passengers in the event of denied

boarding and of cancellation or long delay of flights, and repealing Regulation (EEC) No 295/91. *In:* OFFICIAL JOURNAL OF THE EUROPEAN UNION (ed.) *(EC) No. 261/2004.* Brussels.

FAO 2011. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) Rome: Food and Agriculture Organization of the United Nations.

FARRIERS, P. & EYERS, C. 2008. Aviation CO_2 Emissions Abatement Potential from Technology Innovation London Committee on Climate Change

FLIGHT AWARE. 2013. *Flight Aware Live Flight Tracking* [Online]. [Accessed 11.11.13.

GANDER, K. 2014. Russia may close airspace in response to Western sanctions *The Independent* 8 September 2014.

GEGG, P., BUDD, L. & ISON, S. 2014. The market development of aviation biofuel: Drivers and constraints. *Journal of Air Transport Management,* 39**,** 34-40.

GELHAUSEN, M. C., P. BERSTER & WILKEN, D. 2013 Do airport capacity constraints have a serious impact on the future development of air traffic? *Journal of Air Transport Management,* 28**,** 3-13.

HAMILTON, J. D. 2009. Causes and Consequences of the Oil Shock of 2007-2008. *Brookings Papers on Economic Activity,* Spring**,** 215-283.

HARVEY, G., WILLIAMS, K. & PROBERT, J. 2012. Greening the airline pilot; HRM and the green performance of airlines in the UK *The International Journal of Human Resource Management* 1-15.

HELMAN., C. 2015. *How Cheap Oil Has Delta Air Lines Jet Fooled* [Online]. Forbes Available: http://www.forbes.com/sites/christopherhelman/2015/01/21/how-cheap-oil-has-delta-air-lines-jet-fooled/3/ [Accessed 20/07/2015.

HEPHER, T. 2015. *Airbus upbeat on sales as A380 marks bitter-sweet anniversary* [Online]. Reuters Available: http://www.businessinsider.com/r-airbus-upbeat-on-sales-as-a380-marks-bitter-sweet-anniversary-2015-4?IR=T [Accessed 16/07/2015.

IATA 2008 IATA 2008 Report on Alternative Fuels Montreal

IATA 2010. IATA Economic Briefing - Airline Fuel and Labour Cost Share. Montreal.

IATA 2013a. The IATA Technology Roadmap Report 4th Edition Montreal: International Air Transport Association

IATA 2013b. Profitability and the Air Transport Value Chain Montreal: IATA Economic Briefing No.10.

IATA 2013c. Technology Roadmap 4th Edition Montreal.

IATA 2013 Profitability and the Air Transport Value Chain Montreal.

IATA 2014a. Airline Maintenance Cost Executive Commentary: An Exclusive Analysis (FY2013) by IATA's Maintenance Cost Task Force. Montreal, Canada.

IATA. 2014b. *Fact Sheet: Industry Statistics* [Online]. Available: https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/industry-facts.pdf [Accessed 05/04/2015.

IATA 2015a. Fact Sheet: Economic and Social Benefits of Air Travel. Montreal.

IATA. 2015b. *Fact Sheet: Fuel* [Online]. Available: http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf [Accessed 15/06/15.

IATA. 2015c. *Fact Sheet: Industry Statistics* [Online]. Available: http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-industry-facts.pdf [Accessed 08/07/2015.

ICAO 2013a. 2013 Environment Report Montreal.

ICAO 2013b. Report of the Assessment of Market-based Measures Montreal.

IEA 2008. From 1st to 2nd Generation Biofuel Technologies Paris.

IEA 2014 Medium Term Oil Market Report 2014 - Market Analysis and Forecasts to 2019. Paris.

IEA. 2015a. *Oil FAQs* [Online]. Available: http://www.iea.org/aboutus/faqs/oil/ [Accessed 09/09/2015.

IEA. 2015b. *Statistic: Oil* [Online]. Available: http://www.iea.org/statistics/statisticssearch/report/?country=WORLD&product=Oil&year=2004.

IPCC 1999. IPCC Special Report Aviation and the Global Atmosphere *In:* PENNER, J., LISTER, D., GRIGGS, D., DOKKEN, D. & MCFARLAND, M. (eds.).

KIVITS, R., CHARLES, M. B. & RYAN, N. 2010. A post-carbon aviation future: Airports and the transition to a cleaner aviation sector. *Futures,* 42**,** 199-211.

KOETSE, M. J. & RIETVELD, P. 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment,* 14**,** 205-221.

KORN, B. & KUENZ, A. 2006. 4D FMS for Increasing Efficiency of TMA Operation. *25th Digital Avionics Systems Conference, 2006 IEEE/AIAA.* Portland, USA.

LANGE, K., GEPPERT, M., SAKA-HELMHOUT, A. & BECKER-RITTERSPACH, F. 2015. Changing Business Models and Employee Representation in the Airline Industry: A Comparison of British Airways and Deutsche Lufthansa. *British Journal of Management* 26**,** 388-407.

LAW, C. K., LAW, J. S. & TSE, D. S. M. 2008. An Investigation of Airspace Congestion and Possible Air Traffic Management Integration in the Pearl River Delta Region of Southern China Aviation Policy and Research Center, The Chinese University of Hong Kong

LAWSON, C. 2012. Aviation lock-in and emissions trading *Cambridge Journal of Economics,* 36**,** 1221-1243.

LEE, D. S., FAHEY, D. W., FORSTER, P. M., NEWTON, P. J., WIT, R. C. N., LIM, L. L., OWEN, B. & SAUSEN, R. 2009. Aviation and global climate change in the 21st century *Atmospheric Environment* 43**,** 3520-3537.

LEE, D. S., LIM, L. L. & OWEN, B. 2013. Mitigating future aviation CO2 emissions –"timing is everything". Manchester: Centre for Aviation Transport and the Environment.

LEE, J. 2003. The potential offered by aircraft and engine technologies *In:* UPHAM, P., MAUGHAN, J., RAPER, D. & THOMAS, C. (eds.) *Towards Sustainable Aviation* London Earthscan Publications Ltd.

LIDEN, S. 1985. Practical Considerations in Optimal Flight Management Computations *American Control Conference* Boston, USA IEEE.

LISSYS LTD. 2010. *Piano-X* [Online]. Available: http://www.lissys.demon.co.uk/PianoX.html [Accessed 14/08/2013.

LOVEGREN, J. A. & HANSMAN, R. J. 2011. *Estimation of potential aircraft fuel burn reduction in cruise via speed and altitude optimization strategies.* MSc, Massachusetts Institute of Technology.

MARAIS, K. & WEIGEL, A. L. 2006. A Framework to Encouraging Successful Technology Transition in Civil Aviation *25th Digital Avionics Systems Conference* Portland, USA

MAURICE, L. Q. & LEE, D. S. 2009. Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts Washington DC and Manchester, UK: International Civil Aviation Authority Committee on Aviation and Environmental Protection, US Federal Aviation Administration, Manchester Metropolitan University

MIHETEC, T., ODIC, D. & STEINER, S. 2011. Evaluation of Night Route Network on Flight Efficiency in Europe. *International Journal for Traffic and Transport Engineering* 1(3)**,** 132-141.

MIROSAVLJEVIC, P., SL. GVOZDENOVIC, S. & VASOV, L. 2012. THE TURBO FAN TRANSPORT AIRCRAFT DINAMIC COST INDEX DETERMINATION METHOD BY SPECIFIC RANGE FUNCTIONS. *Machines, Technologies, Materials,* Year VI**,** 18-22.

MORRELL, P. & SWAN, W. 2006. Airline Jet Fuel Hedging: Theory and Practice. *Transport Reviews,* 26**,** 713-730.

MOZDZANOWSKA, A. L., WEIBEL, R. E. & HANSMAN, R. J. 2008. Feedback Model of Air Transportation System Change: Implementation Challenges for Aviation Information Systems. *Proceedings of the IEEE,* 96**,** 1976-1991.

MUTUEL, L. H., NERI, P. & PARICAUD, E. 2013. Initial 4D Trajectory Management Concept Evaluation *Tenth USA/Europe Air Traffic Management Research and Development Seminar.* Chicago, USA.

MYERS., A. 2015. *Aviation Fuel Price Collapse - A Hedging Disaster* [Online]. Aviation Analytics Available: http://www.aviationanalytics.com/blog/planes/aviation-fuel-price-collapse---a-hedging-disaster [Accessed 20/07/2015.

NYGREN, E., ALEKLETT, K. & HÖÖK, M. 2009. Aviation fuel and future oil production scenarios. *Energy Policy,* 37**,** 4003-4010.

PERIYARSELVAM, U., TAMILSELVAN, T., THILAKAN, S. & SHANMUGARAJA, M. 2013. Analysis on Costs for Aircraft Maintenance. *Advances in Aerospace Science and Applications.,* 3**,** 177-182.

PETERSON, E., NEELS, K., BARCZI, N. & GRAHAM, T. 2013. The Economic Cost of Airline Flight Delay. *Journal of Transport Economics and Policy* 47**,** 107-121.

PILARSKI, A. M. 2007. *Why Can't We Make Money in Aviation* Aldershot, Hampshire Ashgate.

PWC 2012. Fasten seat belts: The future of aviation emissions regulation London: Price Waterhouse Coopers.

RADNOTI., G. 2002. *Profit Strategies for Air Transportation* New York, McGraw-Hill

ROBERSON, B. 2007. Fuel Conservation Strategies: Cost Index Explained *Boeing Aero Quarterly* 2 26-28.

RUMLER, W., GUNTHER, T., FRICKE, H. & WEISSHAAR, U. 2010. Flight Profile Variations due to the Spreading Practice of Cost Index Based Flight Planning. *4th International Conference on Research in Air Transportation* Budapest

SIMS, R. E. H., MABEE, W., SADDLER, J. N. & TAYLOR, M. 2010. An overview of second generation biofuel technologies *Bioresource Technology,* 101**,** 1570-1580.

SREEKANTHA, K. J., SUDARSANA, N. & JAYARAJA, S. 2014. Clean development mechanism as a solution to the present world energy problems and a new world order: a review. *International Journal of Sustainable Energy* 33**,** 49-75.

STEVENSON, D. S., DOHERTY, R. M., SANDERSON, M. G., COLLINS, W. J., JOHNSON, C. E. & DERWENT, R. G. 2004. Radiative forcing from aircraft NOx emissions: Mechanisms and seasonal dependence. *Journal of Geophysical Research: Atmospheres,* 109**,** D17307.

SWAN, W. M. & ADLER, N. 2006. Aircraft trip cost parameters: A function of stage length and seat capacity. *Transportation Research Part E,* 42**,** 105-115.

THE ECONOMIST. 2015. *Fuel hedging and airlines: Gambles that haven't paid off* [Online]. Available: http://www.economist.com/blogs/gulliver/2015/01/fuel-hedging-and-airlines [Accessed 20/07/2015.

UNIVERSITY OF WESTMINSTER TRANSPORT STUDIES GROUP 2008a. Technical Discussion Document 5.0: Aircraft crewing - marginal delay costs. EUROCONTROL.

UNIVERSITY OF WESTMINSTER TRANSPORT STUDIES GROUP 2008b. Technical Discussion Document 6.0: Airline costs of delayed passengers and how to estimate full network delay costs EUROCONTROL.

UNIVERSITY OF WESTMINSTER TRANSPORT STUDIES GROUP 2008c. Technical Discussion Document 9.0: Aircraft maintenance - marginal delay cost. EUROCONTROL.

UPHAM, P., TOMEI, J. & BOUCHER, P. 2009. Biofuels, Aviation and Sustainability: Prospects and Limits *In:* GOSSLING, S. & UPHAM, P. (eds.) *Climate Change and Aviation: Issues, Challenges and Solutions.* London Earthscan

VERA-MORALES, M. & SCHAFER, A. 2008. Final Report: Fuel Cycle Assessment of Alternative Aviation Fuels. Cambridge OMEGA, University of Cambridge Institute for Aviation and the Environment

VERA-MORALES, M. & SCHAFER, A. 2009. Fuel-Cycle Assessment of Alternative Aviation Fuels Institute for Aviation and the Environment, University of Cambridge

WILD, O., PRATHER, M. J. & AKIMOTO, H. 2001. Indirect long-term global radiative cooling from NOx Emissions. *Geophysical Research Letters,* 28**,** 1719-1722.

WUEBBLES, D., GUPTA, M. & KO, M. 2007. Evaluating the impacts of aviation on climate change. *Eos, Transactions American Geophysical Union,* 88**,** 157-160.

Appendix

Scenario Inputs and Results

Pessimistic-A	2015	2020	2025	2030	2035	2040	2050
Fuel Price ($/kg)	0.5	1.23	1.19	1.13	1.08	1.043	0.941
Carbon Price ($/kg)	0	0	0	0	0	0	0
Time Costs ($/min)	26	27.6	29.2	31.0	32.8	34.8	39.1
Delay Minutes	15	30	60	120	180	210	240
Biofuels %	0	0	0	0	0	0	0
Efficiency %	0	0.8	1.6	2.4	3.2	4	4.8
CI (kg/min)	40	23	44	50	237	250	282
Mach	0.828	0.8235	0.8275	0.8275	0.844	0.844	0.844
Fuel Use (kg)	89664	88813	88210	87493	88373	87642	86912
Flight Time (mins)	719	722	719	719	706	706	706
CO2	283069	280382	278478	276214	278992	276687	274381
Total Cost ($)	77049	129991	127791	124941	124985	123783	117185

Pessimistic-B	2015	2020	2025	2030	2035	2040	2050
Fuel Price ($/kg)	0.5	1.38	1.55	1.73	1.94	2.02	2.342
Carbon Price ($/kg)	0	0	0	0	0	0	0
Time Costs ($/min)	26	27.5	29.2	31	32.8	34.8	39.1
Delay Minutes	15	30	60	120	180	210	240
Biofuels %	0	0	0	0	0	0	0
Efficiency %	0	0.8	1.6	2.4	3.2	4	4.8
CI (kg/min)	40	21	34	33	132	129	113
Mach	0.828	0.8235	0.825	0.825	0.8365	0.8365	0.8365
Fuel Use (kg)	89664	88813	88127	87411	87304	86582	85861
Flight Time (mins)	719	722	721	721	712	712	712
CO2	283069	280381	278217	275955	275618	273340	271062
Total Cost ($)	77049	143294	159451	1773156	198997	207344	236598

Likely	2015	2020	2025	2030	2035	2040	2050
Fuel Price ($/kg)	0.5	1.38	1.55	1.72	1.92	1.96	2.17
Carbon Price ($/kg)	0	0.008	0.062	0.116	0.120	0.129	0.237
Time Costs ($/min)	26	26	26	26	26	26	26
Delay Minutes	15	30	45	60	90	135	180
Biofuels %	0	0	0	1	2.5	5	10
Efficiency %	0	1.2	2.4	3.6	4.8	6	7.2
CI (kg/min)	40	34	28	23	22	22	85
Mach	0.828	0.825	0.8235	0.8235	0.8235	0.8235	0.8325
Fuel Use (kg)	89664	88485	87380	86306	85232	84157	83416
Flight Time (mins)	719	721	722	722	722	722	715
CO2	283069	279348	275860	270045	263095	253873	239930
Total Cost ($)	77049	144299	172902	200421	217087	221546	266929

Optimistic	2015	2020	2025	2030	2035	2040	2050
Fuel Price ($/kg)	0.5	1.97	2.19	2.39	2.56	2.68	2.63
Carbon Price ($/kg)	0	0.06	0.12	0.17	0.1805	0.238	0.353
Time Costs ($/min)	26	24.4	23.0	21.6	20.3	19.1	17.8
Delay Minutes	15	30	45	60	45	30	15
Biofuels %	0	0	0	5	10	15	30
Efficiency %	0	1.50	3.00	4.50	6.00	7.50	9
CI (kg/min)	40	12	18	15	14	6	5
Mach	0.828	0.8225	0.8235	0.8235	0.8225	0.8215	0.8215
Fuel Use (kg)	89664	88172	86843	85500	84144	82794	81451
Flight Time (mins)	719	723	722	722	723	724	724
CO2	283069	278360	274164	257924	242024	226520	188552
Total Cost ($)	77049	208819	240749	267172	278975	298492	318257