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Aircraft Cost Index and the Future of Carbon Emissions from Air Travel

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Abstract

Air travel accounts for 2% of global CO_2 emissions and this proportion is set to grow in the future. There are currently no large scale solutions to drastically reduce the industry's dependence on oil. Therefore, airlines are looking to use a basket of measures to reduce fuel consumption. Optimisation of the use of cost index (CI) could be a valuable addition to this. By balancing time-dependent costs with the cost of fuel, it controls the speed of the aircraft to achieve the most economic flight time. This has a direct impact on the CO_2 emissions from the aircraft, with higher speeds resulting in higher fuel consumption. The aim of this study is to assess the impact that CI has on CO_2 emissions for six different aircraft models on a flight-by-flight basis and to evaluate how the CI could be affected by future impacts on the industry for a representative aircraft. Results show that a range of representative CI values for different aircraft models exist and suggest that the maximum benefit for optimising CI values occurs for long range flights. The average saving in CO_2 emissions is 1%. Results show that time-related costs have the greatest effect on the optimum CI values, particularly delay costs. On the fuel side of the equation it is notable that a carbon price resulting from the implementation of a market based mechanism has little impact on the optimum CI and only reduces CO_2 emissions by 0.01% in this case. The largest savings in CO_2 emissions result from the use of biofuels, with reductions of between 9% and 44% for 10% and 50% blends respectively. This study also highlights the need for further research into crew and maintenance costs, cumulative costs and delay induced by congestion and climate change events, as well as policy considerations to ensure that there is a reduction in CO_2 emissions. The study concludes that CI should be seen as a valuable tool in both helping to reduce CO_2 emissions, as well to assess the impact of future events on the industry.

Keywords: Cost Index; Carbon Emissions; Aviation; Climate Change.

1 Introduction

Aviation emissions currently account for approximately 2% of global CO_2 emissions, but with few large-scale technological solutions and an annual average increase in demand for air travel of 5%, these emissions are set to represent a greater proportion of global emissions in the future. The industry is therefore reliant on a basket of smaller measures to contribute to stabilising emissions. These measures include improvements in aircraft technology such as propulsion efficiencies, reduction of drag and structural weight, operational improvements, such as more efficient flight paths, and market based measures. With the majority of these measures only producing small savings of less than 5% by 2020 (ICAO, 2013), this highlights the need for the use of multiple measures to stabilise emissions. The International Civil Aviation Organisation (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.

The cost index (CI) is a tool, which has been available in most commercial aircraft since the 1970s, has the potential to contribute to the basket of measures. Fuel costs have increasingly become one of the largest burdens to airlines accounting for 32% of global airline operating expenses in 2014, five times higher than in 2003 (IATA, 2015) . Therefore, there would appear to be an impetus to optimise flight operations in favour of lower fuel use. One of the easiest ways to do this is to reduce the speed of a flight. However, fuel is not the only cost that needs to be considered, as slower flights can also increase other costs. These are termed time-dependent costs and refer primarily to crew costs and maintenance, which are paid by the flight hour. In the case of delay, time-dependent costs associated with passenger compensation also become important. Therefore, the purpose of the CI is to find the speed which results in the minimum cost when both fuel costs and time-dependent costs are taken into account.

The CI represents the cost per unit of time divided by the cost per unit of fuel, for a specific flight. The value that results from this calculation is supplied to the pilot in the briefing package, who enters it into the Flight Management Computer (FMC) prior to departure. As CI values are determined in advance, the FMC will automatically calculate the final flight profile by adjusting the figure to incorporate conditions for that particular flight, such as wind speed and altitude. The CI is the tool that ultimately determines the CO_2 emissions on a flight-by-flight basis, which are directly proportional to the amount of fuel used, and therefore should not be overlooked as contributing to the basket of measures to reduce emissions.

There has been very limited research on the effect that CI has on fuel use and CO_2 emissions, given its importance on a flight-by-flight basis. There are two early studies that relate the CI to fuel use savings, Liden (1985) and Dejonge and Syblon (1984). These studies highlighted the importance of optimising CI in terms of its impact on fuel use and in reducing CO_2 emissions. More recent studies have also looked at the issue of fuel use and the speed of the aircraft but have principally addressed the problem from the delay recovery point of view rather than optimisation of CI on a flight-by-flight basis (Aktürk et al., 2014; Franco and Rivas, 2014; Rumler et al., 2010).

Optimisation of CI is still an area that needs a significant amount of research and effort by airlines for implementation. There are reports of a small number of airlines putting significant efforts into this issue. The most notable is Air Canada, who began their efforts in the early 1990s. In 2009 it was reported that the airline had carried out the initial stages of their City Pair CI program, resulting in fuel savings of $4.7 million annually and a greenhouse gas reduction of 20,000 tonnes. The program tailors CI values to specific city pairs and the latter stages alter schedules to accommodate optimum CI values (Saint-Martin and Wagner, 2009).

However, there can be difficulties amongst airlines in optimising CI values. Burrows et al. (2001) highlights some of the ways in which CI is misused, such as general miscalculation, the use of average CI values when fuel costs diverge widely on different flight sectors and failing to revise CIs when fuel or other cost elements change substantially enough to vary optimum CI speeds. Aktürk et al. (2014) adds that the current standard CI does not fully capture the flexibility of controllable flight times and even in the area where there has been the most research, delay management, optimisation decision support tools are still at the early stage of implementation at major airlines. Cook et al. (2009) is one of the only recent studies that has included CO_2 emissions in its analysis. A Dynamic CI is proposed including an environmental decision support tool, although there is no in-depth analysis of savings in emissions from changing CI values. Another is (Lovegren, 2011) who examine the use of optimum speeds and altitudes against those currently used. The study finds that higher savings can be made from optimising speed compared to altitude with savings of 2.4% compared to 1.5% respectively. This has a system wide benefit of a saving in 300 billion gallons of fuel and 3.3 billion tonnes of CO_2 annually.

From examining the literature it is clear that there are significant gaps in research regarding the value of CI, not just for delay recovery, but also for normal operations to reduce fuel and CO_2 emissions. There have been no recent studies which have examined the effect of CI on different aircraft models across different distances in terms of flight time, fuel use and CO_2 emissions.

The opportunity to use the CI as a tool to establish the impact of future events on the aviation industry for individual flights has also not been realised. An important addition to the CI equation in the near future could be putting a price on carbon from the introduction of a market-based mechanism by ICAO. There are a number of other factors that will have an impact in the longer term. Time-related costs may increase significantly in the future owing to delay if capacity issues are not resolved and there may be more weather related delay owing to the effects of climate change. Positive developments, such as the introduction of biofuels and more efficient routing can also help to further reduce CO_2 emissions whilst maintaining competitive flight times.

The aim of this study is to assess the impact that CI has on aircraft CO_2 emissions and how this impact could evolve in the future. The objectives are to examine the CI range for a variety of aircraft models over different flight distances and assess the change in fuel consumption between CI values. The other key objective is to see how future events on the aviation industry may affect CI values and highlight where further research and policy intervention is needed. The value in this research is two-fold, firstly to assess the importance of CI in fuel use and emissions savings, which will aid airlines in understanding the importance of the CI, and secondly to demonstrate how the CI can also be used as a tool for policy makers and aviation organisations in helping to assess the impact of future policy decisions on climate change mitigation on an individual flight basis.

2 Methodology

2.1 Calculating Cost Index Values for Six Aircraft Models

The effect of CI on the fuel use and flight time for different aircraft models was determined using Piano-X (Lissys Ltd., 2010). This is an aircraft analysis tool based on Piano, which is a widely used tool worldwide by airframe and engine manufacturers and in major environmental studies and by ICAO. Flight profiles can be created by adjusting performance characteristics, drag, fuel consumption and environmental emission indices. The six aircraft models analysed using this software were the A300-600R; A340-600; A380-800; B767-300ER, B777-300ER; and the B787-8. The six aircraft were chosen based on their availability in Piano-X. They have different design ranges to provide insight into the effect that CI has on different types of aircraft.

Figure 1 shows the process involved with producing a range of CI values for each aircraft model. Distances between 1000NM and 6000NM were used, along with the design ranges of each aircraft. Standard Piano-X settings for thrust, drag and fuel reserves were used, along with passenger numbers for the different aircraft types. These were obtained from the aircraft manufacturer, with seating configurations for two classes for the A300-600R and three classes for the other aircraft models. The economy speed setting is used in the first instance to find the speed that corresponds to the maximum range cruise (MRC). This is the speed at which CI = 0 i.e. the optimum value if there were no time-dependent costs, and therefore the speed for maximum fuel conservation. From this flight profiles were created for Mach numbers at suitable increments above MRC until the max Mach number had been reached, which is the speed constraint of the aircraft model.

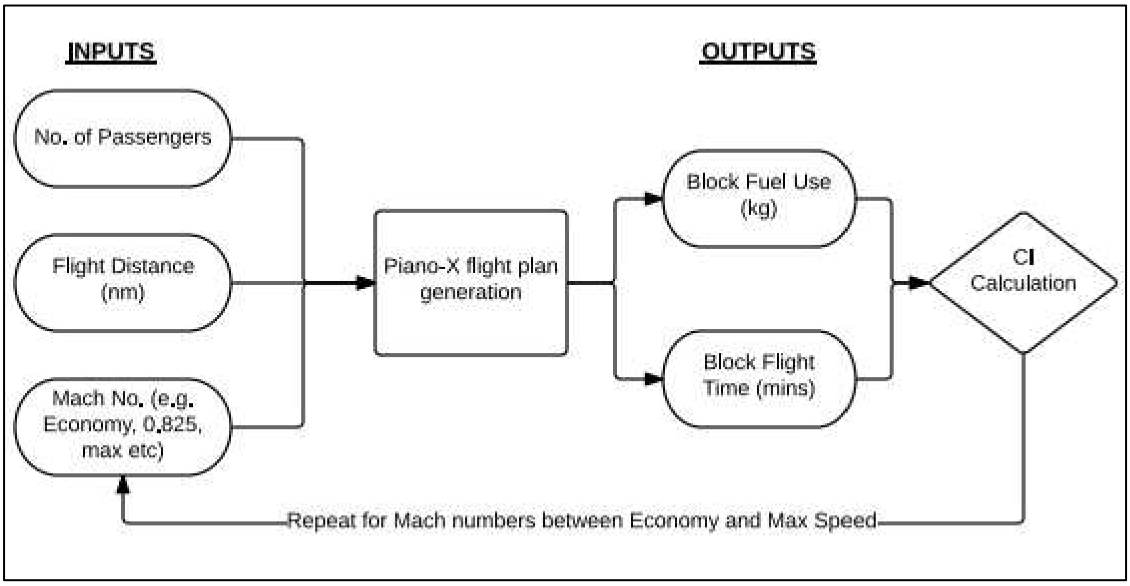


Figure 1: Cost Index generation process using Piano-X

For each Mach number the block fuel and block time were taken from the Piano-X output. Accurate time costs were not available for each aircraft model so CI values are representative in order to show the relationship between fuel and flight time for different aircraft models. Working from CI=0, the CI represents the cost of fuel for every minute of flight time saved above this value. The representative CI (RCI) value is calculated from Equation 1 to show this relationship. This is not the CI equation that is used in real operations but allows analysis of the relationships between fuel use and flight time to be examined. The relationship will be the same although CI values will change depending on specific airline costs. For this purpose it is unnecessary for exact CI values to be known but it is important that the same methodology is used for each aircraft type in order to allow for comparison between them.

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

Where:

RCI_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 X

2.2 Identification and Quantification of Future Impacts on Cost Index

The methodology relies on a literature review to identify the key factors and events that will affect the CI, and therefore CO_2 emissions, in the future. Factors are included which will either directly affect the fuel side of the CI equation or will change the time-dependent costs (Table 1).

Table 1: Future factors Affecting CI

Factor	Impact on Cost Index	Data Source
Cost of Jet Fuel (3 scenarios to 2035)	Fuel cost	DECC (2013a)
Biofuel use (at 10%, 20% and 30% blends)	Fuel cost and use	Bauen et al. (2009)
Carbon Price (3 scenarios to 2035)	Fuel cost	DECC (2013b)
Delay from extreme weather and capacity constraints (1-15 mins; 16-30 mins; 31-45 mins delay)	Time-dependent costs	University of Westminster Transport Studies Group (2008b)
Direct Routing (great circle distance)	Fuel use and flight time	Recalculation of flight distance in Piano-X

2.2.1 Factors Impacting Fuel Costs and Use

A factor which is expected to have a significant impact on future optimum CI values is the cost of jet fuel. 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) (2013a), which provides three scenarios until 2030. 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).

On the fuel side of the equation there are two further factors that will affect the cost. The first is the possibility of a drop-in biofuel being introduced. 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. It is assumed that airlines will only use biofuels when they are price competitive with conventional jet fuel (Bauen et al., 2009). Three scenarios are used for this study based on the price parity for BtL in 2030 of a10%, 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.

The second additional impact on the fuel cost is likely to be the addition of a carbon price. In 2013 ICAO announced that a market based measure would be introduced into the industry from 2020, although the type of measure to be implemented will not be decided until 2016. One of the likely measures is a cap-and-trade scheme in which airlines would be subject to a carbon price depending on the amount of fuel used. Future carbon price projections were taken from DECC (2013b) for 2030. These represent the average daily settlement prices of the European Union emissions allowances for the central scenario; a pessimistic outlook assuming continued oversupply and lack of demand for allowances for the low scenario; and a situation where there is higher economic growth, low prices of coal relative to gas and tighter caps from the European Union Emissions Trading Scheme (EUETS) for the high scenario.

2.2.2 Factors Impacting Time-dependent Costs

Generalised costs are obtained from the University of Westminster Transport Studies Group (2008) for low, base and high scenarios. These scenarios are based on aircraft type, number of crew on-board, the number of classes and whether there are additional flight crew for longer flights. This study primarily examines the base and high time-dependent costs as these are the more likely scenarios for long haul flights in 2030. The low scenario is dismissed as it does not include the extra crew that would be required for a long haul flight with multiple passenger classes.

A well-known impact on time-dependent costs is the cost of delay. This represents a situation where airlines have to pay out when passengers miss connections to onward flights owing to delayed flights. The likelihood of delay could be increased as a result of key two factors. The first is congestion in the system. With an average increase of 5% per year in demand for air travel, the system is increasingly pressured. Many hub airports are already facing capacity constraints, and the same can be said of busy air routes.

The second is the impact of climate change on extreme weather events. There may be benefits, for example a reduction in the number of cold days, but there may also be more extreme weather events in response to rising temperatures and changes in precipitation. An increase in delay is taken into account with figures from the University of Westminster Transport Studies Group (2008c), which provide low, base and high figures for three delay periods of 1-15 minutes, 16-30 minutes and 31-45 minutes.

Table 2: Cost inputs for the calculation of CI for three scenarios.

	Low	Base/Central	High
Jet Fuel ($/kg)	0.79	1.42	2.0
Biofuel ($/kg)	NA	0.99	NA
Carbon ($/kg)	0.06	0.11	0.17
Time-dependent (Crew and Maintenance) ($/min)	0.9	19.2	50.7
Delay 1-15 minutes ($/min)	19.5	43.5	51.0
Delay 16-30 minutes ($/min)	49.5	121.5	141.0
Delay 31-45 minutes ($/min)	76.5	210.0	240.0

2.2.3 Calculation of Future Impacts on CI values – a B767-300ER Case Study

These factors where quantified (Table 2) for a B767-300ER flight from a major European hub to a Southeast Asian hub. This aircraft model was chosen based on the cost data available and the aircraft types available for analysis in Piano-X. The methodology followed is initially the same as that in section 2.1 with flight time and fuel use extracted for Mach numbers between MRC and the maximum speed of the aircraft. As complete cost data is available for this aircraft model CI values are calculated for each combination of scenarios according to the standard CI calculation used by airlines seen in Equation 2.

$$\text{CI (kg/min)} = \frac{\text{Time dependent costs (\$/min)}}{\text{Fuel costs (\$/kg)}} \qquad [2]$$

Using the fuel use and flight time for each Mach, the cost function (Cf) is calculated according to Equation 3. The cost function represents the cost per nautical mile flown. As Cf is proportional to direct operating costs, the Mach number at which this is minimised represents the optimal speed corresponding to a specific CI value. CO_2 emissions are then calculated by multiplying fuel use by the standard conversion faction of 3.157 $kgCO_2/kg_{fuel}$ (Jardine, 2009), apart from in the case of the use of biofuels, in which a conversion factor of 0.35 $kgCO_2/kg_{fuel}$ is integrated into the calculation depending on the drop in percentage.

$$\text{Cf} = F_m\,(CIt_f) \qquad [3]$$

Where:

Cf = cost function

F_m = mass of block fuel use (kg)

CI = cost index (kg/min)

t_f = block flight time (min)

More direct routing was also included in the analysis to represent a situation where improvements in air traffic management make this possible. This involved recalculating the data in Piano-X keeping all other variables the same, but changing the flight distance from that currently flown to the great circle distance (i.e. the shortest route).

Validation of the Piano-X methodology was performed using real aircraft data from a major international airline. A known CI value for the real flight with a B777-300ER was compared with the flight profile for the same CI value in Piano-X, adjusted for the average wind conditions, over a year's worth of flight data for 2013. Similar data was not available for the B767-300ER but the methodology for calculation is the same. The B777-300ER could not be used over the B767-300ER in the current analysis owing to unavailability of full cost data for this aircraft model for analysis of future events.

This study acknowledges that using such data and modeling methods results in uncertainties. Piano-X contains data that is the best available to its developers, but aircraft models can vary. Limitations also exist with only using the B767-300ER for evaluation of costs and future impacts, as this is the only model where both Piano-X and full time cost data from the University of Westminster Transport Studies Group was available, including cost of delay. As the results of the analysis of the six aircraft models show, because different aircraft have different CI ranges, CO_2 impacts can vary significantly so CI values do need to be calculated for each aircraft model to be accurate. Whilst the authors are currently developing methodology to account for more aircraft assessments based on specific flights, the example of the B767-300ER is effective at showing the magnitude of various future impacts relative to one another, giving a good indication of where further research is needed.

A sensitivity analysis was undertaken which showed that for a 10% increase in fuel costs and time costs, time costs only have a slightly higher impact on total costs of a 2.5% increase compared to 2.2% for a rise in fuel costs. There was a negligible effect on total emissions at less than 0.1%, which could suggest that the accuracy of costs is unimportant. However, this sensitivity analysis was conducted at a relatively low CI value. When the same analysis was conducted at a higher CI value of 100, the resulting values were more significant. This would suggest that for low CI values, a change in costs does not have a significant impact on a flight. However, if aircraft are flying at higher CI values (which evidence suggests they are) the more important the accuracy of the CI input costs becomes.

3 Results

The CI can have a substantial effect on fuel burn and consequently CO_2 emissions. Results from Piano-X show that when aircraft are flown at their design range the difference in CO_2 emissions between the maximum RCI and MRC is 0.7% to 3.9% per flight. This is the maximum saving that could be made but in reality it is very unlikely that an aircraft would be flying at its maximum speed. CI values for different aircraft are not readily available but it is widely accepted that aircraft tend to fly around their LRC speed. This is supposed to represent a Mach number where there is an approximate 1% penalty in fuel burn for a faster flight time from MRC. However, there is also evidence that in many cases aircraft are flying above their LRC speeds (Lovegren, 2011). The difference between this speed and MRC is in the range of 0.6% to 0.9% for the six aircraft. These figures represent the design range of the aircraft but at different distances values can be higher suggesting that the 1% penalty equating to LRC is not valid for every speed. This is important as aircraft do not always fly their exact design range. For example the difference between MRC and LRC for an A340-600 can be up to 19.3%.

As aircraft are generally found to be flying above their LRC for the majority of their flight time and optimum CI values are usually found between MRC and LRC, the average saving is found to be at least 1% for the six aircraft in this analysis. However, this could be significantly higher depending on the aircraft and its average speed. This may seem small but if 1% of the global CO_2 emissions from aviation of 705,000,000 tonnes were reduced, this would be equivalent to the CO_2 emissions of around 1000 long-haul flights. This is also significant as aircraft are already equipped with the CI tool and therefore there are only small costs and time involved in implementing changes.

Figure 2 demonstrates the relationship between fuel burn per passenger and flight time across RCI values. The relationship is not linear with changes from higher RCI values resulting in better fuel savings per minute than at lower CI values. The relationship also suggests that there are negative RCI values. In theory this is possible, but it is very unlikely a negative value would be used as it would result in higher flight times with higher fuel burn. This is the same general relationship found by Liden (1985), although this study provides more in-depth analysis to the implications this has on flight time and carbon savings for a variety of aircraft. The smaller aircraft (A300-600, B767-300ER and B787- 8) have flatter curves, demonstrating less potential for fuel burn reductions. This suggests that the biggest gains in optimising CI values are from long haul aircraft.

This relationship does vary depending on flight distance. Generally at greater flight distances, higher fuel savings can be made across the range of RCI values, backing up the conclusion that the greatest potential for reduction in CI for CO_2 savings is with long haul flights. Overall the B777-300ER performs the best across all distances with fast flight times and low fuel burn across its range of RCI values. Whilst the A380-800 demonstrates fast flight times, its fuel burn is substantially higher than the other aircraft models, with the exception of the A340-600. This may be a reflection of the fact that the A380 only has 47 more seats, given the standard seating configuration for three classes, than the B777-300ER, but its weight is 228,806kg more than the B777-300ER according to standard Piano-X settings.

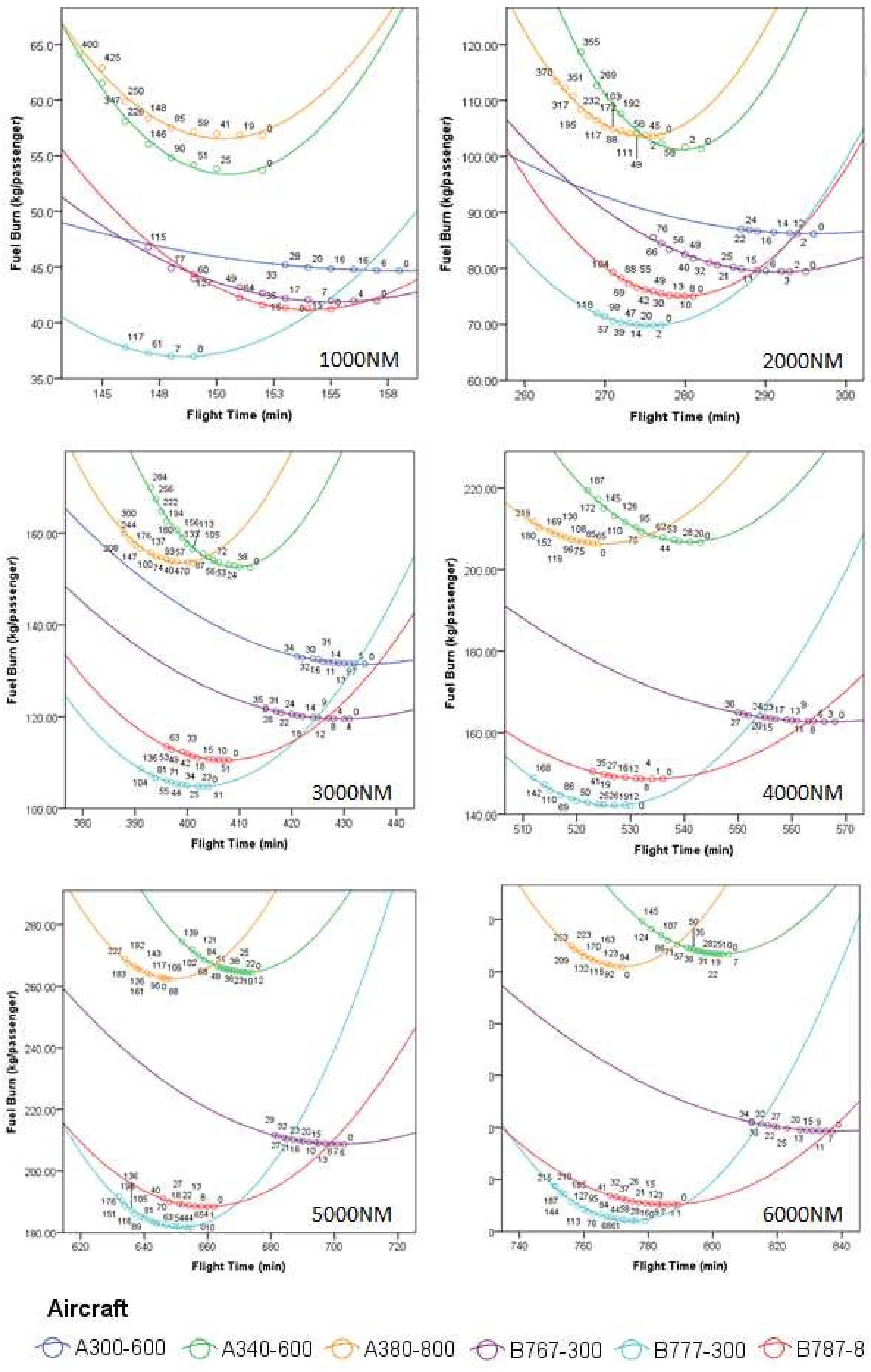
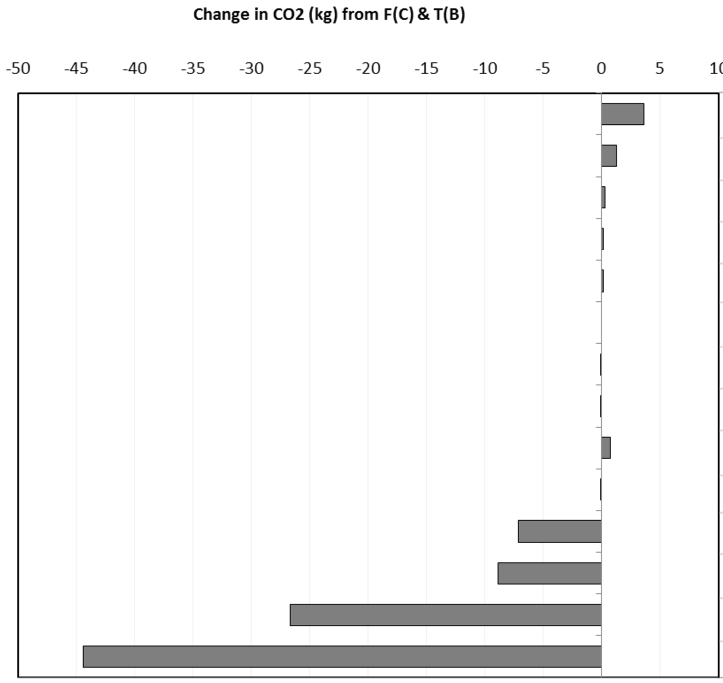


Figure 2: Relationship between fuel per passenger and flight time for six aircraft types between 1000NM and 6000NM flight distances (A300-600 is unable to fly the last three distances) with labelled representative cost index values.

In terms of the more in-depth analysis looking solely at the B767-300ER, Figure 3 shows the CO_2 savings that could be achieved under different cost scenarios. It is assumed that the airline would choose the optimum CI value for a flight. The base scenario of central fuel and time costs gives an optimum CI value, where operating costs are minimised, of 14 in 2030. This is a change from the optimum CI of 18 for the same scenario in 2013. This represents a 0.1% decrease in CO_2 emissions per flight and an increase in flight time of six minutes, as the decrease in CI results in a lower Mach speed, reducing fuel use but also resulting in a slower flight.

Working from the base scenario in 2030 it is evident that time related costs have a greater effect on the optimum CI value than fuel costs. Changing from a base time cost to the low time cost, holding fuel costs at their central price, results in a reduction in emissions of 0.74%, from an optimum CI of 14 to 1 with an increase in 4 minutes of flight time. Whilst moving to a high cost of time increases the emissions by 0.31%, to an optimum CI value of 38.



	CI	Flight Time (min)	Fuel Use (kg)
F(C) & C(C) & D3	136	739	58257
F(C) & C(C) & D2	79	754	56931
F(C) & T(H)	38	765	56375
F(C) & C(C) & D1	28	767	56295
F(H) & T(H)	25	769	56274
F(C) & T(B)	14	773	56203
F(C) & C(H) & T(B)	12	774	56196
F(H) & T(B)	10	775	56186
F(C) & T(L)	1	777	56159
F(L) & T(L)	1	777	56151
Direct	14	732	52175
10% Bio	14	772	56205
30% Bio	15	771	56210
50% Bio	16	770	56215

Figure 3: Per cent CO_2 savings per flight from the base scenario of central fuel and time costs, with CI, flight time and fuel use indicated for each scenario for B767-300ER over 5553 nm in 2030. F = fuel price; C = carbon price; T = time cost; Bio = biofuel blend used with jet fuel A; D1 = cost for 1-15 minutes delay; D2 = cost for 16-30 minutes delay; D3 = cost for 31-45 minutes delay; (L), (C/B), (H) indicates whether the cost is low, central/base or high.

In comparison, changing the fuel cost from central to low and holding the time cost at base, there is only a 0.18% increase in carbon emissions, with the optimum CI value changing from 14 to 24. Whilst moving to a high fuel price and an optimum CI value of 10 only saves 0.03% in emissions.

Notably, the addition of even a high carbon price only results in a saving in emissions of 0.01% with a change in optimum CI value from 14 to 12. In contrast the biggest impact comes from adding delay costs into the equation. A delay of 1-15 minutes requires an optimum CI of 28 representing a 0.6% increase in emissions for a time saving of six minutes. A delay of 16-30 minutes requires an optimum CI value of 79 for a 19 minute saving and this results in a 1.3% increase in CO_2 emissions. Finally a longer delay of 31-45 minutes requires the use of an optimum CI value of 136 to gain 34 minutes in time and results in a 3.7% increase in overall flight CO_2 emissions.

The effect of biofuel use is slightly different. In the scenarios used in this study for 2030 the biofuel prices are very competitive with jet fuel prices, particularly in the central and high scenarios. Owing to this the optimum CI values are very similar at 14 and 16 for the base scenario and the highest biofuel scenario of a 50% blend respectively. However, the amount of CO_2 per kg of biofuel is only about a tenth of that for jet fuel so the savings in CO_2 are significant. Figure 3 shows that the savings ranges from 9% for a 10% blend of biofuel to 44% for a 50% blend of biofuel. This means that the flight can be made in either the same time, or slightly quicker, for substantial reductions in CO_2 emissions.

Without the use of biofuels, direct routing is the next best option for reducing CO_2 emissions. Conducting the flight at great circle distance can save 7% in fuel and CO_2 emissions. However, direct routing has the added benefit that it also saves flight time. In this flight example, the time saving would be 42 minutes for a CI of 14.

4 Discussion

The results of this study demonstrate that the CI is more complex than it may first appear from its simple equation. 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. This demonstrates the importance of choosing the right aircraft for specific routes. Results suggest that the area that should be focussed on is the long haul market as this is where the highest savings can be seen for only a small increase in time.

To ensure that savings in CO_2 are made, it is important that airlines address issues with miscalculation and take future impacts into account, as discussed in the following sections. Whilst there are reports of some airlines, such as Air Canada, being proactive about optimising their CI values there is evidence that a large number of airlines have not paid this issue the appropriate attention (Burrows et al., 2001). Anecdotal evidence from a number of airlines suggests that this is still an ongoing issue.

4.1 Time-Dependent Costs

From examining different cost scenarios for the B767-300ER, it is evident that time-dependent costs have the greatest impact on the optimum CI value for the flight. Whilst this study has used generalised values which account for some of the complexities involved with the CI calculation, in practice the main uncertainty for airlines is regarding time-dependent costs, namely separating out those costs that are cyclic vs. time dependent and taking into account cumulative effects.

Crew labour costs can vary significantly depending on the country of operation, the type of operation and the size of the aircraft (University of Westminster Transport Studies Group, 2008a). There are also issues with estimating costs for relief pilots, overtime payments and rest hours required between flights (Burrows et al., 2001; Swan and Adler, 2006). These latter issues are complicated by the fact that they cannot be calculated for just one flight, as they can only be determined over the a course of a month or year, with these cumulative costs needing to be taken into account in the CI calculation.

The other key component of time costs is maintenance. Again there are issues with this calculation owing to the joint costs involved and difficulties in separating those arising from flight cycles and those from flight hours (Burrows et al., 2001; Doganis, 2002). In addition changes in maintenance costs need to be accounted for, as they change with the maturity of the aircraft (University of Westminster Transport Studies Group, 2008b). Issues with the calculation of time-dependent costs by individual airlines are not dealt with in this paper but there is on-going work into this issue by the authors. Standard values are instead taken for specific aircraft models.

Once these costs are correctly calculated, they should not see significant changes over time as they are under the control of the airline, unlike fuel costs, which can change rapidly. However, there are occasionally factors that can substantially change the costs of time outside of the airlines control. For example, in 2013 the European Parliament implemented new aircrew fatigue legislation. Maximum flight duty time was decreased by 45 minutes for pilots on night flights, as well as the maximum number of flight hours in a 12 month period (European Commission, 2013). This puts an increased pressure on scheduling crews and may require either more overtime payments or the addition of extra relief crews, adding to the issue of cumulative costs.

Delay costs can also be particularly difficult to calculate due to the presence of hard and soft costs. Hard costs include actual bottom line costs to the airline from rebooking passengers onto other flights if connections are missed and providing compensation. Soft costs mainly concern a loss of market share owing to passenger dissatisfaction. In theory hard costs should be easier for airlines to calculate, but this is generally not the case as the data involved can be very complex. Soft costs are understandably difficult to calculate as they rely on a number of assumptions and depend on market conditions (Cook et al., 2009).

The results show that delays over 15 minutes can substantially increase the CI value, as more connecting passengers miss flights causing time costs to rise. Congestion can be a significant contributor to this. The primary reason for this is capacity constraints at major airports. Gelhausen et al. (2013) found that in 2008 only 10 to 20 airports could be considered to be operating in capacity constrained conditions, but show that this will increase in the future with continued increased demand for air travel. It is thought that by 2016 70% of all flights to and from the top 177 global airports will arrive or depart from a capacity constrained airport. Without expansion of airports and/or demand management this will likely lead to increased delay and CO_2 emissions.

One of the greatest uncertainties regarding delay costs is the effect climate change will have on the industry, particularly regarding extreme weather events. This is something that aviation authorities are beginning to take more seriously and ICAO include it in their Environmental Strategy (2013). An example of this is a study by Koetse and Rietveld (2009) of 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.

To address these issues airlines will need to ensure that accounting and operations departments work together to ensure that costs are calculated correctly. There is also a need for more research in the industry concerning delay management and the effect of future events on this. Stakeholder collaboration will be needed to ensure that solutions to these delay issues can be implemented.

4.2 Fuel Costs

Results demonstrate that costs on the fuel side of the equation generally have less of an impact on the optimum CI value compared with time-dependent costs. However, they still represent a significant challenge to airlines owing to the volatility in price. Fuel prices are a major concern for the aviation industry as they now represent around a third of all operating costs. There is still significant uncertainty concerning how oil prices will change over the coming years. Nygren et al. (2009) examined the potential for supply to meet demand in the future and suggests that even with a 10% biofuel blend in 2017, supply will not be sufficient, suggesting oil prices are likely to increase. Volatility in prices will still play a part year-to-year, as is the case with low oil prices at the beginning of 2015.

As expected the best carbon savings result from a high fuel and carbon price. But even the high carbon price does not have a great impact on significantly reducing CO_2 emissions. Including a central carbon price the optimum CI changes only result in a saving of 0.01% in CO_2. This questions whether current carbon price projections will promote enough innovation to reduce emissions to required levels.

There are varying opinions on whether a global market based measure will be successful in reducing CO_2 emissions from aviation. Some studies conclude that in theory a cap-and-trade system would work if designed correctly (Carlsson and Hammar, 2002; Kopsch, 2012). But, Lawson (2012, p.1238) states that emissions trading could be “not only ineffective but damaging”. It is argued that emissions trading does not solve the problem of how to break out of a system where demand is being increased, with the need to sell more services to remain profitable and lack of technological solutions playing driving roles.

Carbon pricing becomes more important when fuel prices can be very unpredictable. A cap-and-trade carbon price could therefore provide some stability in encouraging reductions of CO_2 emissions. Whilst it is generally assumed that oil prices will continue to rise, Figure 3 demonstrates that this may not be the case, with the low fuel price being lower in 2030 than it is now. This would have the effect of increasing the CI value. It is important that carbon prices are set at the correct level to ensure CO_2 reductions. Either higher prices are needed or alternative measures also need to be considered.

Significant savings in CO_2 can be made from changes on the fuel side of the CI equation with the use of biofuels. If these fuels can be produced in a sustainable way and achieve a competitive price with jet fuel, the optimum CI value does not change significantly but it is evident from Figure 2 that CO_2 savings can range from 9% to 44% for blends of 10% to 50% respectively. For the airline, this would mean that flight times could still be kept within schedule, assuming no other delay.

Although there have been a number of successful test flights using biofuels, there are still significant challenges in meeting strict fuel 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).

Another issue is that from an airline perspective the price of fuel is still not reduced. It would take substantial effort by an airline to start using biofuel blends across their fleet but the only result would be a reduction of CO_2 emissions. This study has demonstrated that a carbon price would only have a small impact on costs for an airline compared with fuel costs and therefore this is unlikely to persuade an airline to put significant efforts into biofuel use. Other policy interventions are likely to be needed to encourage their use, either in addition or as an alternative to a market based measure.

Although biofuels have the most significant effect on CO_2 emissions, it must be stressed that their penetration into the industry is expected to be slow. If emissions are to be stabilized at 2020 levels, a number of other short term measures will be needed until biofuels are developed enough to be used on a large scale. CI is a perfect candidate for this as it is already available on most commercial aircraft and requires minimum costs to implement.

4.3 Time and Fuel Savings

Significant benefits can also be obtained from flying more direct routes. This causes a decrease in flight time, resulting in lower time-related costs, and the shorter distance will decrease fuel burn. The effect is a win-win situation in that the CI may be increased slightly without losing these benefits. A common cause for indirect flights is diversion around restricted airspace. An example of this is in the Pearl River Delta region in Southern China. 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.

For this study direct routing was considered, using the great circle distance compared to the regularly flown distance. This is an ideal situation in which flight time can be increased but fuel is also saved. Therefore little sacrifice is needed from airlines, whilst saving 7% in CO_2 emissions for each flight. However, a lot of work needs to be undertaken for this to become a possibility. There will need to be a significant amount of stakeholder engagement between airports, air service navigation providers, airlines and individual countries. This is particularly difficult where there are political issues between countries, for example between EU countries and Russia.

4.4 Further work

The use of CI in analysis of future impacts is beneficial as it allows for the identification of future research needs to be evaluated effectively. For instance, from the analysis it can be seen that not only are areas such as biofuels important for CO_2 reductions but operational research is also essential to allow for more direct routing which offers the optimal solutions in terms of both reducing CO_2 emissions from a flight as well as reducing flight time, therefore resulting in the greatest cost savings for airlines. On the other hand delays have been shown to have the opposite effect on CO_2 emissions and flight times; therefore further research in this is area is also very important.

This study has highlighted the complexities in using the CI in a practical manner for airlines. A key barrier for airlines at present is the difficulty they have in understanding their flight costs. This is complicated by the fact that the CI equation is simply focused on costs representing one minute and one kg of fuel. However, there are many intricacies to using CI that may not be truly represented by this on a full flight scale. For an airline, not just one flight will be affected, all flights over longer time scales need to consideration, particularly in terms of crew assignment. On a larger scale there can also be network effects from airlines flying different CI values. For example, an aircraft may have to divert around a slower flying aircraft, which may have the effect of counteracting any fuel savings the slower aircraft is achieving. This is already an issue in aircraft operations, but is likely to become more important as airspace capacity becomes more constrained.

In addition there will also be spatial effects in the use of CI, with some routes facing higher costs than others. For example, some flight routes may be more affected by extreme weather in the future and others will need to use airports that are more severely capacity constrained. It appears that routes over the US, Europe and Southeast Asia will be most affected by these issues.

5 Conclusion

This study aimed to examine the potential for CI to contribute to aircraft CO_2 emission reductions and assess the effect that future impacts will have on optimum CI values. Optimisation of CI can be an effective tool in reducing carbon emissions by an average of 1%, which can contribute to the basket of measures to reduce overall emissions within the airline industry. These emission reductions are dependent on the aircraft model, with evidence that long haul flights should be prioritized, as they result in higher CO_2 reductions for small changes in flight time.

A major benefit of using CI as a tool to reduce emissions is that it is already available in commercial aircraft and there are minimal costs to implementation of changes with few time constraints. It also has a dual role in reducing CO_2 emissions and helping to predict the effect of future impacts on the industry.

It is generally assumed that a rise in fuel costs will cause airlines to pick lower CI values, but this study has highlighted that it will not be enough on its own to promote significant reductions in CO_2 emissions. Even when a carbon price is added, it has been demonstrated that this only has a small impact on the emissions of an individual flight.

With time costs having the greatest influence on optimum CI values it is important that further research is carried out in order to ensure that the correct values are being used, as this is something that airlines currently struggle greatly with. This includes delay costs, with further research needed into the effect of climate change on future aviation related weather events and the effects of congestion in the system.

Whilst the greatest impact in terms of CO_2 reductions is likely to be a result of technology change and operational improvements, including the use of biofuels, it is unlikely that carbon pricing with its current projections will be enough to encourage this sort of change. Therefore, other policy measures will also be needed either in addition or as an alternative to a market based measure.

Further work is required in this establish the best way to calculate the CI accurately which the authors are currently undertaking. This analysis has also highlighted the need for research and action concerning mitigation of capacity constraints and climate change effects, as well as development of biofuels and operational improvements for direct routing.

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Glossary

Block Flight Time: Total flight time from push-back from the gate (off-blocks) at the departure airport to arrival at the gate and engine shutdown (on-blocks) at its arrival airport after landing.

Block Fuel: Fuel use for flight from push-back from the gate (off-blocks) at the departure airport to arrival at the gate and engine shutdown (on-blocks) at its arrival airport after landing.

Long Range Cruise (LRC): The speed above MRC that will result in a 1% penalty in fuel mileage in exchange for a 3-5% increase in cruise velocity.

Max Mach: The highest Mach number a particular aircraft can fly depending on the flight parameters and conditions.

Maximum Range Cruise (MRC): The speed that will provide the furthest distance travelled for a given amount of fuel burned and the minimum fuel burned for a given cruise distance

Mach Number: The speed ratio of the aircraft referenced to the speed of sound. E.g. aircraft flying at the speed of sound is Mach 1. Commercial aircraft fly at subsonic Mach numbers of less than 1.

Appendix – Scenario Settings

Scenario Cost Inputs

Input	Cost
Low Time-dependent cost (LT)	0.9 $/min
Base Time-dependent cost (BT)	19.2 $/min
High Time-dependent cost (HT)	50.7 $/min
Low Fuel Cost (FL)	0.79 $/kg
Central Fuel Cost (FC)	1.42 $/kg
High Fuel Cost (FH)	2.00 $/kg
Low Carbon Price (CL)	0.061 $/kg
Central Carbon Price (CC)	0.123 $/kg
High Carbon Price (CH)	0.184 $/kg
1-15 minutes delay (D1)	43.5 $/min
16-30 minutes delay (D2)	121.5 $/min
31-45 minutes delay (D3)	210.0 $/min
Low Biofuel Cost (Bio L)	0.99 $/kg
High Biofuel Cost (Bio H)	0.74 $/kg

711

712 **Cost Index values from scenario combinations**

Time Cost / **Fuel Cost**	**Low**	**Base**	**High**	**D1**	**D2**	**D3**
Fuel (Low)	1.14	24.3	64.2	55.1	153.8	265.8
Fuel (central)	0.63	13.5	35.7	30.6	85.6	147.9
Fuel (High)	0.45	9.6	25.4	21.8	60.8	105.0
F L + C L	1.06	22.6	59.6	51.1	142.8	246.8
F L + C C	0.99	21.0	55.5	47.7	133.1	230.0
FL + C H	0.92	19.7	52.1	44.7	124.7	215.6
F C + C L	0.61	13.0	34.2	29.4	82.0	141.8
F C + C C	0.58	12.4	32.9	28.2	78.7	136.1
F C + C H	0.56	12.0	31.6	27.1	75.7	130.9
F H + C L	0.44	9.3	24.6	21.1	59.0	101.9
F H + C C	0.42	9.0	23.9	20.5	57.2	98.9
F H + C H	0.41	8.8	23.2	19.9	55.6	96.2
Bio L + CL	0.86	18.3	48.3	41.4	115.8	200.1

Bio L + C C	0.81	17.3	45.6	39.1	109.3	188.9
Bio L + C H	0.77	16.4	43.2	37.1	103.6	179.1
Bio H + C L	1.12	23.9	63.2	54.2	151.4	261.7
Bio H + CC	1.04	22.2	58.7	50.3	140.6	243.0
Bio H + C H	0.97	20.7	54.8	47.0	131.3	226.9