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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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions by 0.01% in this case. The largest savings in CO<sub>2</sub> 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<sub>2</sub> emissions. The study concludes that CI should be seen as a valuable tool in both helping to reduce CO<sub>2</sub> emissions, as well to assess the impact of future events on the industry.

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

## 40 **1 Introduction**

41

42 Aviation emissions currently account for approximately 2% of global CO<sub>2</sub> emissions, but with few  
43 large-scale technological solutions and an annual average increase in demand for air travel of 5%,  
44 these emissions are set to represent a greater proportion of global emissions in the future. The industry  
45 is therefore reliant on a basket of smaller measures to contribute to stabilising emissions. These  
46 measures include improvements in aircraft technology such as propulsion efficiencies, reduction of  
47 drag and structural weight, operational improvements, such as more efficient flight paths, and market  
48 based measures. With the majority of these measures only producing small savings of less than 5% by  
49 2020 (ICAO, 2013), this highlights the need for the use of multiple measures to stabilise emissions.  
50 The International Civil Aviation Organisation (ICAO) aims for a 2% improvement in fuel efficiency  
51 per annum in the short term, with the objective of stabilisation of global CO<sub>2</sub> emissions at 2020 levels  
52 through incremental improvements in efficiency.

53

The cost index (CI) is a tool, which has been available in most commercial aircraft since the  
54 1970s, has the potential to contribute to the basket of measures. Fuel costs have increasingly become  
55 one of the largest burdens to airlines accounting for 32% of global airline operating expenses in 2014,  
56 five times higher than in 2003 (IATA, 2015) . Therefore, there would appear to be an impetus to  
57 optimise flight operations in favour of lower fuel use. One of the easiest ways to do this is to reduce  
58 the speed of a flight. However, fuel is not the only cost that needs to be considered, as slower flights  
59 can also increase other costs. These are termed time-dependent costs and refer primarily to crew costs  
60 and maintenance, which are paid by the flight hour. In the case of delay, time-dependent costs  
61 associated with passenger compensation also become important. Therefore, the purpose of the CI is to  
62 find the speed which results in the minimum cost when both fuel costs and time-dependent costs are  
63 taken into account.

64

The CI represents the cost per unit of time divided by the cost per unit of fuel, for a specific  
65 flight. The value that results from this calculation is supplied to the pilot in the briefing package, who  
66 enters it into the Flight Management Computer (FMC) prior to departure. As CI values are determined  
67 in advance, the FMC will automatically calculate the final flight profile by adjusting the figure to  
68 incorporate conditions for that particular flight, such as wind speed and altitude. The CI is the tool that  
69 ultimately determines the CO<sub>2</sub> emissions on a flight-by-flight basis, which are directly proportional to  
70 the amount of fuel used, and therefore should not be overlooked as contributing to the basket of  
71 measures to reduce emissions.

72

There has been very limited research on the effect that CI has on fuel use and CO<sub>2</sub> emissions,  
73 given its importance on a flight-by-flight basis. There are two early studies that relate the CI to fuel  
74 use savings, Liden (1985) and Dejonge and Syblon (1984). These studies highlighted the importance  
75 of optimising CI in terms of its impact on fuel use and in reducing CO<sub>2</sub> emissions. More recent studies  
76 have also looked at the issue of fuel use and the speed of the aircraft but have principally addressed

77 the problem from the delay recovery point of view rather than optimisation of CI on a flight-by-flight  
78 basis (Aktürk et al., 2014; Franco and Rivas, 2014; Rumler et al., 2010).

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

86 However, there can be difficulties amongst airlines in optimising CI values. Burrows et al.  
87 (2001) highlights some of the ways in which CI is misused, such as general miscalculation, the use of  
88 average CI values when fuel costs diverge widely on different flight sectors and failing to revise CIs  
89 when fuel or other cost elements change substantially enough to vary optimum CI speeds. Aktürk et  
90 al. (2014) adds that the current standard CI does not fully capture the flexibility of controllable flight  
91 times and even in the area where there has been the most research, delay management, optimisation  
92 decision support tools are still at the early stage of implementation at major airlines. Cook et al.  
93 (2009) is one of the only recent studies that has included CO<sub>2</sub> emissions in its analysis. A Dynamic CI  
94 is proposed including an environmental decision support tool, although there is no in-depth analysis of  
95 savings in emissions from changing CI values. Another is (Lovegren, 2011) who examine the use of  
96 optimum speeds and altitudes against those currently used. The study finds that higher savings can be  
97 made from optimising speed compared to altitude with savings of 2.4% compared to 1.5%  
98 respectively. This has a system wide benefit of a saving in 300 billion gallons of fuel and 3.3 billion  
99 tonnes of CO<sub>2</sub> annually.

100 From examining the literature it is clear that there are significant gaps in research regarding  
101 the value of CI, not just for delay recovery, but also for normal operations to reduce fuel and CO<sub>2</sub>  
102 emissions. There have been no recent studies which have examined the effect of CI on different  
103 aircraft models across different distances in terms of flight time, fuel use and CO<sub>2</sub> emissions.

104 The opportunity to use the CI as a tool to establish the impact of future events on the aviation  
105 industry for individual flights has also not been realised. An important addition to the CI equation in  
106 the near future could be putting a price on carbon from the introduction of a market-based mechanism  
107 by ICAO. There are a number of other factors that will have an impact in the longer term. Time-  
108 related costs may increase significantly in the future owing to delay if capacity issues are not resolved  
109 and there may be more weather related delay owing to the effects of climate change. Positive  
110 developments, such as the introduction of biofuels and more efficient routing can also help to further  
111 reduce CO<sub>2</sub> emissions whilst maintaining competitive flight times.

112 The aim of this study is to assess the impact that CI has on aircraft CO<sub>2</sub> emissions and how  
113 this impact could evolve in the future. The objectives are to examine the CI range for a variety of

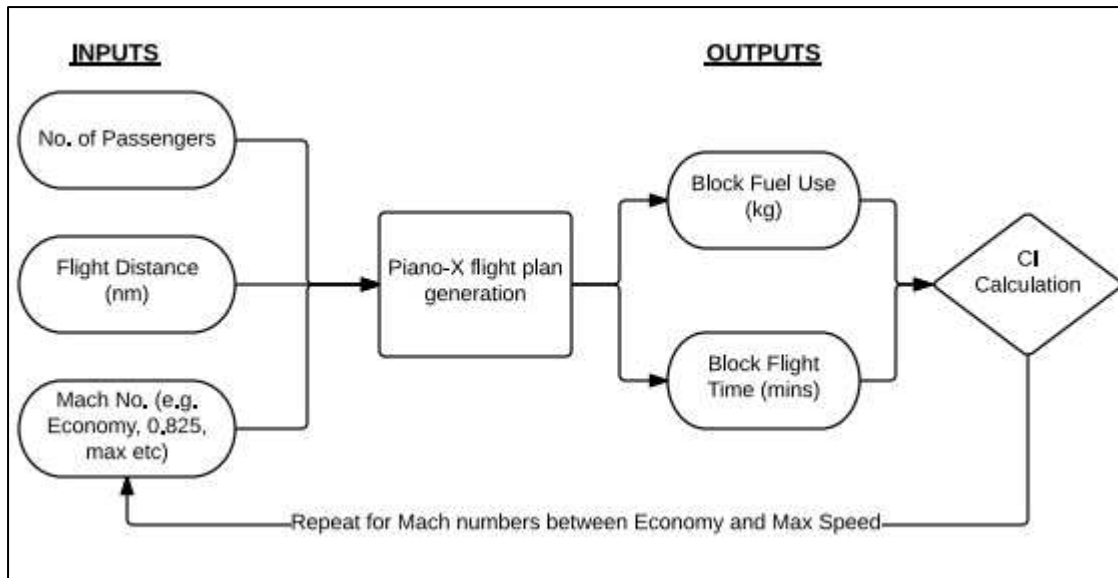
114 aircraft models over different flight distances and assess the change in fuel consumption between CI  
115 values. The other key objective is to see how future events on the aviation industry may affect CI  
116 values and highlight where further research and policy intervention is needed. The value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

## 121 **2 Methodology**

### 122 **2.1 Calculating Cost Index Values for Six Aircraft Models**

123  
124 The effect of CI on the fuel use and flight time for different aircraft models was determined using  
125 Piano-X (Lissys Ltd., 2010). This is an aircraft analysis tool based on Piano, which is a widely used  
126 tool worldwide by airframe and engine manufacturers and in major environmental studies and by  
127 ICAO. Flight profiles can be created by adjusting performance characteristics, drag, fuel consumption  
128 and environmental emission indices. The six aircraft models analysed using this software were the  
129 A300-600R; A340-600; A380-800; B767-300ER, B777-300ER; and the B787-8. The six aircraft were  
130 chosen based on their availability in Piano-X. They have different design ranges to provide insight  
131 into the effect that CI has on different types of aircraft.

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



142

143 **Figure 1: Cost Index generation process using Piano-X**

144

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

155

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

156 Where:

157  $RCI_X$  = Representative Cost Index at Mach number X158  $F_X$  = Block fuel use in kg at Mach number X159  $F_{MRC}$  = Block fuel use in kg at Maximum Range Cruise160  $t_X$  = Block flight time in minutes at Mach number X161  $t_{MRC}$  = Block flight time in minutes at Mach number X

162

## 163 2.2 Identification and Quantification of Future Impacts on Cost Index

164

165 The methodology relies on a literature review to identify the key factors and events that will affect the  
166 CI, and therefore CO<sub>2</sub> emissions, in the future. Factors are included which will either directly affect  
167 the fuel side of the CI equation or will change the time-dependent costs (Table 1).

168

169 **Table 1: Future factors Affecting CI**

| <b>Factor</b>   | <b>Impact on Cost Index</b> | <b>Data Source</b>  |
|---|-----------------------------|---|
| 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               |

170

### 171 2.2.1 Factors Impacting Fuel Costs and Use

172

173 A factor which is expected to have a significant impact on future optimum CI values is the cost of jet  
174 fuel. Ultimately reserves will affect the price of oil but at present political and technological impacts  
175 can have an equal, if not more important impact on prices. Projections for future crude oil prices were  
176 taken from Department of Energy and Climate Change (DECC) (2013a), which provides three  
177 scenarios until 2030. The low scenario represents a situation in which unconventional oil remains  
178 economic; the central fuel scenario is based on DECC's long term forecast model, checked against the  
179 Energy Information Agency (EIA) and the International Energy Agency (IEA) oil price scenarios;  
180 whilst the high scenario represents a zero global supply growth for oil post 2030. As these prices are  
181 for crude oil, the application of an average crack spread of 24% was added to the values to represent  
182 jet fuel prices. The crack spread is dependent on the cost of refining crude oil to jet fuel, which is  
183 likely to change over time, but owing to uncertainty over the future values, this study uses the average  
184 margin since 1990 (IATA, 2008).

185 On the fuel side of the equation there are two further factors that will affect the cost. The first  
186 is the possibility of a drop-in biofuel being introduced. Biofuels are now certified for use in  
187 commercial aviation in 50% blends with jet fuel. This study uses scenarios based on Biomass-to-  
188 Liquid (BtL) fuels from energy crops, as this is one of the better developed routes for conversion of  
189 biomass to jet fuel. It is assumed that airlines will only use biofuels when they are price competitive  
190 with conventional jet fuel (Bauen et al., 2009). Three scenarios are used for this study based on the  
191 price parity for BtL in 2030 of a 10%, 30% and 50% biofuel blend. The emission factor of 0.35

192 kgCO<sub>2</sub>/kg<sub>fuel</sub> is also taken from Bauen et al. (2009) for analysis of CO<sub>2</sub> emissions savings. This  
193 represents lifecycle emissions but excludes land use change. This is in contrast to the emissions factor  
194 for jet fuel which is only based on direct combustion of the fuel. Therefore, emissions savings could  
195 be higher if this was also taken into account.

196 The second additional impact on the fuel cost is likely to be the addition of a carbon price. In  
197 2013 ICAO announced that a market based measure would be introduced into the industry from 2020,  
198 although the type of measure to be implemented will not be decided until 2016. One of the likely  
199 measures is a cap-and-trade scheme in which airlines would be subject to a carbon price depending on  
200 the amount of fuel used. Future carbon price projections were taken from DECC (2013b) for 2030.  
201 These represent the average daily settlement prices of the European Union emissions allowances for  
202 the central scenario; a pessimistic outlook assuming continued oversupply and lack of demand for  
203 allowances for the low scenario; and a situation where there is higher economic growth, low prices of  
204 coal relative to gas and tighter caps from the European Union Emissions Trading Scheme (EUETS)  
205 for the high scenario.

### 206 2.2.2 Factors Impacting Time-dependent Costs

207

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

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

220 The second is the impact of climate change on extreme weather events. There may be  
221 benefits, for example a reduction in the number of cold days, but there may also be more extreme  
222 weather events in response to rising temperatures and changes in precipitation. An increase in delay is  
223 taken into account with figures from the University of Westminster Transport Studies Group (2008c),  
224 which provide low, base and high figures for three delay periods of 1-15 minutes, 16-30 minutes and  
225 31-45 minutes.

226

227 **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 |

228

### 229 2.2.3 Calculation of Future Impacts on CI values – a B767-300ER Case Study

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These factors were 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.

238

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

239

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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<sub>2</sub> emissions are then calculated by multiplying fuel use by the standard conversion factor of 3.157 kgCO<sub>2</sub>/kg<sub>fuel</sub> (Jardine, 2009), apart from in the case of the use of biofuels, in which a conversion factor of 0.35 kgCO<sub>2</sub>/kg<sub>fuel</sub> is integrated into the calculation depending on the drop in percentage.

$$Cf = F_m (CI t_f) \quad [3]$$

248

249 Where:

250 Cf = cost function

251 F<sub>m</sub> = mass of block fuel use (kg)

252 CI = cost index (kg/min)

253  $t_f$  = block flight time (min)

254

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

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

265 This study acknowledges that using such data and modeling methods results in uncertainties.  
266 Piano-X contains data that is the best available to its developers, but aircraft models can vary.  
267 Limitations also exist with only using the B767-300ER for evaluation of costs and future impacts, as  
268 this is the only model where both Piano-X and full time cost data from the University of Westminster  
269 Transport Studies Group was available, including cost of delay. As the results of the analysis of the  
270 six aircraft models show, because different aircraft have different CI ranges, CO<sub>2</sub> impacts can vary  
271 significantly so CI values do need to be calculated for each aircraft model to be accurate. Whilst the  
272 authors are currently developing methodology to account for more aircraft assessments based on  
273 specific flights, the example of the B767-300ER is effective at showing the magnitude of various  
274 future impacts relative to one another, giving a good indication of where further research is needed.

275 A sensitivity analysis was undertaken which showed that for a 10% increase in fuel costs and  
276 time costs, time costs only have a slightly higher impact on total costs of a 2.5% increase compared to  
277 2.2% for a rise in fuel costs. There was a negligible effect on total emissions at less than 0.1%, which  
278 could suggest that the accuracy of costs is unimportant. However, this sensitivity analysis was  
279 conducted at a relatively low CI value. When the same analysis was conducted at a higher CI value of  
280 100, the resulting values were more significant. This would suggest that for low CI values, a change  
281 in costs does not have a significant impact on a flight. However, if aircraft are flying at higher CI  
282 values (which evidence suggests they are) the more important the accuracy of the CI input costs  
283 becomes.

### 284 **3 Results**

285

286 The CI can have a substantial effect on fuel burn and consequently CO<sub>2</sub> emissions. Results from  
287 Piano-X show that when aircraft are flown at their design range the difference in CO<sub>2</sub> emissions

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

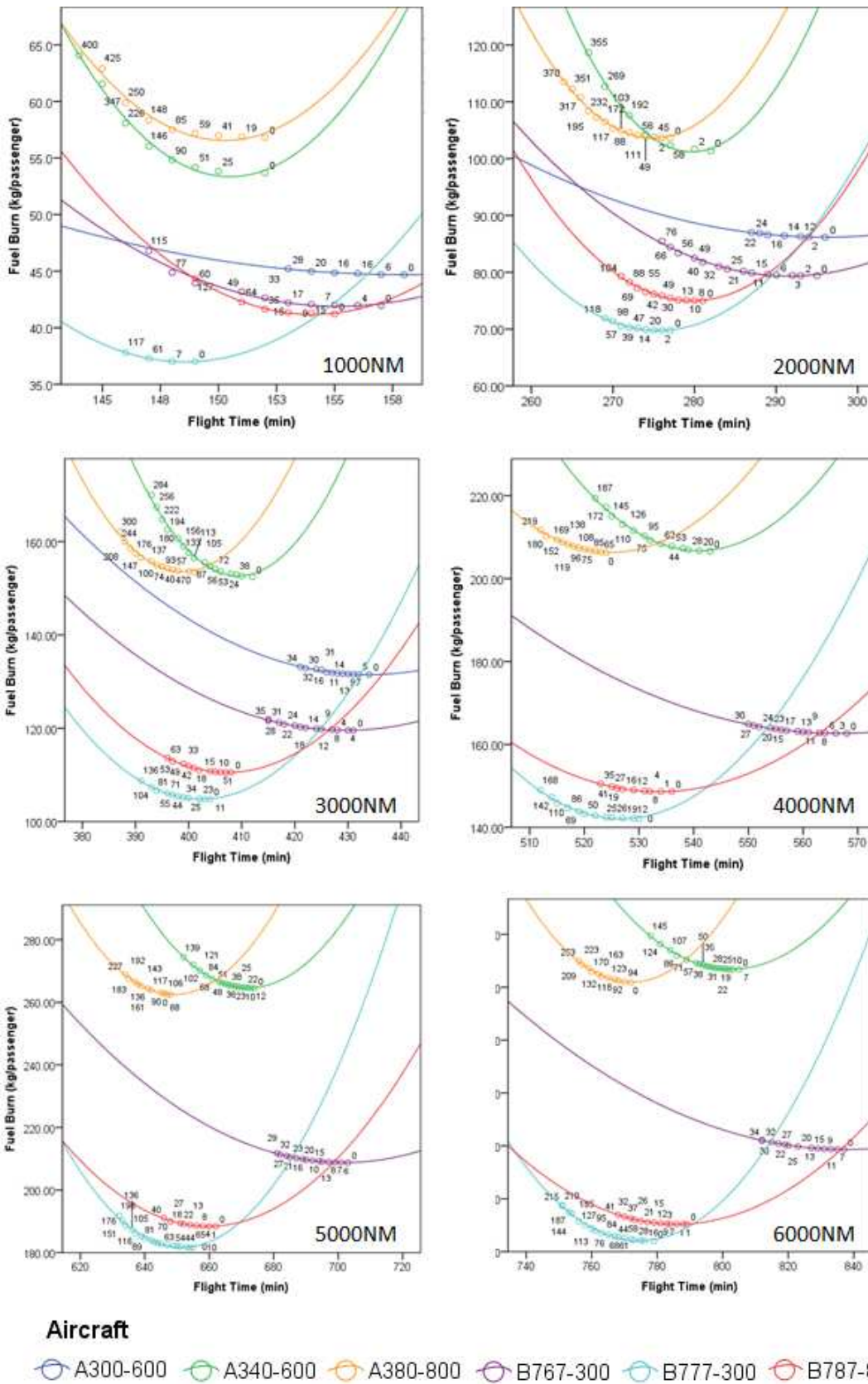
299 As aircraft are generally found to be flying above their LRC for the majority of their flight  
300 time and optimum CI values are usually found between MRC and LRC, the average saving is found to  
301 be at least 1% for the six aircraft in this analysis. However, this could be significantly higher  
302 depending on the aircraft and its average speed. This may seem small but if 1% of the global CO<sub>2</sub>  
303 emissions from aviation of 705,000,000 tonnes were reduced, this would be equivalent to the CO<sub>2</sub>  
304 emissions of around 1000 long-haul flights. This is also significant as aircraft are already equipped  
305 with the CI tool and therefore there are only small costs and time involved in implementing changes.

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

315 This relationship does vary depending on flight distance. Generally at greater flight distances,  
316 higher fuel savings can be made across the range of RCI values, backing up the conclusion that the  
317 greatest potential for reduction in CI for CO<sub>2</sub> savings is with long haul flights. Overall the B777-  
318 300ER performs the best across all distances with fast flight times and low fuel burn across its range  
319 of RCI values. Whilst the A380-800 demonstrates fast flight times, its fuel burn is substantially higher  
320 than the other aircraft models, with the exception of the A340-600. This may be a reflection of the  
321 fact that the A380 only has 47 more seats, given the standard seating configuration for three classes,  
322 than the B777-300ER, but its weight is 228,806kg more than the B777-300ER according to standard  
323 Piano-X settings.

324

325



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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.

330

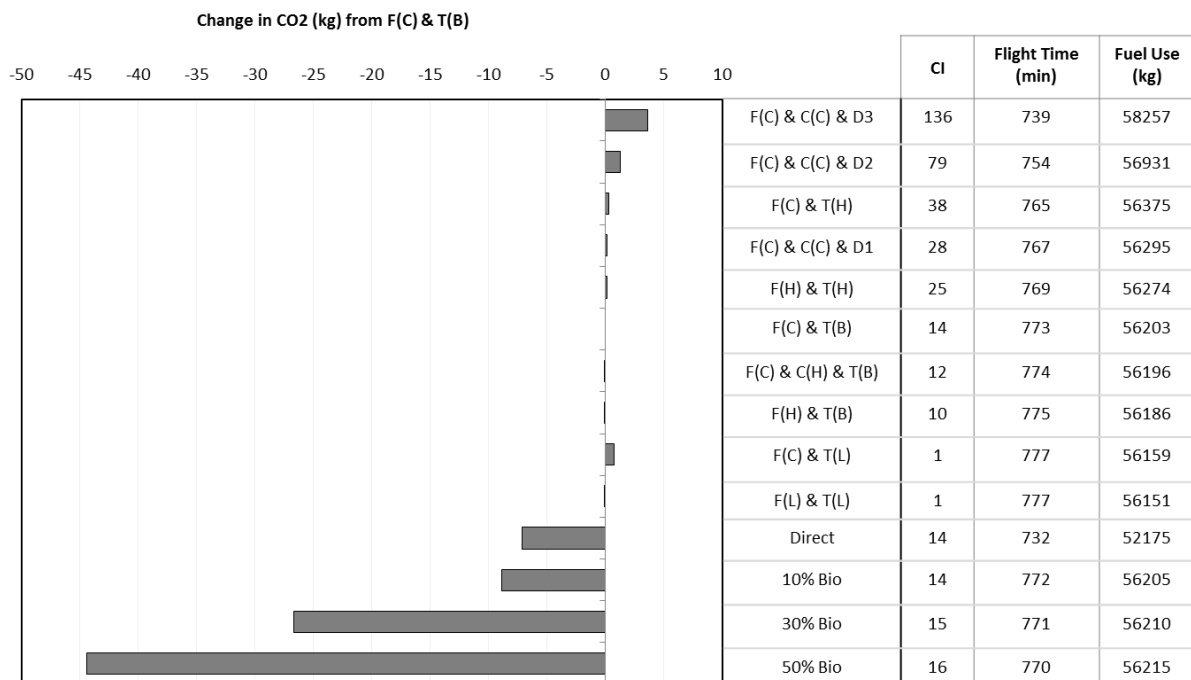
331

In terms of the more in-depth analysis looking solely at the B767-300ER, Figure 3 shows the CO<sub>2</sub> 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<sub>2</sub> 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.

338

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.

343



344

345

**Figure 3: Per cent CO<sub>2</sub> 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.**

349

350

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.

352

Whilst moving to a high fuel price and an optimum CI value of 10 only saves 0.03% in emissions.

353 Notably, the addition of even a high carbon price only results in a saving in emissions of  
354 0.01% with a change in optimum CI value from 14 to 12. In contrast the biggest impact comes from  
355 adding delay costs into the equation. A delay of 1-15 minutes requires an optimum CI of 28  
356 representing a 0.6% increase in emissions for a time saving of six minutes. A delay of 16-30 minutes  
357 requires an optimum CI value of 79 for a 19 minute saving and this results in a 1.3% increase in CO<sub>2</sub>  
358 emissions. Finally a longer delay of 31-45 minutes requires the use of an optimum CI value of 136 to  
359 gain 34 minutes in time and results in a 3.7% increase in overall flight CO<sub>2</sub> emissions.

360 The effect of biofuel use is slightly different. In the scenarios used in this study for 2030 the  
361 biofuel prices are very competitive with jet fuel prices, particularly in the central and high scenarios.  
362 Owing to this the optimum CI values are very similar at 14 and 16 for the base scenario and the  
363 highest biofuel scenario of a 50% blend respectively. However, the amount of CO<sub>2</sub> per kg of biofuel is  
364 only about a tenth of that for jet fuel so the savings in CO<sub>2</sub> are significant. Figure 3 shows that the  
365 savings ranges from 9% for a 10% blend of biofuel to 44% for a 50% blend of biofuel. This means  
366 that the flight can be made in either the same time, or slightly quicker, for substantial reductions in  
367 CO<sub>2</sub> emissions.

368 Without the use of biofuels, direct routing is the next best option for reducing CO<sub>2</sub> emissions.  
369 Conducting the flight at great circle distance can save 7% in fuel and CO<sub>2</sub> emissions. However, direct  
370 routing has the added benefit that it also saves flight time. In this flight example, the time saving  
371 would be 42 minutes for a CI of 14.

## 372 **4 Discussion**

373  
374 The results of this study demonstrate that the CI is more complex than it may first appear from its  
375 simple equation. The relationship between fuel burn and flight time is not linear and CI values can  
376 vary widely depending on aircraft model and flight distance. The comparison of six aircraft models  
377 has highlighted some clear differences in performance. This demonstrates the importance of choosing  
378 the right aircraft for specific routes. Results suggest that the area that should be focussed on is the  
379 long haul market as this is where the highest savings can be seen for only a small increase in time.

380 To ensure that savings in CO<sub>2</sub> are made, it is important that airlines address issues with  
381 miscalculation and take future impacts into account, as discussed in the following sections. Whilst  
382 there are reports of some airlines, such as Air Canada, being proactive about optimising their CI  
383 values there is evidence that a large number of airlines have not paid this issue the appropriate  
384 attention (Burrows et al., 2001). Anecdotal evidence from a number of airlines suggests that this is  
385 still an ongoing issue.

386  
387

#### 388 **4.1 Time-Dependent Costs**

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

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

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

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

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

423 The results show that delays over 15 minutes can substantially increase the CI value, as more  
424 connecting passengers miss flights causing time costs to rise. Congestion can be a significant

425 contributor to this. The primary reason for this is capacity constraints at major airports. Gelhausen et  
426 al. (2013) found that in 2008 only 10 to 20 airports could be considered to be operating in capacity  
427 constrained conditions, but show that this will increase in the future with continued increased demand  
428 for air travel. It is thought that by 2016 70% of all flights to and from the top 177 global airports will  
429 arrive or depart from a capacity constrained airport. Without expansion of airports and/or demand  
430 management this will likely lead to increased delay and CO<sub>2</sub> emissions.

431 One of the greatest uncertainties regarding delay costs is the effect climate change will have  
432 on the industry, particularly regarding extreme weather events. This is something that aviation  
433 authorities are beginning to take more seriously and ICAO include it in their Environmental Strategy  
434 (2013). An example of this is a study by Koetse and Rietveld (2009) of San Francisco Airport, where  
435 delays due to wind, rainstorms and poor visibility could be significant. Cancellations per day could  
436 increase by a factor of two to three when bad weather is experienced in the morning and a factor of  
437 three to four when there is bad weather all day, with similar figures for delay.

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

443

#### 444 **4.2 Fuel Costs**

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

454 As expected the best carbon savings result from a high fuel and carbon price. But even the  
455 high carbon price does not have a great impact on significantly reducing CO<sub>2</sub> emissions. Including a  
456 central carbon price the optimum CI changes only result in a saving of 0.01% in CO<sub>2</sub>. This questions  
457 whether current carbon price projections will promote enough innovation to reduce emissions to  
458 required levels.

459 There are varying opinions on whether a global market based measure will be successful in  
460 reducing CO<sub>2</sub> emissions from aviation. Some studies conclude that in theory a cap-and-trade system

461 would work if designed correctly (Carlsson and Hammar, 2002; Kopsch, 2012). But, Lawson (2012,  
462 p.1238) states that emissions trading could be “not only ineffective but damaging”. It is argued that  
463 emissions trading does not solve the problem of how to break out of a system where demand is being  
464 increased, with the need to sell more services to remain profitable and lack of technological solutions  
465 playing driving roles.

466 Carbon pricing becomes more important when fuel prices can be very unpredictable. A cap-  
467 and-trade carbon price could therefore provide some stability in encouraging reductions of CO<sub>2</sub>  
468 emissions. Whilst it is generally assumed that oil prices will continue to rise, Figure 3 demonstrates  
469 that this may not be the case, with the low fuel price being lower in 2030 than it is now. This would  
470 have the effect of increasing the CI value. It is important that carbon prices are set at the correct level  
471 to ensure CO<sub>2</sub> reductions. Either higher prices are needed or alternative measures also need to be  
472 considered.

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

478 Although there have been a number of successful test flights using biofuels, there are still  
479 significant challenges in meeting strict fuel standards and the feedstocks used. Only second and third  
480 generation biofuels are suitable, as conventional biofuels do not meet strict fuel quality standards,  
481 which still require significant development before they reach large scale commercial production.  
482 Other issues include sustainability concerns; lack of policy incentives and funding; lack of feedstocks;  
483 and new infrastructure requirements (Gegg et al., 2014; Upham et al., 2009).

484 Another issue is that from an airline perspective the price of fuel is still not reduced. It would  
485 take substantial effort by an airline to start using biofuel blends across their fleet but the only result  
486 would be a reduction of CO<sub>2</sub> emissions. This study has demonstrated that a carbon price would only  
487 have a small impact on costs for an airline compared with fuel costs and therefore this is unlikely to  
488 persuade an airline to put significant efforts into biofuel use. Other policy interventions are likely to  
489 be needed to encourage their use, either in addition or as an alternative to a market based measure.

490 Although biofuels have the most significant effect on CO<sub>2</sub> emissions, it must be stressed that  
491 their penetration into the industry is expected to be slow. If emissions are to be stabilized at 2020  
492 levels, a number of other short term measures will be needed until biofuels are developed enough to  
493 be used on a large scale. CI is a perfect candidate for this as it is already available on most  
494 commercial aircraft and requires minimum costs to implement.

495

496

### 497 **4.3 Time and Fuel Savings**

498 Significant benefits can also be obtained from flying more direct routes. This causes a decrease in  
499 flight time, resulting in lower time-related costs, and the shorter distance will decrease fuel burn. The  
500 effect is a win-win situation in that the CI may be increased slightly without losing these benefits. A  
501 common cause for indirect flights is diversion around restricted airspace. An example of this is in the  
502 Pearl River Delta region in Southern China. One of the major issues is the presence of the “invisible  
503 wall” between Zhuhai and Hong Kong airspaces, which aircraft have to cross at a height of 15,000ft.  
504 This results in aircraft leaving Hong Kong International Airport circling to gain sufficient height to  
505 cross the boundary. Cathay Pacific has estimated that this situation has resulted in fuel wastage of  
506 nearly 100 million kilograms and 531,000 minutes of flight time per year (Law et al., 2008).

507 Extended flight paths can also result from the cost of airspace. Europe has experienced this  
508 problem with vastly varying airspace charges according to 67 national boundaries. The Single  
509 European Sky programme has recognised that a common charging scheme is essential if Europe is to  
510 have an integrated air traffic management system (Eurocontrol, 2014). Mihetec et al. (2011) give an  
511 indication that 56,000 tonnes of CO<sub>2</sub> savings could result from reducing route extensions in Europe.

512 For this study direct routing was considered, using the great circle distance compared to the  
513 regularly flown distance. This is an ideal situation in which flight time can be increased but fuel is  
514 also saved. Therefore little sacrifice is needed from airlines, whilst saving 7% in CO<sub>2</sub> emissions for  
515 each flight. However, a lot of work needs to be undertaken for this to become a possibility. There will  
516 need to be a significant amount of stakeholder engagement between airports, air service navigation  
517 providers, airlines and individual countries. This is particularly difficult where there are political  
518 issues between countries, for example between EU countries and Russia.

519

### 520 **4.4 Further work**

521 The use of CI in analysis of future impacts is beneficial as it allows for the identification of future  
522 research needs to be evaluated effectively. For instance, from the analysis it can be seen that not only  
523 are areas such as biofuels important for CO<sub>2</sub> reductions but operational research is also essential to  
524 allow for more direct routing which offers the optimal solutions in terms of both reducing CO<sub>2</sub>  
525 emissions from a flight as well as reducing flight time, therefore resulting in the greatest cost savings  
526 for airlines. On the other hand delays have been shown to have the opposite effect on CO<sub>2</sub> emissions  
527 and flight times; therefore further research in this area is also very important.

528 This study has highlighted the complexities in using the CI in a practical manner for airlines.  
529 A key barrier for airlines at present is the difficulty they have in understanding their flight costs. This  
530 is complicated by the fact that the CI equation is simply focused on costs representing one minute and  
531 one kg of fuel. However, there are many intricacies to using CI that may not be truly represented by  
532 this on a full flight scale. For an airline, not just one flight will be affected, all flights over longer time  
533 scales need to consideration, particularly in terms of crew assignment. On a larger scale there can also

534 be network effects from airlines flying different CI values. For example, an aircraft may have to divert  
535 around a slower flying aircraft, which may have the effect of counteracting any fuel savings the  
536 slower aircraft is achieving. This is already an issue in aircraft operations, but is likely to become  
537 more important as airspace capacity becomes more constrained.

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

## 542 **5 Conclusion**

543  
544 This study aimed to examine the potential for CI to contribute to aircraft CO<sub>2</sub> emission  
545 reductions and assess the effect that future impacts will have on optimum CI values. Optimisation of  
546 CI can be an effective tool in reducing carbon emissions by an average of 1%, which can contribute to  
547 the basket of measures to reduce overall emissions within the airline industry. These emission  
548 reductions are dependent on the aircraft model, with evidence that long haul flights should be  
549 prioritized, as they result in higher CO<sub>2</sub> reductions for small changes in flight time.

550 A major benefit of using CI as a tool to reduce emissions is that it is already available in  
551 commercial aircraft and there are minimal costs to implementation of changes with few time  
552 constraints. It also has a dual role in reducing CO<sub>2</sub> emissions and helping to predict the effect of future  
553 impacts on the industry.

554 It is generally assumed that a rise in fuel costs will cause airlines to pick lower CI values, but  
555 this study has highlighted that it will not be enough on its own to promote significant reductions in  
556 CO<sub>2</sub> emissions. Even when a carbon price is added, it has been demonstrated that this only has a small  
557 impact on the emissions of an individual flight.

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

563 Whilst the greatest impact in terms of CO<sub>2</sub> reductions is likely to be a result of technology  
564 change and operational improvements, including the use of biofuels, it is unlikely that carbon pricing  
565 with its current projections will be enough to encourage this sort of change. Therefore, other policy  
566 measures will also be needed either in addition or as an alternative to a market based measure.

567 Further work is required in this establish the best way to calculate the CI accurately which the  
568 authors are currently undertaking. This analysis has also highlighted the need for research and action

569 concerning mitigation of capacity constraints and climate change effects, as well as development of  
570 biofuels and operational improvements for direct routing.

571

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575

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686

## 687 **Glossary**

688

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

692

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

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

698

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

701

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

704

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

708

## 709 **Appendix – Scenario Settings**

710 **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

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

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

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