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Adding Carbon to the Equation in Online Flight Searches

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Abstract. GreenFLY (greenfly.ucdavis.edu) is an airline flight search website that prominently displays greenhouse gas emissions estimates along with the other important flight information, such as price and times, for each possible flight itinerary. We describe its software components and graphic design principles. Then we present a discrete choice experiment in which we asked participants to choose between itineraries presented in the GreenFLY format. Results suggest that consumers are willing to pay a significant amount for lower-emissions flights in the context of online flight search, especially when lower emissions are combined with fewer layovers.

Keywords: Air travel emissions · Flight carbon calculator · Flight search engine

1 Introduction

Air travel is now estimated to contribute as much as 5% of worldwide greenhouse gas emissions [13]. A single round-trip coach flight from San Francisco to Miami is responsible for about one metric ton of emissions; for comparison, annual greenhouse gas emissions in the United States are about 20 metric tons per person. Therefore, reducing emissions due to air travel is an important goal.

Although generally high relative to other travel modes, emissions for different flight itineraries with the same origin and destination can vary greatly, depending mainly on the number and location of connections/layovers and on the aircraft used [9]. Aircraft emissions are measured in carbon dioxide equivalent, CO_2E, which measures the environmental impact of all greenhouse gasses emitted by giving the corresponding weight of CO_2 only. Different itineraries for the San Francisco-Miami trip can vary by 0.7 tons of CO_2E or more. Taking advantage of these potential savings is an appealing approach to emissions reductions [13].

Specific and relevant information provided at the purchase decision point has been suggested as an effective strategy to help consumers to make environmentally beneficial choices [4]. Online flight searching presents an excellent opportunity for this kind of intervention: someone making an air travel purchase is already carefully examining a website that presents detailed information on many possible itineraries, and choosing a

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flight based on a variety of factors (e.g., cost, number and length of layovers, airline, airport of departure and arrival, and departure and arrival times). Displaying a CO_2E emissions estimate for each flight would allow the consumer to consider emissions among these other factors.

With greater awareness of the environmental costs of air travel, some consumers might also consider other transportation options, e.g., driving to a slightly farther airport in order to get a direct flight, or driving rather than flying for a family vacation if the distance was not too great. Many consumers making lower-carbon choices would encourage airlines to invest in more efficient aircraft or routing. Increasing public awareness of the environmental costs of air travel would also help inform government regulation and public investment in transportation.

In this paper, we describe the design and development of GreenFLY, a flight search tool that displays CO_2E emissions estimates along with the usual data for different flight itineraries. We describe a discrete choice experiment based on the GreenFLY interface that provides some insight into the potential influence such a tool might have on consumer behavior.

2 Prior Work

Before we describe GreenFLY in detail and present our choice experiment, we review prior relevant work. Specifically, we survey carbon calculators and eco-feedback apps that focus on accounting for carbon in travel behavior and promoting greener travel. Then, we summarize previous economic valuation studies that consider consumer willingness to pay for flight carbon offsets. Finally, we describe past efforts to integrate carbon emissions estimates into the online flight search process.

2.1 Transportation Carbon Calculators and Eco-Feedback Apps

Estimating flight emissions in enough detail to distinguish fairly between specific itineraries requires detailed information about the flight legs, and the more information available the better the estimates (we discuss the information we use below). Detailed carbon calculators have been developed by transportation analytics companies that provide a variety of information to commercial clients on their travel costs and practices. Calculators by TRX (now part of Concor) and Sabre, the travel technology company providing the largest commercial flight search engine, provide very high-quality data but are expensive and not accessible to individual consumers.

Many publicly available personal online carbon calculators provide estimates of the environmental costs of air travel, but not in sufficient detail to compare different flights. Good examples ask users to enter the number of short, long, and extensive flights taken (e.g., UC Berkeley's CoolClimate Network carbon calculator: http://coolclimate.berkeley.edu/calculator) and the origin and destination of flights taken (e.g., Terrapass: https://www.terrapass.com/carbon-footprint-calculator). Layovers are taken into account by the air travel-specific calculators at myclimate (https://co2.myclimate.org/en/portfolios?calculation_id=681294) and the International Civil

Aviation Organization (ICAO; http://www.icao.int/environmental-protection/Carbon-Offset/Pages/default.aspx). None of these freely available calculators take into account aircraft model, which has a substantial impact on emissions.

In addition to carbon calculator websites, there are mobile apps that track transportation behavior and provide eco-feedback [5], including carbon emissions estimates, to promote greener travel. These include some publicly available apps (e.g., CarbonDiem.com, CommuteGreener.com) and apps created for human-computer interaction research [e.g., 6, 10]. However, these apps have focused mainly on non-motorized (walking, cycling) and motorized ground transportation. An exception is E-Mission [18], a smartphone app that automatically recognizes multiple travel modes, including air, with a companion web interface that provides feedback on carbon emissions (based on averages for each travel mode).

Emissions estimates resulting from these tools can increase users' awareness of the large impact that air travel has on their personal carbon footprints, but they are not geared toward helping consumers proactively reduce their air travel carbon footprint. There are two strategies that enable a more proactive approach. One is the integration of carbon emissions information into online flight search tools, which is the subject of this study. The other is carbon taxes or offsets that the consumer can purchase to compensate for the emissions created by their air travel.

2.2 Economic Valuation of Air Travel Carbon Offsets

There have been a number of studies attempting to quantify air travelers' willingness to pay (WTP) for carbon offsets for their flights [1, 2, 15, 16, 19]. The purchase of carbon offsets is distinct from the goals of GreenFLY and similar tools that integrate emissions information into online flight searching. Carbon offsets provide the consumer with an opportunity to pay for activities that combat climate change in order to offset the carbon they are responsible for producing with their air travel. In contrast, GreenFLY and similar tools provide the consumer with an opportunity to avoid some emissions entirely. To our knowledge, ours is the first study of consumer WTP for carbon in this context. However, previous studies on WTP for carbon offsets are relevant as a point of comparison.

Brouwer et al. [1] recruited 400 air travelers (mostly European) at Amsterdam Schiphol Airport in 2006 to participate in a contingent valuation (CV) study of WTP for carbon offsets. After receiving an explanation of the concept of a carbon tax, participants were asked if, in general, they were will to pay such a tax on their plane ticket. Those who said yes (75%) were then asked if they were willing to pay a specific amount of money for that tax. Using the CV method, if the response was no, the interviewer asked about a second amount that was lower; if the initial response was yes, the interviewer asked about a second amount that was higher. This process continues until an interval is reached between an amount the consumer is willing to pay and an amount they are not willing to pay. Mean WTP for a flight carbon tax was 23.1 Euros (equivalent to 25 Euros per ton of CO_2E).

Similar CV studies were subsequently conducted by Jou and Chen [11], Lu and Shon [15], and MacKerron et al. [16]. MacKerron et al. [16], in 2007, asked 321 UK adults aged 18–34 to imagine flying from New York to London and having the opportunity to purchase a carbon offset for the flight. Mean WTP was GBP £24. Lu and Shon [15] interviewed 1,339 air travelers at Taoyuan International Airport in Taiwan late 2010 to early 2011. They found that passengers flying to China, Northeast Asia, Southeast Asia, and western countries were willing to pay $5, $8.80, $10.80, and $28.60, respectively, to offset their flight carbon emissions (amounting to 1–1.5% of participant flight cost).

Overall, studies have shown that most air travelers say they are willing to pay some amount to offset flight carbon emissions, and often at rates higher than standard carbon offset prices [e.g., 11, 16]. However, as Jou and Chen [11] caution, stated valuation is an easier commitment than actually making the donation. In Brouwer et al. [1], when participants were asked how likely they would be to pay their stated WTP amount if it were a voluntary tax, only 37% percent of North American participants, 47% of European participants, and 50% of Asian participants said they were likely to pay. In Choi and Ritchie [2], most participants agreed that voluntary offset payments must be "a convenient thing to do", and they talked about the importance of the position of the offset option during online booking as well as convenient payment procedures. Providing salient information in a flight search tool about the range of carbon emissions for flight alternatives could be the most convenient strategy, as users could simply purchase a lower emissions flight without any additional donation and payment procedure.

2.3 Integrating CO_2 Estimates into Flight Search Tools

The idea of displaying greenhouse gas emissions estimates during flight search was pioneered, as far as we know, by a company called Brighter Planet, whose main business was carbon accounting for industrial and institutional clients. They developed an air travel emissions calculator, and a plug-in, Careplane, for the major web browsers. Careplane decorated Expedia, Orbitz, Kayak, and a few other flight search sites with emissions estimates during search. Unfortunately, when Brighter Planet went out of business neither their calculator nor the plug-ins were supported, so they no longer give correct results.

Calasi, a later start-up, has a business model in which they market an emissions calculator and information on other flight details, such as in-flight entertainment options, to flight search engine companies. Unfortunately, we are not aware of any flight search sites currently using their emissions data. Calasi also developed a browser plug-in, but again maintenance is a problem.

Flight search is a competitive, low-margin industry. Flight search engines, which provide the data on flight schedules, prices and availability, are expensive, so it is difficult to build a profitable custom flight search site based on a commercial engine. While web plug-ins do not incur the cost of a flight search engine, they are difficult to build and even more difficult to maintain, as both browsers and flight search websites change quickly. In addition, decorating existing flight search pages adds to their clutter instead of providing a sense of clarity and purpose, and plug-ins do not allow for more complex functions (e.g., allowing the user to sort flights by carbon emissions).

3 GreenFLY

GreenFLY is an example of a flight search tool in which emissions estimates are the focus rather than an afterthought. Earlier tools either forced estimates into flight search pages that were not designed to accommodate them, or they were not in the flight search page at all and required users to navigate between multiple interfaces. GreenFLY sorts flight options according to emissions, displays emissions information cleanly and prominently, and provides contextual information for the magnitude of the potential emissions savings.

3.1 Design

GreenFLY's home page and flight search background screen depict clouds rolling through a mountain range to elevate the user as if in flight and suggest cleanliness and nature. The flight search input interface (Fig. 1) resembles a plane ticket on which the user enters origin, destination, flight legs (one-way or round trip), departure/return dates, and cabin (economy, business, etc.).

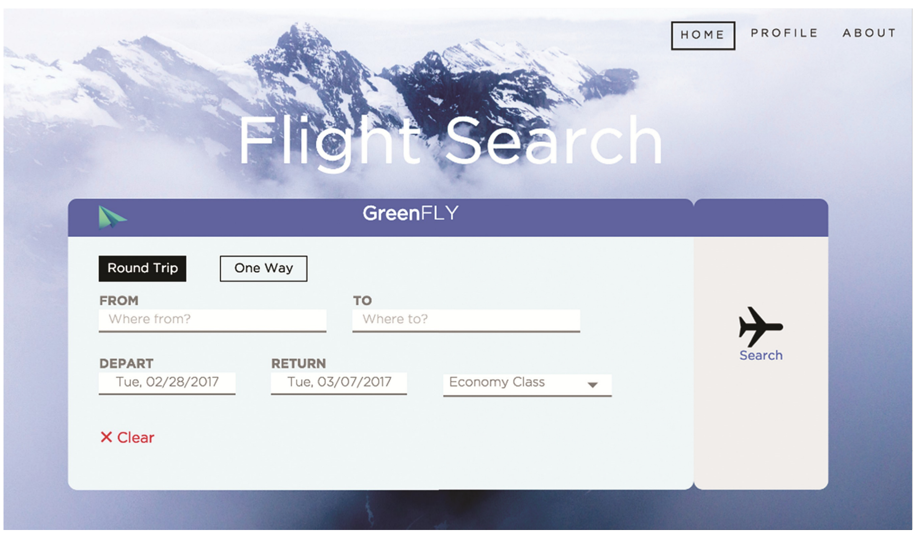

Fig. 1. The query interface for flight search in GreenFLY. The background is meant to suggest cleanliness and nature as well as flight, while the form resembles a ticket.

Once the information is entered, the user clicks the "search" button on the ticket stub and is directed to the flight search results (Fig. 2), which populate the same page, just below the flight search ticket. Continuing with the ticket theme, each flight search result can be expanded to view a ticket for each leg of the trip giving detailed information.

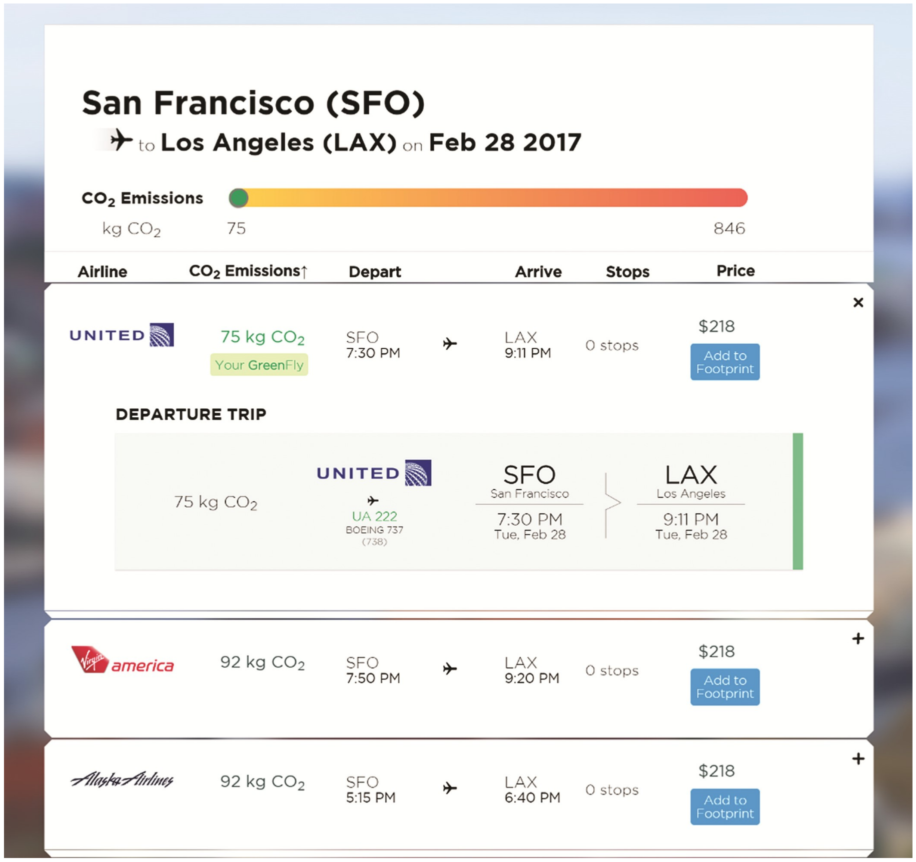

Fig. 2. Flight results in GreenFLY. Emissions estimates appear on the left, and price on the right. Flights can be expanded to show details.

GreenFLY's design attempts to make emissions information both salient and persuasive. A CO_2E emissions range summary is displayed as a meter at the top of the flight search output page, indicating the minimum, maximum, and average emissions of the available flight options. The meter uses a gradient of yellow-orange-red to imply that higher emissions is negative and undesirable. A green dot on the far left of the meter marks the flight option(s) with the lowest emissions. Lowest emissions flight(s) are also labeled as "Your GreenFLY" in green text, with the emissions number also in green text to imply that these are the most positive and desirable flights. To further emphasize the significance of flights with lower emissions, search results appear sorted from least to most emissions by default; the user can also choose to search by price.

Users have the option to add a flight to their personal profile by clicking "Add to Footprint". The profile page (Fig. 3) tracks a user's flight history and three metrics: total CO_2E emissions, kilometers travelled, and number of trips; each statistic is accompanied by an illustrative icon and distinct color. The user can also delete flights from the history, which readjusts the statistics.

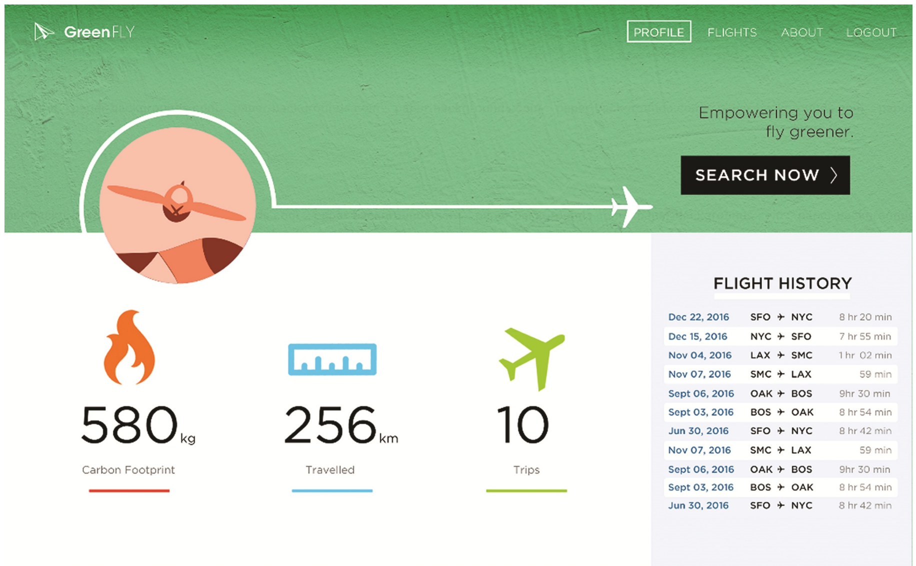

Fig. 3. GreenFLY user profile page. The user can keep track of their flight history and overall carbon footprint.

3.2 Flight Search Engine

GreenFLY uses Google's QPX Express flight search engine API (application program interface) to obtain flight schedule and price information. QPX provides a free interface for low volumes of flight searches (up to 50 per day); but using it for many searches is currently expensive. GreenFLY sends a query containing the origin, destination, class of travel, dates of travel, and trip type (round trip or one-way) to QPX, which returns a list of possible flight itineraries. Using QPX to develop GreenFLY gave us complete control over the presentation of both flight and emissions information.

3.3 Flight Emissions Calculator

GreenFLY's emissions calculator is based on the following formulae:

$$\text{CO}_2\text{E Emission}\,[\text{kg/person}] = 3.16 \times (\text{Total fuel for journey}\,[\text{kg}]/\#\,\text{seats}) \times 1.5 \quad (1)$$

$$\text{Total fuel for journey}\,[\text{kg}] = (\text{Aircraft fuel burn rate}\,[\text{kg/km}]) \times (\text{Distance}[\text{km}]) \quad (2)$$

This computation is a simplification of the formula proposed by the International Civil Aviation Organization (ICAO) [7], a UN agency, which was designed for estimating the emissions assignable to an airport from the airport's specific mix of flights.

The constant 3.16[1] in Formula (1) represents the kilograms of CO_2 produced by burning one kilogram of aviation fuel. The constant 1.5 in Formula (2) is a radiative forcing factor that accounts for the effect of releasing emissions high in the atmosphere rather than at the surface of the earth and for other emissions besides CO_2. Various radiative forcing factors are used for flight emissions estimates, and 1.5 is a relatively conservative choice (giving lower emissions estimates). Distance is great-circle distance calculated from the geographic positions (latitudes and longitudes)[2] of the origin and destination input by the user, using the Geodesy package[3].

QPX provides the aircraft model for each flight leg, which can affect the carbon emissions per seat by up to a factor of two [12]; in general, regional jets are less fuel efficient than long-range and medium-range jets, and more modern aircraft are more fuel efficient than older planes. Our emissions estimates use the aircraft model to determine the fuel burn rate and the number of economy class seats on the plane.

Aircraft fuel burn rate is the amount of fuel burnt by an aircraft per kilometer in flight. We collected fuel burn data from a variety of sources. Most of the data were obtained from European Environmental Agency (EEA) [3, Appendix], which provided fuel burn data for a selection of representative aircraft models for a number of specific flight distances (updating an earlier table published by the ICAO [6, page 14]). For distances not provided, we used linear interpolation to estimate fuel burn. Many aircraft not included in the EEA data are mapped to the representative aircraft using tables provided by the ICAO [6, p. 13] and the EEA [3, p. 23]. For aircraft models not provided, we obtained data on the max fuel weight (MFW), maximum range, and capacity for different aircraft models from Jane's Information Group [8]. We estimated fuel burn with the following formula:

$$\text{Fuel burn}\left[\text{kg/km}\right] = \text{MFW}\left[\text{kg}\right] \times \text{Maximum range}\,[\text{km}] \quad (3)$$

This estimate is not as accurate as EEA data, which was based on simulations of flights of various lengths, and takes into consideration the fuel required for taxi, take-off, holding patterns, approaches, and landings. However, matching estimates based on Formula (3) allows us to map unknown aircraft to representative aircraft with similar calculated fuel burns.

The number of seats on a particular aircraft model, in Formula (1) above, varies between airlines, depending on how the aircraft is configured. The standard capacity of most aircraft models was taken from Jane's. Some missing seat number data were obtained from aircraft profiles found on the websites of major airlines.

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[1] From [6], p. 6.
[2] Available online; we used www.openflights.org/data.html.
[3] The Geodesy repository can be found here: https://github.com/chrisveness/geodesy.

3.4 Software Design

GreenFLY is built on Node.js, supported by a number of JavaScript packages, including Webpack, ES6 and JQuery in the frontend, and Express.js, socket.io, and async on the server side. The main database storing airline, aircrafts, and airports information uses SQLite3. The user registration information is stored in another database using MongoDB.

GreenFLY first takes a user's input including origin, destination, class of travel, dates of travel, and trip type (round trip or one-way), and sends it to the server for query construction. The server then sends the query to QPX to retrieve possible itineraries, as described in Sect. 3.2. After getting back a response from QPX, it parses each itinerary into legs, with each leg containing information about departure airport, arrival airport, departure time, arrival time, aircraft model, price, etc. Then it computes CO_2E emissions for each leg, as described in Sect. 3.3. The parameters needed for computation, namely the number of seats and fuel burn rate for specific aircraft, and the longitude and latitude of airports, are retrieved from the main database. The calculated emissions are then appended to the response received from QPX, and returned to the frontend code in the browser for display.

4 Experiment

We used choice modeling, and in particular a discrete choice experiment, to explore the potential for GreenFLY and similar tools to promote the purchase of greener flights. Choice experiments allow the researcher to examine whether and to what degree specific attributes, or attribute combinations, influence the value of an economic good, i.e., the consumers' willingness to pay (WTP) for those attributes [14]. The general method of a discrete choice experiment is to have research participants choose among options that vary in terms of the attributes of interest.

Discrete choice is a common method in marketing research as it resembles real purchase situations. In our context, asking participants which flight they would choose from visually presented options that vary in terms of cost and number of layovers is a familiar task to anyone who has experience online flight searching. Adding carbon emissions as an attribute, however, is novel to most consumers. We therefore prefaced the experiment by providing participants with some contextual information about air travel carbon emissions.

4.1 Methodology

We designed our discrete choice experiment using Qualtrics survey software and recruited participants via Amazon Mechanical Turk. Participation was restricted to US residents at least 18 years of age (Mechanical Turk provided these filters), with experience purchasing flight tickets and traveling by plane (survey items required participants to confirm they met these inclusion criteria).

Participants were asked where they last traveled to by plane and whether the trip was for business, pleasure, or both. Their responses to those questions were piped into instructions for the later flight choice questions, i.e., "For the next three questions, please imagine you are searching for a flight for an upcoming [business, pleasure, or business and pleasure] trip to [last flight destination]. … Which flight would you choose given the following options and information?"

We presented the flight itinerary choices using a modified version of our visual design for GreenFLY in order to approximate the experience of using a flight search that emphasized emissions estimates. In addition, it allowed us to give the questions a realistic "look and feel" typical of the flight search task.

Our main research question was: How much more money, if any, are consumers willing to pay to take a flight with less emissions? This issue is complicated, however, by the fact that itineraries with fewer layovers typically have significantly lower emissions, and many consumers will pay more for a flight with fewer layovers, regardless of emissions. Therefore, a second question was: How much do emission reductions encourage consumers to choose a flight with fewer layovers?

To answer these questions, we developed three flight choice scenarios, detailed below, to present to each participant. Each flight choice scenario consisted of three flight options that varied along one or more of the dimensions: cost, carbon emissions, and number of layovers (Table 1). Cost and carbon emissions levels were determined by calculating the average of each for a sample of popular domestic one-way flights, then building levels around that average. Specifically, for cost we used the mean, two standard deviations below and three standard deviations above. For carbon emissions we used the mean, one standard deviation on either side of the mean, and the minimum and maximum values.

Table 1. Attributes varied in our choice experiment.

Cost ($)	480, 459, 438, 417, 396, 375
Carbon emissions (kg CO_2)	231, 274, 381, 488, 595, 634
Number of layovers	Nonstop, 1 layover, or 2 layovers

Flight Choice Scenario 1: Cost and Layovers. The user was asked to choose one of three flight options that varied in terms of cost and number of layovers, which were negatively correlated; e.g., Figure 4. Each flight choice scenario consisted of one nonstop option, one 1 layover option, and one 2 layover option. Participants were randomly assigned to view one of eight possible flight option combinations for this flight choice scenario.

Flight Choice Scenario 2: Cost and Carbon. The user was asked to choose one of three flights that varied in terms of cost and carbon emissions, which were negatively correlated; e.g., Figure 5. Participants were randomly assigned to view one of twenty possible flight option combinations for this flight choice scenario.

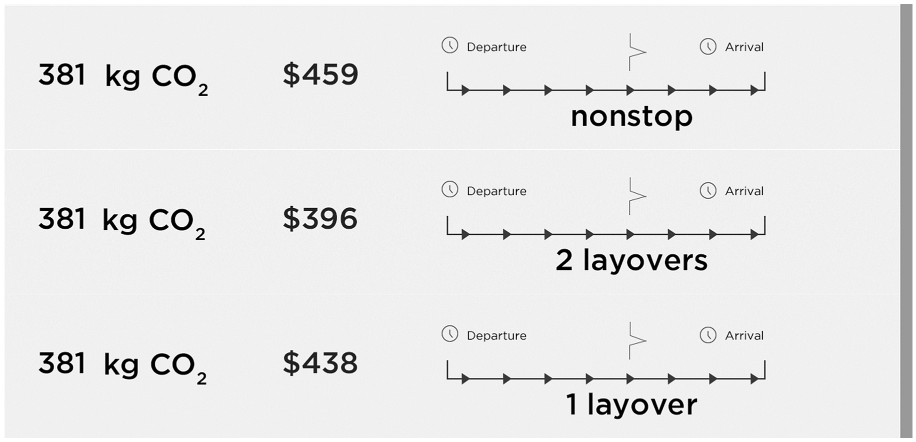

Fig. 4. Example of options presented to respondents in flight choice scenario 1.

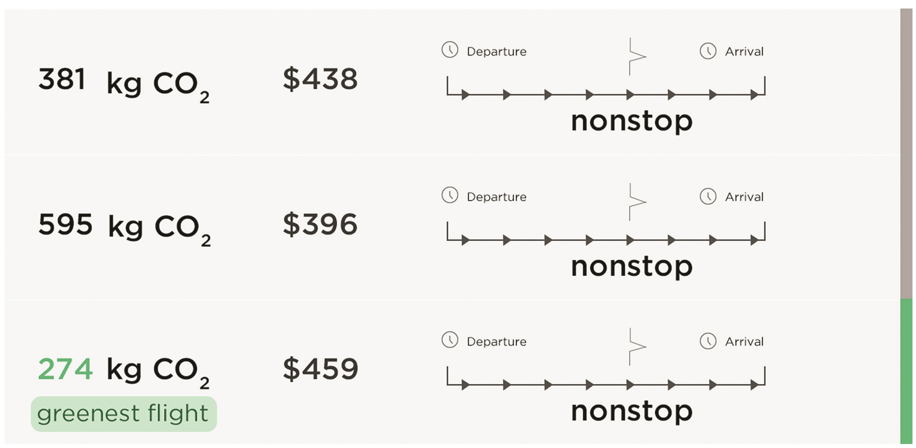

Fig. 5. Examples of options presented to respondents in flight choice scenario 2.

Flight Choice Scenario 3: Cost, Carbon, and Layovers. The user was asked to choose one of three flights that varied in terms of cost, carbon emissions, and number of layovers; carbon emissions was positively correlated with number of layovers and negatively correlated with cost; e.g., Figure 6. Participants were randomly assigned to view one of twenty possible flight option combinations for this flight choice scenario.

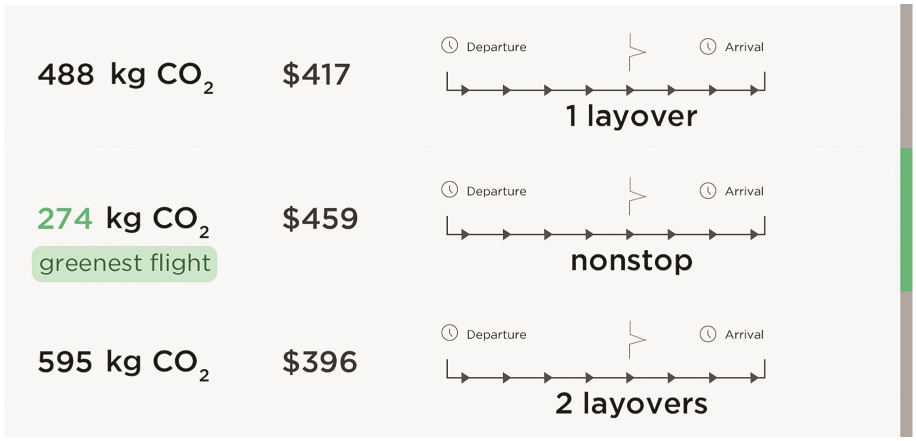

Fig. 6. Example of options presented to respondents in flight choice scenario 3.

After the flight choice scenarios, there was a "trick question" that looked like the flight choice scenarios except the prompt was to indicate which of the three flight options had one layover; all data for participants who answered incorrectly were removed. After removing cases with incomplete data, incorrect responses to the trick question, and invalid responses to the open-ended text entry item, "What was the last place you traveled to by plane?" (the latter would confuse the instructions for the flight choice scenarios that piped in that response), we retained a sample size of 1417 participants. Each participant did not receive all questions, so sample sizes vary and are specified in each analysis. Participants were 52% male and 42% female. Mean age was 33 (min = 18, max = 70, *SD* = 10) and mean annual income was $49,096 (min = 0; max = $450,000, *SD* = $37,989).

Most participants reported that they had traveled by plane once or twice in the previous 12 months (60%); 28% reported three or more flights; and 12% had not traveled by plane in the last 12 months. Most participants reported that these recent trips were mostly for pleasure (74%); 11% indicated they were mostly for business, and 15% indicated they were about half and half. Of those who traveled by plane for business ($n = 372$), 73% indicated that their flight costs were typically covered by work. In terms of their most recent flight, which was used to frame the flight choice selection questions, 78% reported this trip was for pleasure, 12% indicated it was for business, and 10% indicated it was for both business and pleasure. Destinations for most recent flight naturally varied widely, but frequent answers included cities in Florida (236) and California (178), as well as Las Vegas (74) and New York (66).

4.2 Analysis and Results

We computed a conditional logit model for each of the three flight choice scenarios using the *clogistic* function of the *Epi* package in R. This package calculates a model predicting, given the three flight alternatives, the probability that each flight option will be chosen. The probabilities are assigned to each of the three choices using three linked non-linear functions, which take as input a utility score for each of the flight choices. Utility is modeled as a linear function, which the *clogistic* package fits using maximum likelihood. We can think of the linear utility function as describing how the most likely user values each of the factors describing the flight choice. Since cost is one of the factors, it lets us explain other factors in terms of WTP.

The analysis of Question 1, which varied flight options' cost and number of layovers, showed, unsurprisingly, that participants were willing to pay more for flights with fewer layovers. It produced the utility function:

$$U = -1.494 * layovers + -0.0291 * dollars + constant$$

These coefficients, and the model itself, were all highly statistically significant (see Table 2). Note that the coefficients are not standardized and should not be directly compared. This model implies that, when comparing a nonstop flight to a one-layover flight, or a two-layover to a one-layover, the extra layover should cost –1.494 / –0.0291 = \$51.34 less to be equally desirable to our maximum likelihood consumer. That is, the two flights in Fig. 7 would be roughly equally desirable.

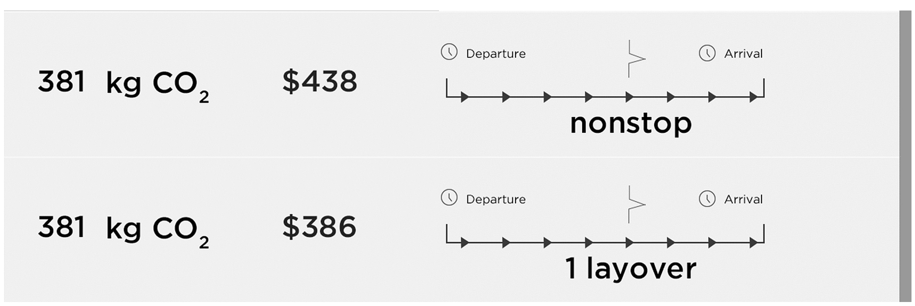

Fig. 7. Equally desirable flights that differ in cost and number of layovers.

The model for Question 2, which varied flight options' carbon emissions and cost, showed that participants were willing to pay more for lower-carbon flights. It produced the utility function:

$$U = -0.00679 * carbon + -0.03532 * dollars + constant$$

These coefficients, and the model itself, were again all highly statistically significant (Table 2). This model implies that, when comparing flights with varying carbon emissions, our maximum likelihood consumer would be willing to pay –0.00679/–0.03532 = \$.192 per kg CO_2 spared. This implies a remarkable carbon cost of \$192/ton CO_2. For example, the two flights in Fig. 8 are roughly equally desirable according to the model.

Fig. 8. Equally desirable flights that differ in cost and carbon.

Question 3 varied flight options' cost, layovers, and carbon emissions. Our hypothesis for this question was that including carbon emissions estimates would encourage people to choose flights with fewer layovers, so we designed the question so that carbon emissions are lower for flights with fewer layovers (as they usually are in reality). As a result, the *carbon* and *layover* variables are highly correlated.

Again, our data gave a statistically significant model, with all of it coefficients significant (Table 2):

$$U = -1.15775 * layovers + -0.04908 * dollars + -0.00957\, kg\, carbon + constant$$

This model gives a carbon cost of $.194/kg, similar to Question 2, but a WTP of $29.76 to avoid a layover, less than Question 1; that is, the model attributes some of the layover cost to carbon, because they are closely correlated. For example, this model assigns roughly equal utility to the two flights in Fig. 9.

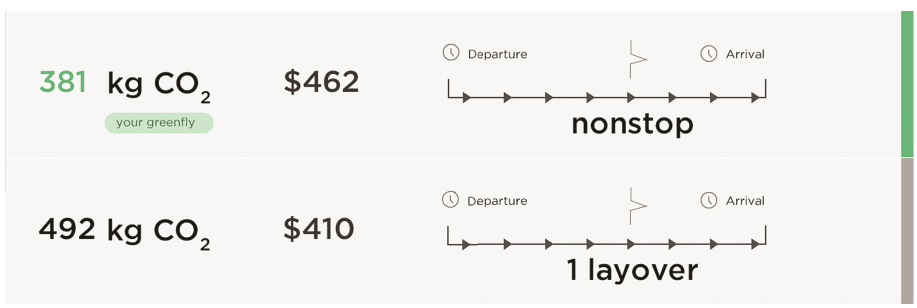

Fig. 9. Equally desirable flights that differ in cost ($52 difference), number of layovers, and carbon (111 kg CO_2 difference).

Thus, assuming the customer is willing to pay $51.34 more for a non stop (the value predicted in Question 1), they also expect to get 111 kg of correlated emissions reductions "for free". But as the emission reductions increase, so does willingness to pay to avoid the layover. For instance, the flights in Fig. 10 also have equal utility.

Fig. 10. Equally desirable flights that differ in cost ($69 difference), number of layovers, and carbon (200 kg CO_2 difference).

That is, if the emissions reduction is 200 kg, the model predicts that the customer would pay as much as $68.60 to avoid the layover.

We analyzed this tradeoff in another way, by computing models from the data in Question 3 that just included one factor or the other. We found that a statistically significant model only using the number of layovers and cost implied a WTP of $82.76 to avoid a layover. That is, showing realistic emission reductions raised WTP very significantly from the value of $51.34 that we found when emissions did not vary in Question 1. Similarly, a model computed from Question 3 using only cost and carbon implied a carbon cost of $0.302/kg, significantly greater than the $0.194/kg we saw when number of layovers did not vary in Question 2.

Table 2. Significance of the conditional logistic models for Questions 1-3. The *lrt* statistic is likelihood ratio test and *df* is degrees of freedom.

Question	Regression statistics	Variable	Coefficient (se)	z-statistic	p-value
Question 1 ($N = 1403$)	$lrt = 126$; $df = 2$; $p = 0$	Cost	–0.0291 (0.00325)	–9.06	< .0001
		Layovers	–1.4940 (0.143)	–10.43	<.0001
Question 2 ($N = 1055$)	$lrt = 54.9$; $df = 2$; $p = < .0001$	Cost	–0.03532 (0.00728)	–5.24	< .0001
		Carbon	–0.00679 (0.00171)	–4.25	.00021
Question 3 ($N = 1055$)	$lrt = 296$; $df = 3$; $p = 0$	Cost	–0.04908 (0.00817)	–5.90	< .0001
		Layovers	–1.15775 (0.196)	–5.79	< .0001
		Carbon	–0.00957 (0.00236)	–3.95	.00020

5 Discussion

A flight search tool like GreenFLY requires two parts, a flight search engine and an emissions calculator. As we previously mentioned, flight search engines are expensive to license, so we implemented our own emissions calculator. The biggest challenge in doing so was finding the data. In particular, it would be useful to have complete fuel burn tables, extending the ICAO data to a range of aircraft covering most modern flight itineraries.

There are many other ways in which our emissions calculator could be improved. Some relevant factors that we cannot determine at the time of purchase are the year of aircraft manufacture and the engine (different engines can be installed in the same aircraft model). We might, however, be able to estimate these based on average values for each airline. Number of seats in a given aircraft model varies by airline; we currently use only a single estimate per aircraft regardless of airline. Passenger load (occupancy) and passenger to freight weight ratios can be estimated from historical data, which could be purchased. We plan to open-source our emissions calculator, along with an API, so that other researchers can contribute to its database and algorithms.

Our Mechanical Turk experiment showed that a design like GreenFLY, which displays emissions estimates clearly and with context, very strongly encourages respondents to choose flights with lower greenhouse gas emissions. In the context of flight search with an interface like GreenFLY's, respondents' choices indicated willingness to pay a carbon cost of $192/ton of CO_2E, almost a factor of ten greater than that seen in other contexts. Showing realistic emissions data and flagging the greenest choice increased the WTP to avoid a layover to $82.76 from $51.34, again a very significant change.

While these results show that our existing design does a great job of encouraging emissions reductions, it would be very interesting to study a variety of design factors and see how they affect user behavior. Also, we need to add several features, such as choosing a first-class flight (with corresponding emissions cost), multiple passengers, multi-city flights, and so on, that users expect in a flight search site.

It is also important to verify these results, and any further ideas, in a real flight search application, when respondents are actually spending money. In order to do this, we need to improve GreenFLY. Currently, the user cannot actually purchase flights through GreenFLY; we need to send them to another site to make the actual purchase. Somewhat disturbingly, we find that flights listed as available through QPX are sometimes not available on other search sites. Possibly both of these problems could be solved by switching to another flight search engine (e.g., WeGo). This is a rapidly evolving market and we expect that we should be able to find a good solution in the near future.

This research suggests something like GreenFLY, either as its own niche site or as part of a larger flight search site, would allow consumers to make significant reductions in their personal carbon footprints, help educate the general public on the environmental costs of air travel, and encourage improved aircraft and airline efficiency.

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