Nudging consumers toward greener air travel by adding carbon to the equation in online flight search

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DATA ACCESSIBILITY

Data analyzed in this study are archived in Dryad public data repository, accessible via this url: https://datadryad.org/stash/dataset/doi:10.25338/B81S5M

ABSTRACT
This study explores the potential to promote lower-emissions air travel by providing consumers with information about the carbon emissions of alternative flight choices in the context of online flight search and booking. We surveyed over 450 employees of the University of California, Davis, asking them to choose among hypothetical flight options for university-related business trips. Emissions estimates for flight alternatives were prominently displayed alongside cost, layovers and airport, and the lowest-emissions flight was labeled "Greenest Flight". We found an impressive rate of willingness to pay for lower-emissions flights: around $200/ton of CO2e saved, a magnitude higher than that seen in carbon offsets programs, and consistent with findings from a prior study with a non-university-based sample. In a second step of analysis, we estimated the carbon and cost impacts if the university were to adopt a flight-search interface that prioritizes carbon emissions information and displays alternatives from multiple regional airports in their employee travel-booking portal. We estimated potential annual savings of 79 tons of CO2e, while reducing airfare costs by $56,000, mainly due to an increased willingness of travelers to take advantage of cheaper nonstop (lower-emissions) flights from a more distant airport in the region over indirect flights from their preferred airport for medium-distance flights. Institutionalizing this strategy within organizations with large travel budgets could reduce personal and organizational carbon footprints. If implemented across major flight search engines, it could potentially reduce the demand for higher-emissions flights leading to an industry-wide impact on aviation emissions.

Keywords: Carbon Emissions, Air Travel, Flight Search, Interface Design, Online Travel Booking

INTRODUCTION

Air travel is estimated to contribute 2% of all human-induced carbon dioxide (CO_2) emissions and 12% of emissions from the transportation sector (*1*). These proportions are expected to grow (*2*). Per-passenger emissions for different flight itineraries with the same origin and destination can vary up to 200%, depending mainly on the number and location of connections and on aircraft type (*3*). Taking advantage of these potential savings is an appealing approach to air travel emissions reductions (*2*), and the focus of this project.

Specific and relevant information provided at the purchase decision point has been suggested as the most effective strategy to help consumers to make environmentally beneficial choices (*4*). Online flight search presents an excellent opportunity to promote lower-emissions flights at the point of purchase. Someone making an air travel purchase is already carefully examining a website that presents detailed information on possible itineraries, and choosing a flight based on a variety of factors (cost, layovers, airline, etc.). Displaying a CO_2e emissions estimate for each flight alongside these other attributes would allow the consumer to consider emissions among these other factors. CO_2e takes into account the environmental impact of all emitted greenhouse gasses in terms of the equivalent weight of CO_2 only.

Only one study (*5*) has examined this strategy, and the results were compelling. Participants were asked to choose among hypothetical flight alternatives that differed in price, carbon emissions, and number of layovers. The results indicated a willingness to pay (WTP) for lower-emissions flights at a rate of $192 per ton of CO_2e saved, a magnitude higher than most carbon offset prices.

In contrast, studies of air travelers' WTP for carbon offsets have arrived at values more comparable to typical carbon offset prices (e.g., see *6*-*8*). The purchase of carbon offsets to pay for activities that combat climate change is distinct from the strategy of integrating emissions information into online flight search which offers the opportunity to avoid some emissions entirely. Offsets are relatively inconvenient separate purchases (*7*), which might explain the low adoption rate: by one estimate, only 2% of travelers purchase carbon offsets for their flights (*6*). Integrating emissions information in flight search would enable users to simply purchase a lower-emissions flight. This greater convenience could result in a greater net impact.

If online travel agencies (e.g., Google Flights) adopted this practice, they could enable, and perhaps encourage, consumers to choose lower-emissions flights. Corporations and institutions could leverage these tools by requiring or encouraging employees to use them for booking flights for business travel, which accounts for 33-40% of global civil air travel (*9*). This research replicates and expands upon a prior study focused on flight choice among the general population (*5*). It features a choice experiment to demonstrate the potential for carbon-centric flight-search interface to promote lower-emissions flights for business travel among University of California, Davis, employees and estimates the net emissions and cost outcomes such a strategy could have for this particular institution, as a case study.

BACKGROUND

The idea of displaying emissions estimates during flight search was pioneered 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 changed the display of Expedia, Orbitz, Kayak, and a few other online travel sites, decorating their flight search displays with emissions estimates. When Brighter Planet went out of business neither the calculator nor the plug-ins were supported, so they no longer give correct results. Other similar efforts (e.g., Calasi and Glooby) seem to have met a similar fate.

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

We developed GreenFLY (greenfly.ucdavis.edu) as a demonstration flight search website to provide an example for flight-search companies who may want to incorporate or emphasize emissions information. GreenFLY leverages choice architecture strategies to nudge consumers toward lower-emissions flights. Choice architecture refers to ways a choice is presented that influence what a decision-maker chooses (*10*). Subtle features of a choice scenario can predictably influence behavior, for example, by increasing the salience of a particular choice attribute that might otherwise be overlooked (such as carbon emissions in flight choice).

GreenFLY highlights lowest emissions flight(s) with the label "Your GreenFLY" (**Figure 1**). This is an example of attribute parsimony, a strategy to increase salience by simplifying a choice attribute to enable easier interpretation. Translating highly quantitative information, especially in an unfamiliar domain, into simple categories (e.g., "greenest flight") enables quick affective reactions and a shortcut in cognitive processing, particularly for less numerate consumers (*11-12*). This kind of "attribute translation" into evaluative labels can also have a signpost effect, which activates otherwise dormant objectives, such as pro-environmental values, and directs the decision-maker toward the choice most aligned with those objectives (*13*).

FLIGHT CHOICE EXPERIMENT

This research focused on the University of California, Davis, as a case study for investigating the influence of a GreenFLY-like flight-search interface on emissions associated with business travel. The first part of this research was guided by the following primary question:

1. Are UC Davis employees willing to pay (i.e., allocate from funding sources) more to take a flight with lower emissions, and if so at what rate?

This issue is complicated 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 is:

2. What additional encouragement do emission reductions contribute to choosing a flight with fewer layovers?

Access to the airport is an important factor in flight choice. For employees residing within a typical commute range of Davis, the Sacramento International Airport (SMF) is the nearest airport. However, like many places in the country, Davis is in a multiairport region, served also by the larger San Francisco International Airport (SFO), about 85 miles to the Southeast, which offers nonstop flights to many destinations for which SMF only offers flights with layovers. Even accounting for emissions from ground transportation to and from SFO, a nonstop flight from SFO will typically be more efficient than an indirect flight from SMF. Thus, a third question was:

3. What additional encouragement do emission reductions contribute to choosing a roundtrip direct flight out of SFO over a flight with layovers out of SMF?

Methods

These three questions were addressed through a stated preference choice experiment, which was selected because it mirrors naturalistic flight choice scenarios: Flight alternatives that vary on a number of attributes (e.g., cost, layovers) are presented and the participant must choose one. The flight choice experiment involved an online survey in which UC Davis employees were asked to make a series of discrete choices between roundtrip flight alternatives that varied in terms of cost, carbon emissions, layovers (0 or 2: one layover each way), and airport (SMF or SFO), for hypothetical business trips.

Models were created for willingness to pay (WTP) for lower emissions, also taking into consideration airport choice and nonstop versus indirect options.

Using Historical Employee Travel Data to Create Realistic Trip Scenarios

The hypothetical scenarios (trip destinations and cost and carbon levels of flight alternatives) were based on actual UC Davis employee air travel data to increase the social and statistical validity of the choice models, first by making the scenarios realistic to participants, and second by building the models in the range in which they would be applied (rather than extrapolating to unsampled contexts). UC Davis Accounting and Financial Services (AFS) provided data for one complete year (2017) of UC Davis business travel booked through the university travel portal supplied by BCD Travel[1] (hereafter called the AFS History dataset). According to AFS, roughly 50% of reimbursed air travel is booked though the university portal, and thus represented in the AFS History dataset. The AFS History dataset includes 7,593 trips, both roundtrip and one-way, to over 300 different destinations. For each flight leg, data include origin and destination city and airport, airline and ticket class; and at the trip level: cost, distance, and emissions estimates.

The first task with these data was to identify common business trip destinations that represent a significant portion of total air travel emissions for UC Davis employee travel, to inform the hypothetical trip destinations in the choice experiment. We focused on roundtrip and one-way flights originating from SMF and SFO (65%), omitting one-way flights into SMF or SFO, flights from Oakland, and flights between two other cities. We divided the resulting flights into short (up to 1,400 miles roundtrip), medium (1,400 to 6,000 miles), and long trips (more than 6,000 miles). **Figure 2** shows the contributions of each group to total emissions. While there are many short trips, their impact on emissions is small. Medium-length trips, which includes all destinations in North America in this context, account for most of the emissions, and long trips have a disproportionately large impact given their low frequency. For this reason, we decided to include two hypothetical trip scenarios in our choice experiment: one medium-length (domestic) and one long (international) trip.

Ordered by total emissions for all trips to each destination city (regardless of specific airport), Washington, DC, and London were the most frequent domestic and international destinations. It was also important that each of these destinations were reasonably accessible from both SMF and SFO since we planned to study the choice of airport. The top 23 destinations departing from Sacramento (SMF) were all domestic, followed by London, while the top seven destinations departing from SFO were all international, followed by Washington, DC. Thus, although SMF is more popular among UCD employees for domestic flights, flights to London are not uncommon. Similarly, although international flights are most common out of SFO, flights to DC are not uncommon.

AFS data was also used to determine realistic cost and carbon levels for flight alternatives in the choice experiment. This was done by analyzing the distributions of cost and carbon emissions for employees' roundtrip flights to each of Washington, DC, and London in the AFS data. Cost and carbon variables in the AFS data are provided by the BCD Travel service. **Table 1** presents the central tendencies for trip cost (across all trips regardless of number of layovers) and carbon (separately for nonstop and layover flights) for each city.

TABLE 1 Distributions of Cost and Carbon Emissions for DC and London Flights in AFS History

Destination	Cost mean (*SD*)	Emissions, layover mean (*SD*)	Emissions, nonstop mean
Washington, DC	$502 (109)	2,127 lbs (204)	1,645 (negligible variation)
London	$1,135 (375)	4,084 lbs (165)	3,638 (negligible variation)

For layover flights to each destination, four carbon emissions levels were selected around (but not including) the mean, each separated by .5 standard deviation. For nonstop flights, the mean emissions for

[1] https://www.bcdtravel.com/

each destination was used as a single level of carbon emissions for all nonstop flight options to each respective destination. For layover flights to each destination, cost levels were selected around the mean to result in a distribution of levels from -1 standard deviation below the mean to .5 standard deviation above the mean, each separated by half a standard deviation. For nonstop flights, four cost levels were selected by increasing each of the four layover cost levels by .25 standard deviation. This helped ensure nonstop flights would be more expensive when paired with layover flights, to give respondents the opportunity to demonstrate WTP for nonstop. This also simulated realistic conditions since nonstop flights are typically more expensive than layover flights (from the same airport at least).

Experimental Design and Survey Instrument

With four cost levels, four carbon levels, two airport levels (SMF or SFO) and two layover levels (0 or 2: one layover each way), there were too many possible combinations to include and compare all possible flights in the choice experiment. Instead of randomly sampling from all possible attribute combinations, first a set of individual flight alternatives, and then pairings of two flight alternatives for the choice questions, were specified which would sample the part of the hypothesis space in which we expected our model to fall. In other words, we designed flight alternatives and question pairs to explore trade-offs between attributes, and to avoid questions for which the response was "obvious", based on assumptions that respondents will prefer nonstop to layover flights, cheaper to more expensive flights, and flights with lower emissions, and that most would prefer to use SMF.

Table 2 presents the eight cost-carbon level combinations that were used for the London layover flight alternatives. Each of the four cost and carbon levels were used twice, with no combination repeated, and generally combining the lower carbon levels with higher cost levels. The same eight cost-carbon combinations were used for London layover flight alternatives from both SMF and SFO (for 16 total London layover alternatives). Four London nonstop flight alternatives were created for each airport (eight total) by combining each of the four nonstop cost levels with the single nonstop emissions level. This resulted in a total of 24 possible flights to London. Using the same methods, we created 24 possible flights to Washington, DC.

TABLE 2 Eight Carbon*Cost Combinations for Hypothetical London Layover Flight Choices

	F1	F2	F3	F4	F5	F6	F7	F8
Carbon	4,331	4,331	4,167	4,167	4,002	4,002	3,837	3,837
Cost	$761	$948	$948	$1,322	$761	$1,135	$1,322	$1,135

We organized the flight alternatives into sets of two for the choice experiment questions, according to the following criteria:

1. Every flight alternative should appear the same number of times in the survey.
2. The distribution of flight choice pairs (e.g., layover out of SFO vs. layover out of SMF) should match the distribution of all possible pairs.
3. Avoid questions in which the two alternatives have the same cost or same carbon.
4. Focus on pairs that might have competitive utility (an alternative that is lower cost, lower carbon, nonstop and out of SMF is likely to be selected in almost all cases, so it is not as useful for understanding potential trade-offs).

With these criteria, a solution was created for organizing questions into seven "buckets" for each of the two destinations (14 total), representing different kinds of questions (**Table 3**). Each respondent was asked a randomly chosen question from each bucket. Due to a survey programming error, one DC flight bucket was omitted (at random) for each participant. Thus, each participant received six questions with DC flight choices and seven questions with London flight choices. This only resulted in a smaller sample size for each DC question, therefore had no significant impact on the overall results.

TABLE 3 Logic of Flight Choice Question "Buckets"

Bucket	Flight Alternative A	Flight Alternative B (relative to A)	No. of Items
1	SMF layover	SMF layover (lower carbon, higher cost)	8
2	SFO layover	SFO layover (lower carbon, higher cost)	8
3	SMF layover	SFO layover (mixed carbon and cost)	8
4	SFO layover	SMF layover (mixed carbon and cost)	8
5	SMF or SFO nonstop	Opposite airport layover (higher carbon, mostly lower cost)	8
6	SMF or SFO nonstop	Same airport layover (higher carbon, lower cost)	8
7	SMF nonstop	SFO nonstop (same carbon, mixed cost)	2

The choice experiment was conducted using an online questionnaire programmed in Qualtrics survey software. Questions about travel preferences (e.g., preferred airport, typical modes for accessing airports) were asked first to get participants thinking about business-related air travel and their experience with both SMF and SFO. Following these questions, a prompt to consider the DC trip scenario preceded the six questions for DC flight choices, and then a similar prompt followed by the seven London flight choice questions. The DC prompt read: "Imagine you are searching for a flight to Washington, DC for UCD business (perhaps a conference or training). The flight will be paid for from a University account[2]. You will be shown a series of flight alternatives, with different prices and levels of carbon emissions. Some depart from Sacramento and some from San Francisco, and some have layovers while others are non-stop. Each time, please pick the one you would choose if you were actually taking this trip." The flight choice questions were programmed with image files as the response options, to mimic the look of a flight-search interface, but with prominent information about emissions (**Figure 3**).

The end of the survey included some basic demographic questions (age, position at university, and frequency of work travel) and two questions about the utility of carbon emissions information in the flight-search context. The first was closed-ended: *Would you be interested in seeing more prominent carbon emissions information about flight alternatives when you search for flights? (Yes* or *No).* The second was open-ended: *How might seeing carbon emissions information affect your flight choices?*

Survey Recruitment and Participants

The survey was deployed from June-August 2019. We collected contact information for university department administration from university website searches, culminating in at least one email address for each of 90 departments. These contacts were emailed a request to forward a survey invitation to faculty, staff, post-docs, and graduate students in their departments. Participants had the option to enter their email address at the end of the survey to be entered in a raffle to win a $250 Amazon gift card.

The survey had a 92% completion rate; 488 people initiated and 447 completed it. Of these, 40% were grad students, 33% were faculty, 17% were staff, and were 9% post-docs (a few were undergraduate researchers). Participants ranged in age from 20 to 80; *M(SD)* = 38(13). Participants reported a range of recent air travel (in the past 12 months), with a mean of 2.3 work trips (*SD* = 2.6) and 2.8(2.3) other trips (more than 10 trips counted as 11 for mean calculations).

About one-third (31%) reported that they typically use the university portal (AggieTravel) to book their work-related air travel; Google Flights was also popular (21%). About 90% of participants reported that SMF was their preferred airport for business trips; 8% preferred SFO and 2% preferred

[2] Although the University is technically the payer of most employee travel, faculty and researcher travel typically comes from research budgets that they are motivated to manage frugally and other staff are often encouraged to try to keep costs low; this will be discussed further later; participants discussed their motivations and relevant contingencies in response to open-ended survey questions.

Oakland. Driving to the airport in one's own private car was the most common mode for both SMF (55%) and SFO (41%) access, however taxi/ride-hailing was also common for SMF (53%), and using rail (48%) and/or airport shuttle services (23%) was relatively common for SFO.

Results

Following the standard discrete choice model (*14*), a utility model per **Equation 1** was computed:

utility = a * carbon + b * cost + c * non-stop + d * airport (1)

"Utility" is a function that describes the desirability of a particular itinerary. "Carbon" is an estimate of CO2 equivalent emissions in pounds. "Nonstop" is equal to 1 for a nonstop flight and 0 for a flight with a layover. "Airport" is equal to 1 if the flight leaves from the traveler's preferred airport, and 0 if it leaves from the other airport.

The model was computed in R using the mlogit package, which is based on the assumption that the probability that a flight will be chosen from some set of alternatives is proportional to exp[utility(A)]; flights with greater utility are exponentially more likely to be chosen. Given the empirical probabilities with which one flight is chosen over another, the software "works backwards" to calculate the best coefficients using a maximum likelihood optimization procedure.

All models appear in **Table 4**. Separate models were created for the two trips because combining them in a single model would not make sense (if the traveler is going to London, the utility of a Washington flight is zero). A pair of models was computed with emissions as a factor and another excluding emissions, in order to compare the difference. Normalized versions of the models with all factors were also computed to give some idea of the relative importance of the different factors. The values in the table under each flight attribute (carbon, cost, nonstop, and airport) in the normalized model rows are coefficients that indicate the size, magnitude, and direction of their influence on flight choice.

TABLE 4 Willingness-to-pay Models

	Carbon	Cost (lbs)	Nonstop	Airport	WTP (per ton)	Log-likelihood	p-value carbon
DC	-0.0012	-0.013	1.54	1.60	$184	-1086	$3xe^{-9}$
London	-0.00064	-0.0051	1.76	1.33	$250	-1218	$7xe^{-3}$
DC no emissions		-0.010	1.87	1.48		-1104	
London no emissions		-0.0048	1.94	1.28		-1221	
DC normalized	-1.25	-4.56	1.54	1.60		-1086	$3xe^{-9}$
London normalized	-0.65	-1.79	1.76	1.33		-1218	$7xe^{-3}$

WTP is the willingness-to-pay to save one ton of CO2e (2000*Carbon/Cost). WTP for avoiding emissions is $184/ton for DC flights and $250/ton for London flights. The DC model predicts WTP $115 to avoid a layover and $123 for preferred airport, while the London model predicts $352 to avoid a layover, and $255 for preferred airport.

Similarities of the "nonstop" and "airport" coefficients indicate a near-tie between a flight from the preferred airport with a layover as opposed to a nonstop flight from the less desirable airport. For a flight to DC, the layover flight from the preferred airport is more desirable, but a savings of only $8, or of 87 lbs of carbon emissions, tips the balance the other way. That is, the emissions savings of a nonstop flight is sufficient to motivate travelers to use a less convenient airport.

For the trip to London, the nonstop is already the preferred option; according to the model, employees are willing to pay $97 more for a nonstop from their non-preferred airport over a layover flight from their preferred airport. According to the AFS history data, the real difference in emissions between a layover flight and a nonstop is about 450 lbs, for which the model predicts a $56 difference in WTP (at $0.125/lb of carbon for London). That is, when shown the emissions estimates, a traveler who likes to fly out of SMF will prefer a nonstop from SFO even if a layover flight from SMF is $97+$56 = $153 cheaper.

The coefficients in the normalized models illustrate the importance of nonstops to the London travelers, and the lower (but still significant) importance that they attach to emissions. This kind of estimate involves somewhat arbitrary rescaling, but it is interesting to give a rough comparison of coefficients.

Models that do not use carbon emissions as a predictor were computed to compare to the main models, indicating the difference in consumer choice when booking flights via an interface that emphasizes emissions compared to a standard one that does not. **Equation 2** measures how much including the emissions factor improves the model:

$$\text{Log-likelihood ratio} = 2(\text{EmissionsModelLog-likelihood} - \text{NoEmissionsLog-likelihood}) \quad (2)$$

For the DC models, this calculation is 2*(1104-1086) = 36. For adding one variable, standard tables indicate that a log-likelihood ratio of 7.85 or higher is at the 99.5% confidence level for stating that the factor in question adds to the model. The value of 36 in this case means the carbon emissions factor unequivocally adds to the model. For London, the ratio is 7.2, which is still significant but less so, likely due to the already strong preference for nonstop flights on long trips.

Participants' Direct Assessment of the Importance of Air Travel Emissions Information

A majority (75%) of participants said they would be interested in seeing emissions information during flight search and indicated it would have some impact on their choices, but few said it would be among the most important factors. Price, then layovers and airport, were most often cited as being more important. Many also mentioned the importance of trip timing (time of day and duration). The most common theme by far was that carbon emissions would be a consideration if other more important factors were comparable between options. For example, one participant remarked, "It's not the ultimate deciding factor for me, but it is useful when the other factors I take into consideration make two choices roughly equal. It's like calories on a menu, it's helpful to know when making your final decision."

Some participants mentioned the influence of employer as payer. There were two contrary camps. Much less prevalent of the two was the idea that price mattered less since the university was paying. In contrast, many reported that price is a primary concern particularly for business travel because of limited funding, i.e., obligation, need or requirement to take the cheapest flight due to shared and/or constrained budgets. Many participants suggested that changes in university policy could support their desire to take lower-emissions flights, e.g.: "Some departments do not have the luxury of a well-padded budget to select more expensive flights, even if that means lower CO2 emissions… If departments supported the purchase of flights that had lower CO2 emissions but were more expensive then I would definitely take that route (no pun intended!)."

Some comments indicated that simply highlighting the lowest-emissions flight will not be enough to sway some travelers to use a more distal airport because there is not enough information about net emissions including ground transportation, e.g.: "It would be helpful to know what the average carbon emissions are for ground travel…" A broader theme along these lines was that consumers need more contextual information to interpret, and trust, the emissions estimates and potential impact of choosing a flight with lower emissions, e.g.: "I don't fully understand the exact impact a flight with a few hundred less lbs of emissions has on the environment so it would be more meaningful if there was also more information."

Finally, there were several noteworthy comments that reflect deeper issues to consider, like conveying how consumers' collective choices could influence airlines, e.g.,: I don't really understand enough about the economics of this to really know if choosing a lower carbon flight actually stops the other flight from occurring."; "Carbon pricing schemes often price emissions between $10 and $100 / ton [so] the 'greenest' action would be to purchase the cheaper flight and donate the saved funds to a carbon mitigation effort."; "Airlines themselves should figure out how to cut back on carbon emissions."

MODELING INSTITUTIONAL IMPACTS

The potential net impacts for an institution adopting a GreenFLY-like flight-booking interface depend on the distribution of traveler destinations and the array of options from which travelers make their selections. To estimate potential emissions and cost impact for UC Davis, the WTP models were triangulated with AFS History data (to determine destination distribution) and another dataset created to represent the wider array of available flights for those destinations (Flight Options dataset).

Methods

The first step in creating the Flight Options dataset was to identify the most common destinations in the AFS History (including SMF and SFO departures). The top 70 destinations accounted for a majority (86%) of flights. A web-scraping script (with a tool called DataMiner[3]) was used in Google Flights to collect flight alternatives for each of these destinations, including the airline, price, duration, number of layovers, and the aircraft used on each flight leg. Roundtrip flights two months in the future were collected to get reasonable price estimates. The number of flight alternatives for different destinations ranged from 1 (SMF to Burbank) to 250 (SFO to Singapore). Flights more than twice the duration of the quickest flight, those with more than one layover each way, and a small number with insufficient aircraft information to estimate emissions were excluded.

A second web-scraping script was used to collect accurate carbon emissions estimates for each flight alternative leg from the website Atmosfair[4]. Atmosfair estimated per-passenger emissions based on flight leg origin, destination, airline, and aircraft. Their estimates take into account aircraft type, average age, engine type and use of winglets as a function of airline, and average occupancy and seating configuration.

In addition to these factors, some flight emissions calculators include a multiplicative radiative forcing index (RFI), a "fudge factor" that helps account for climate-altering emissions other than CO2, the fact that emissions take place in the upper atmosphere, and other factors, which can vary from 1.5 to 3. Atmosfair uses a factor of 3. Emissions estimates from Atmosfair were more than twice those given in the AFS History data (supplied by BCD Travel service), likely because they assume a larger RFI. In order to better match the university's accounting system, estimates from Atmosfair were scaled by 1.0478, converting from kilograms to pounds while simultaneously scaling the RFI down; that number is the ratio of the two estimates (AFS and Atmosfair) of emissions from SMF to DC.

We assumed SMF was the preferred airport when modeling the impacts. The DC WTP model was used for all domestic destinations and the London model for all international destinations. For each destination's set of flight options, the two appropriate models (with and without the emissions factor) were used to determine the highest utility flight option, and the probability that a traveler would choose SFO as the departure airport. The expected cost and emissions of the flight with the highest utility under each model was calculated for each destination, multiplied by the number of flights to that destination in 2017, and then compared to determine the net difference in cost and emissions.

Additional emissions and cost were estimated for ground travel from Davis to SFO for the estimated number of trips per year the models suggested would be shifted from SMF to SFO. About half of the survey respondents reported taking a personal car to SFO, and about half used shared van services or rail [Amtrak and Bay Area Rapid Transit (BART)]. Davis to SFO is 164.4 miles round-trip. Assuming

[3] https://dataminer.io/

[4] https://www.atmosfair.de/en/

35 miles-per-gallon (mpg) for single-occupancy car travel and $0.56 per-mile reimbursement (the 2021 General Services Administration Mileage Rate), the additional emissions would be 95 lbs CO2 [(164.4 miles / 35 mpg) * 20 lbs / gallon] and the additional cost would be $92 (164.4 miles * $0.56). Amtrak estimates 0.45 lbs of CO2 emitted per passenger-mile[5] and BART reports 0.11 lbs per passenger-mile. Round trip Davis-Richmond on Amtrak (where the passenger can pick up BART) is 116 miles (* 0.45 = 52 lbs of CO2) and round trip Richmond-SFO is 60 miles (* 0.11 = 6.6 lbs of CO2), for a total of 59 lbs CO2 per trip shifted to SFO via public transit. Median cost for the round trip on Amtrak and BART is about $72[6]. Assuming half driving and half taking public transportation, estimated additional emissions per trip shifted to SFO is the mean of 59 and 95, or 76 lbs; and estimated additional cost is $82, the mean of $72 and $92.

Results

Based on this analysis, UC Davis would save more than 79 tons of CO2e per year for this subset of flight destinations in terms of air travel footprint only, which equates to 3.8% of the annual 2,099 tons. Most of these savings are for medium-haul flights (**Figure 4**). There is less room for improving efficiency of short-haul flights, and long-haul flights are less common.

The models further predict that travelers will use SFO more often for nonstop flights if they see emissions values during flight search, particularly for medium-haul flights (**Figure 5**). Specifically, the models estimated that 317 more flights per year, to this subset of destinations, would be taken from SFO rather than SMF if travelers see emissions estimates during flight search. Fifty percent of medium-haul trips originate in SFO under the model where the traveler sees emissions, while only 39% do under the model in which the traveler does not. Many of these flights are on major airlines with nonstops available from SFO but not SMF. For long-haul trips, most flights originate in SFO under either model, while many of the short flights are inexpensive nonstops on Southwest from SMF. Taking into account the additional emissions of ground transportation for those 317 flights shifted from SMF to SFO, the annual net emissions savings is reduced to 72 tons [79 tons - (76 lbs CO2 per trip * 317 trips)].

Due to an increased willingness of travelers to take advantage of nonstop flight options out of SFO when incentivized with reduced emissions, which were also often cheaper than SMF options, the models estimated a net $56,000 reduction in annual airfare costs for UC Davis. That is, while employees are willing to pay more to avoid emissions, on the existing mix of travel destinations and available flight options, showing them emissions information while searching for flights would reduce, rather than increase, costs. Taking into account the additional cost of ground transportation for those 317 flights shifted from SMF to SFO, the annual net cost savings is reduced to about $30,000 [$56,000 - ($82 * 317 trips)].

DISCUSSION

UC Davis employees demonstrated a willingness to pay (WTP) for lower-emissions flights at a rate of $184 per ton for a domestic trip and $250 per ton for an international trip. This is an order of magnitude more than the typical carbon price used in offsetting schemes. It is also strikingly consistent with the findings of our prior similar study (*5*) despite many differences, including the addition of airport choice as a flight attribute, framing of CO2e in terms of pounds rather than kilograms, and a focus on business travel among a specific population rather than predominately personal travel among the general public.

Respondents indicated that contextual information (e.g., on the range and impacts of emissions) could help make the information more interpretable, trustworthy, and meaningful. Possible solutions for this, illustrated in GreenFLY, include showing the range of emissions for all possible flights and providing information about average transportation carbon footprint for reference. Another strategy is to translate flight emissions into meaningful equivalent metrics (*15*), such as trees required to absorb the

[5] https://www.ucsusa.org/sites/default/files/2019-10/greentravel_report.pdf

[6] https://www.rome2rio.com/s/San-Francisco/Davis

amount of carbon, or miles driven in a car with average fuel economy. However, even within the same comments, respondents both reported a WTP for lower-emissions flights and requested this kind of contextual information, indicating they are willing to pay more despite a lack of clarity. These findings suggest that WTP in this context may be mediated by emotional response to elements of the choice architecture (*16*) such as labelling the greenest flight and relative differences between flight alternatives more than by rational considerations. The much higher WTP when purchasing expensive international compared to domestic flights is further evidence of this. Future studies should also test the impact of labeling flights that use biofuels on consumer choice.

Implemented on a small scale, the GreenFLY strategy would not significantly increase demand for higher-emissions flights, so those flights would continue with different or perhaps fewer passengers, having a negligible impact. In contrast, carbon offsets should result in an actual emissions reduction. Furthermore, the one participant whose comments indicated familiarity with carbon offset pricing recognized that some of the flight alternative price differentials were more than what they might pay for corresponding offsets. This suggests another potential strategy, which is to incorporate carbon offset purchasing within the flight purchase process. Future research should compare this method with the GreenFLY method of including salient emissions information for flight alternatives. Experiments could further seek to determine the relative effectiveness, in different contexts, of including offset purchase as a default (i.e., opt-out), opt-in, or active choice during the flight purchase process (*17*).

A significant limitation of the WTP model is that our survey did not include some of the many factors important in flight search, such as airline, flight duration, and how well the itinerary fits the traveler's schedule (*18*). The influence of travel frequency could also be considered in future WTP models. Our findings regarding WTP for lower-emissions in conjunction with a less-preferred airport should not be generalized directly to other multiairport regions since the different travel times and transit options in other regions will influence the relative desirability of airport alternatives. There were also potential response biases, including that respondents were more concerned with emissions than recruited employees who did not participate, and that some respondents may have overreported their inclination to pay more for lower emissions.

The model has limited generalizability since university employees, on average, have higher income and education than the general population. However, we note again that WTP was remarkably consistent with our prior study with a general population sample. University employees may also be more price sensitive than other business travelers. Future studies should replicate this research with other types of business travelers, including private sector companies.

UC Davis would likely save 4% of total emissions from air travel booked on the UCD portal if a GreenFLY-like interface were adopted, and perhaps considerably more if institutional policy supported employee purchase of lower-emissions flights. The UC system had an overall goal of reducing transportation emissions by 20% from 2010 levels by 2020 (*19*). In this context, an easily achieved 4% savings is clearly worthwhile (3.4% when accounting for emissions associated with additional ground transportation). The modest emissions savings estimate was combined with an annual $56,000 reduction in airfare costs ($30,000 net savings after accounting for additional ground transportation), due to an increased willingness of travelers to take advantage of cheaper (often also nonstop) medium-distance flights out of a less preferred airport when incentivized with reduced emissions. These savings could be leveraged to fund an incentive or subsidy program.

Estimates of potential emissions savings and airfare costs are rough due to limitations of the survey-based models and the distribution of flights to which they were applied (only the most common destinations making up ~80% of air travel booked on the university portal). Long-haul flights make up a greater proportion of the remaining flights (to destinations with only 1-9 trips per year), thus were underrepresented in the analysis. Estimating emissions for these is complicated, but the potential carbon savings per trip are large.

CONCLUSIONS

At the individual level, highlighting emissions during flight search can have a significant effect on behavior, nudging consumers to choose lower-emissions flights. At an organizational level, this strategy could both reduce emissions and save money, especially where travelers have a choice of airports. This research demonstrated university employees' willingness to pay more for lower-emissions flights and suggested this tendency could be strengthened further by supportive university policies. Businesses are increasingly choosing to offset their corporate air travel; steering their employees to choose lower-emissions flights in cases where those flights also tend to be cheaper could reduce company costs. However, the net carbon and cost impacts of this strategy could vary substantially for different organizations depending on the typical employee travel portfolio in terms of costs and emissions of reasonable flight alternatives.

Large organizations with sustainability goals and internal flight-search portals could adopt the GreenFLY approach with minimal effort. These could be the settings for future field experiments to track actual flight purchase decisions in response to flight-search interfaces with versus without emissions information. On a larger scale, the remarkable willingness-to-pay of travelers to avoid emissions might allow air carriers to charge more for fuel-efficient flights, making it possible to invest in more efficient aircraft and biofuels more quickly. Rather than paying more, travelers might be willing to fly at less convenient times, or (as we have shown) from less convenient airports, opening up opportunities to change flight schedules to reduce emissions and improve ground transportation options to access hub airports in multiairport regions.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: N. Amenta, A. Sanguinetti; data collection: A. Sanguinetti; data analysis: N. Amenta; interpretation of results: N. Amenta, A. Sanguinetti; draft manuscript preparation: A. Sanguinetti. All authors reviewed the results and approved the final version of the manuscript.

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Figure Captions

(figure files uploaded separately; included here for reference)

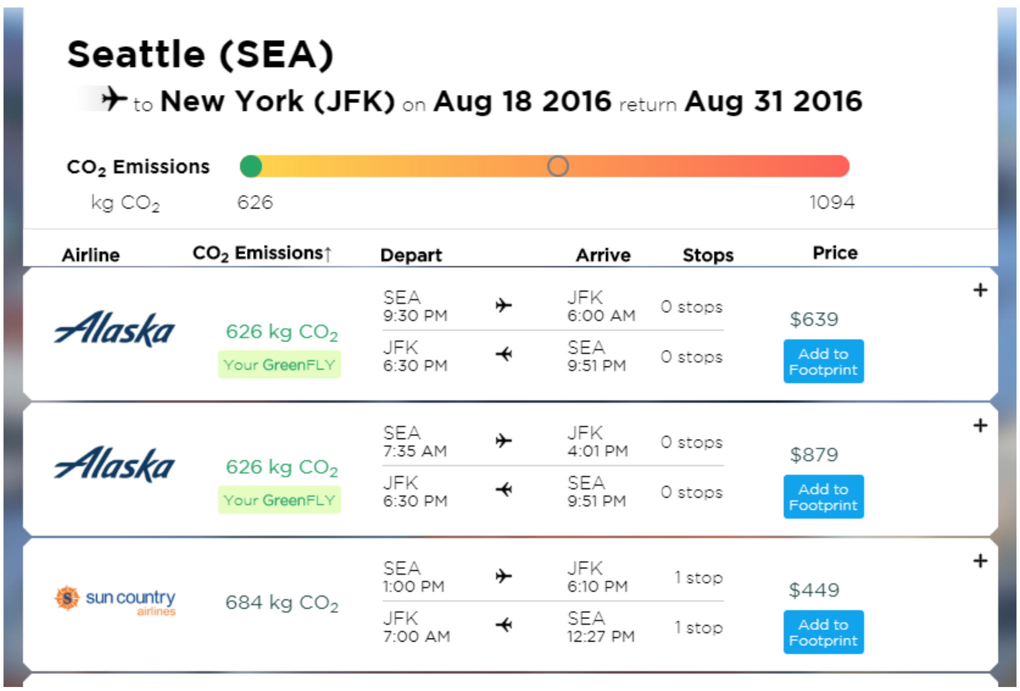

Figure 1 GreenFLY flight search results

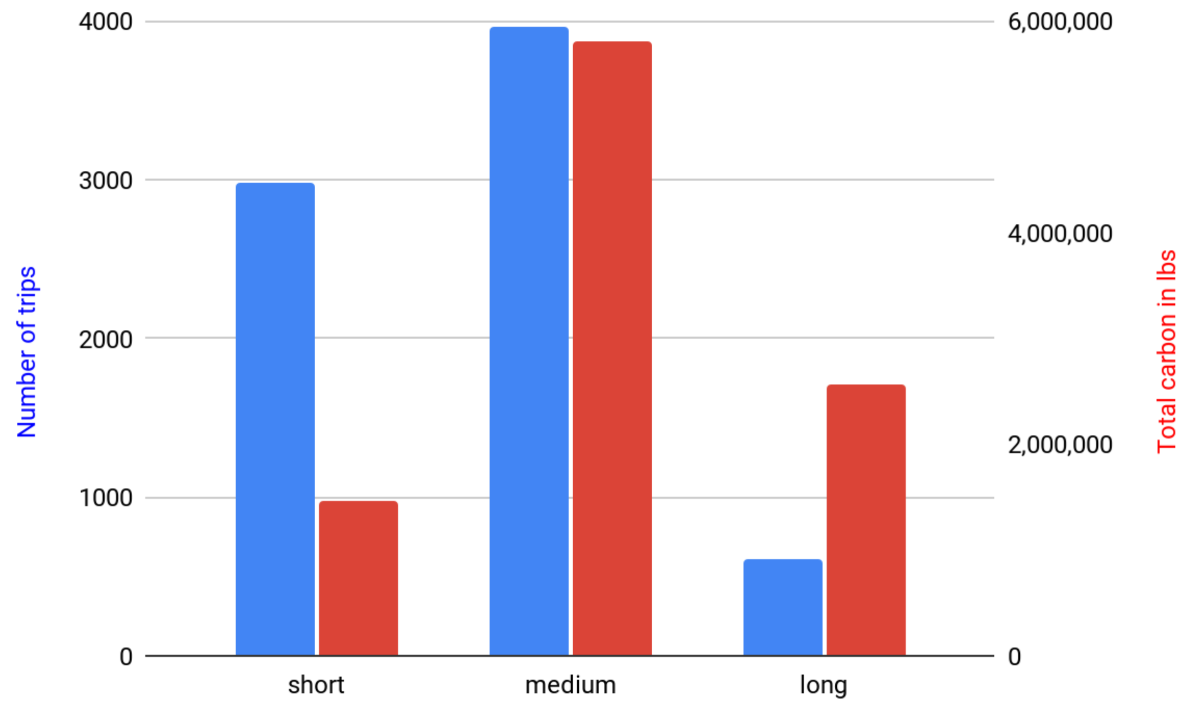

Figure 2 AFS History trip summary by distance, frequency and total carbon impact (lbs)

Figure 3 Example of flight choices, with prompt: "Which flight would you choose?"

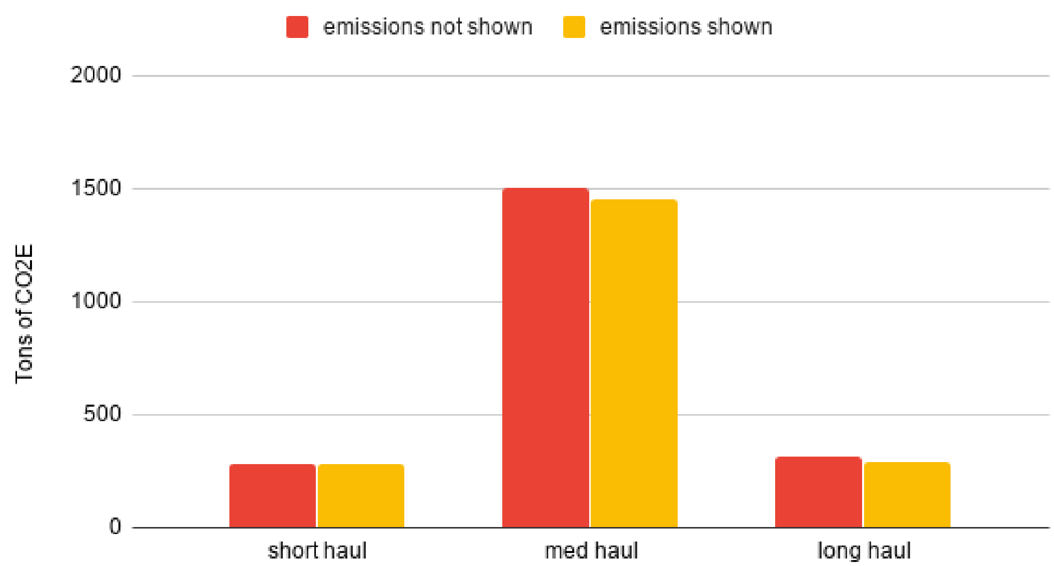

Figure 4 Estimated net emissions savings for UC Davis by flight length (excluding ground transportation)

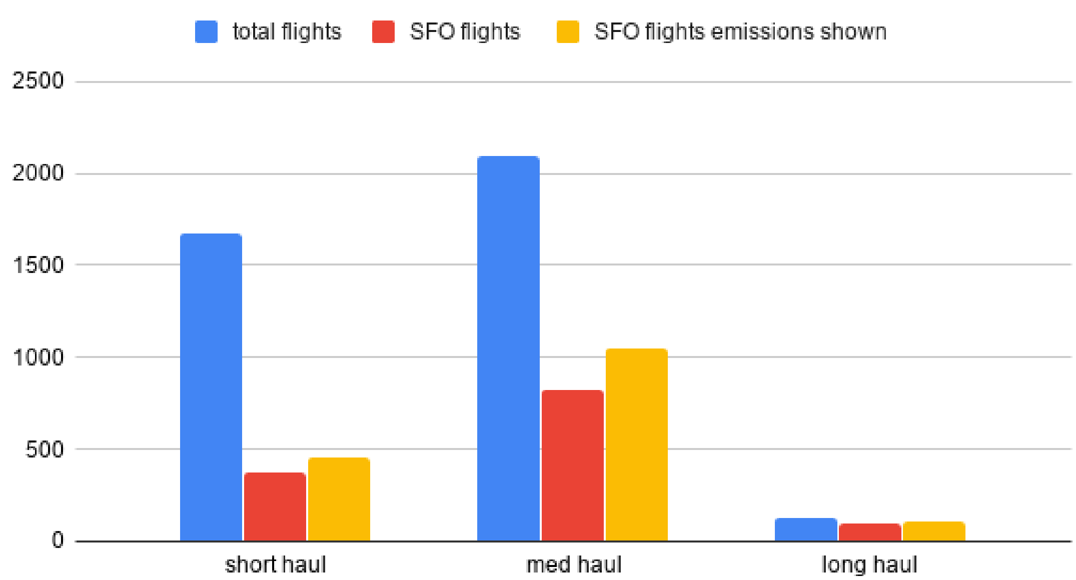

Figure 5 Number of SFO flights relative to all flights under each WTP model (with and without emissions)