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How zero-emission flights might redefine travel behavior

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ABSTRACT

As claimed by the aviation industry, sustainable aviation fuels offer significant environmental benefits, yet their impact on travel behavior remains underexplored. The current study investigates potential shifts in travel behavior in response to the introduction of zero-emission flights. A stated choice experiment using a sample from the UK general public evaluates preferences for flights, trains, and cars based on travel time, cost, and carbon emissions. Covariates, such as attitudes towards zero-emission flights, flight-shaming norms, and sociodemographic factors, are incorporated into a latent class choice model. Results reveal heterogeneity in zero-emission flight preferences, with subgroups showing high sensitivity to travel cost and distance. Overall, travel choices remain stable even with longer zero-emission flight durations, highlighting ticket price as a primary concern. A group with less sustainable choices, characterized by unfavorable attitudes and flight shame norms, leans towards cars if zero-emission flights are costly for short-haul journeys. Notably, this subgroup with limited preference for zero-emission flights, predominantly male and high-income, shifts strongly to zero-emission flights for long-haul journeys, displaying the lowest price sensitivity.

1. Introduction

Air travel is a significant contributor to greenhouse gas emissions, not only CO_2 but also extensive non-CO_2 emissions (Lee et al., 2021; Ge et al., 2022; Chen et al., 2024a, 2024b; Zhao et al., 2024; Wang et al., 2024), which contributes to global warming and climate change (Sky views, 2023; Klöwer et al., 2021). The aviation industry has been experiencing rapid growth, and if left unchecked, it can outpace emissions reduction efforts in other sectors, making it challenging to achieve climate goals. In 2019, there was a total demand for aviation of approximately 11.1 trillion passenger kilometers equivalents, of which 78% were passenger flights and 22% were freight flights (Bergero et al., 2023). There have already been increasing concerns about the environmental impact of air travel, and various policies and initiatives are proposed to encourage more climate-friendly behavior.

Governments and organizations have implemented some policies to address the environmental impact of flying. Carbon offsetting during flights and promoting and investing in alternative modes of travel, such as trains, for shorter distances have been among the main implemented policies around the globe so far (Sky views, 2023; ICAO, 2019). We acknowledge that the climate impact of aviation is significantly influenced by non-CO_2 emissions. However, among various emissions, CO_2 is the most prominently highlighted in public debates and policies. Laypeople are generally more familiar with concepts like CO_2 emissions, carbon emissions, and carbon footprints, while other types of emissions receive less attention.

The use of trains is particularly recommended by climate activists as an alternative to short-haul flights. An illustrative case in point is France, where they are enforcing a ban on domestic short-haul flights if the equivalent train journey can be completed in under two and a half hours (Sky Views, 2023). Meanwhile, environmental activists have been vocal about the negative impacts of flying on the climate and have advocated for reducing air travel whenever possible. Flight shaming, for example, is a social movement and concept that emerged to address the environmental impact of air travel (Korkea-Aho, 2019). The basic idea behind flight shaming is to raise awareness about the carbon footprint associated with air travel and encourage individuals to consider alternative, more sustainable transport modes.

Consequently, several people may have been affected by climate activists' messages and tried to adopt their behavior and switch to rail instead of air travel these days (Korkea-Aho, 2019). But, considering such behavioral change campaigns, what might happen if airlines

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introduce zero-emission airplanes? The potential adoption of zero-emission flights presents intriguing questions: what might travel behavior look like with the emergence of zero-emission flights both for short-haul flights and long-haul flights? What would be people's travel mode choices? How would attitudes and different mode-specific attributes influence such choices? Will those who have already changed their travel habits to support the environment continue to choose zero-emission flights, or are there other factors that might come into play in this rapidly changing landscape? Considering different travel time and cost scenarios for zero-emission flights, what effects do they have on the choice of flights? We aim to address these questions by employing a stated choice experiment data among a sample of people living in the United Kingdom. It is important to acknowledge that achieving absolute zero emissions in aviation is not feasible. This is simply because the build-up and operations of the infrastructure of airports will always create some emissions. Similarly, the production processes involved in manufacturing aircraft and batteries (e.g., for electric aircraft) also contribute to emissions. However, this study assumes that airlines would be inclined to adopt the term "zero-emission flights" in the market. We are also focusing on the emissions just for the "use" phase (so just for the flight itself), not those coming from the whole lifecycle of the plane. This aligns with the objectives set forth by organizations such as EASA (European Union Aviation Safety Agency) or another recent study (Sacchi et al., 2023). Nevertheless, in this study, we designed our experiment to offer participants a more realistic scenario. Carbon emissions were estimated to be less than 2 kg per person for 500 km zero-emission flights and less than 4 kg per person for 1500 km zero-emission flights.

The introduction and widespread adoption of zero-emission flights could have significant positive implications for the environment—assuming they prove to be truly efficient. Of note, zero emission concept is a claim made by the aviation industry, not one grounded in scientific evidence. As authors, our intent is to adopt a neutral stance, avoiding both overly optimistic and overly pessimistic views toward this technology-oriented solution. This zero-emission concept could potentially lead to a change in attitudes towards flights among lay people and climate activists. Bergero et al. (2023) found that, alongside ambitious reductions in air transport demand, enhancements in aircraft energy efficiency through sustainable aviation fuel could potentially avert up to 61% of the forecasted business-as-usual aviation emissions in 2050. In October 2021, the members of the International Air Transport Association (IATA) made a commitment to become net zero by 2050 (IATA, 2021). Sustainable aviation fuel accounts for 65% of this strategy (IATA, 2021). Zero-emission flights may produce nearly zero direct carbon emissions during operation. They rely on electric motors powered by batteries or other clean energy sources. This would significantly lower the greenhouse gas emissions associated with air travel, helping to mitigate climate change. Zero-emission airplanes tend to be quieter than their conventional counterparts, which would reduce noise pollution in and around airports and flight paths, leading to potential improvements in the quality of life for nearby communities. Environmental activists are likely to support the adoption of (true) zero-emission flights and other sustainable aviation technologies. As claimed by many aircraft manufacturers (e.g., Boeing, 2021; Airbus, 2020), this could be seen as a step in the right direction toward reducing the aviation industry's overall impact on the climate and the environment. However, we acknowledge the fact that the true environmental impact of zero-emission flights has not been scientifically verified and appears to be largely driven by aviation industry propaganda (Peeters et al., 2016; Gössling and Humpe, 2024). Activists may continue to advocate for ongoing improvements, such as increased battery efficiency, recycling programs for batteries, and expanding the use of renewable energy for charging airplanes.

As zero-emission aviation technology develops, several factors may play crucial roles in determining travelers' mode choice decisions for short and long-haul flights. First, the perceived environmental benefits of zero-emission flights may appeal to individuals who have already demonstrated a concern for the planet by shifting from air travel to more sustainable options. On the other hand, some may have shaped their travel habits with some specific modes. Accordingly, both attitudes towards the environmental benefits of zero-emission flights and past long-distance travel habits may influence mode choices. Additionally, it has been shown that satisfaction with a particular travel mode can be related to the choice behavior of that mode in the future as well (De Vos, 2019). Second, flight shame attitudes and norms around this movement can also affect travelers' decisions to opt for zero-emission flights or not. Third, the range and efficiency of zero-emission airplanes will be vital in attracting travelers, as long-distance flights without frequent recharging stops will be favored as well and zero-emission airplanes may fly slower than conventional ones. In other words, travel time/speed is a factor that can influence travelers' decisions. Additionally, ticket prices will also be a significant consideration, as cost remains a decisive factor for many travelers. There is a likelihood that zero-emission flights could initially incur higher costs, given that net-zero emissions fuels may be significantly more expensive than the conventional fossil fuels currently utilized in standard flights. Additionally, other modes of transportation, such as trains and cars, may still be preferable for shorter distances and where feasible alternatives to flying exist. Therefore, there is a need for a deep investigation of choice decisions for long-distance travel considering zero-emission flights, trains, and cars with different travel times, travel costs, and CO_2 emission rates as well as considering the relative roles of attitudes, social norms, habits, and satisfaction. We develop a stated choice experiment using three design attributes namely travel time, travel cost, and rate of CO_2 emission for choosing between zero-emission flights, train, and car for 500 km and 1500 km leisure trips. We also test the relative roles of other predictors on such choices.

The main objective of the study is to investigate potential shifts in travel behavior in response to the introduction of zero-emission flights. We examine how zero-emission flights with varying travel times and costs, along with other covariates, can compete with train and car use for both short- and long-haul journeys.

2. A review of the literature background

From the state of the art in this field, it is evident that there is relatively little knowledge in this area. Rains et al. (2017) discovered that customers express a willingness to pay a 13% price premium for biofuels commercial air travel. Goding et al. (2018) estimated a price premium of 11.9% relative to the base ticket price. In one of the very few studies available, Rice et al. (2020) examined the perspectives of a convenience sample of participants immersed in a hypothetical scenario involving commercial air travel. The scenario aimed to achieve a reduction in greenhouse gases ranging from 10% to 50%, presented in 10% increments. Participants were then probed about their willingness to pay for corresponding ticket price increases of 5%, 10%, or 15% linked to each reduction increment. The findings indicated a general trend: a more substantial reduction in greenhouse gases aligned with an increased willingness to pay the supplementary ticket price. However, this inclination was tempered under the 15% ticket price condition, especially in the context of long-haul flights. Interestingly, women demonstrated a greater inclination to pay the additional ticket price compared to men, and this tendency was more conspicuous for shorter domestic flights as opposed to long-haul journeys. The cited study concluded that airlines might anticipate consumers being agreeable to a slight uptick in ticket prices if passengers are persuaded that the aircraft emits fewer greenhouse gases. In another study, Xu et al. (2022) identified three significant factors that elucidate air travelers' willingness to pay for cleaner flights: social trust, perceived risks, and attitude. Despite an overall positive perception of the benefits associated with sustainable aviation fuel, the study revealed a low level of awareness regarding its usage. Notably, while respondents exhibited a favorable attitude toward sustainable aviation fuel, the majority expressed reluctance to pay a premium for carbon-neutral air travel. In a very recent study by Veisten et al. (2024), preferences for electric flights were examined in comparison to conventional flights on a short route between two Norwegian cities, Bergen and Stavanger, using multiple contingent valuation items. The findings indicate that a majority favors electric flight, with some individuals willing to pay a premium. However, a significant portion remains hesitant and would need a discount to consider this option. Veisten et al. (2024) acknowledged the use of a simple stated-preference methodology and suggested that future research enhancements could involve a discrete-choice experiment incorporating a wider range of varied attributes.

Upon closer look at existing studies, it becomes apparent that there is limited understanding of individuals' mode choice behavior following the introduction of zero-emission flights. Notably, there is a dearth of research exploring varied choices in the context of diverse travel time, cost, and carbon emission scenarios. Additionally, there is a lack of investigation into the relative significance of factors such as attitudes towards zero-emission flights, travel habits, satisfaction levels, and adherence to flight shaming norms. Furthermore, none of the existing studies have engaged in estimating mode choice behavior, incorporating zero-emission flights alongside trains and cars, through a stated choice experiment. This gap in the literature underscores the need for comprehensive research that addresses the intricacies of individuals' decision-making processes in the era of zero-emission flights, encompassing factors such as attitudes, habits, satisfaction, societal norms, and the economic value assigned to environmentally friendly air travel.

3. Research focus and conceptualization

As explained in the introduction, this study focuses on the question of whether the presence of zero-emission flights induces people to choose airplanes compared to trains and cars for long-distance travel including short-haul flights (i.e., 500 km) and longer trips, i., e, 1500 km. With increasing distance, the probability increases that people choose to fly, because travel time by car or train may be considered too long for a relatively short holiday. However, due to technical and charging (battery) issues, travel speed/time and cost with zero-emission flights might also increase in some scenarios even though the CO_2 emissions of such flights may be significantly lower than trains and cars.

For specific origin-destinations with 500 km (London-Amsterdam) and 1500 km (London-Barcelona) travel distances, the attributes of travel time, cost, and emitted CO_2 with train, car, and conventional flight will first be calculated and the choice between these options will be recorded. Next, nine choice scenarios incorporating zero-emission flights (instead of conventional flights) with different travel times, costs, and specific CO_2 rates along with cars and trains with their fixed (calculated) attributes will be offered to people to evaluate mode choice both in 500 km and 1500 km leisure travel.

According to the random utility theory, we assume that people choose the mode alternatives from which they derive the highest utility. Fig. 1 shows which (groups of) variables we take into account as explanatory variables that affect this utility. To better capture heterogeneity among individuals a latent class choice model will be tested.

First, travel mode use habits with different alternatives are hypothesized to influence the choice. It has been shown that past travel habits can influence mode choice (Gärling and Axhausen, 2003). Second, the level of past travel satisfaction with every mode is also hypothesized to be associated with mode choice after introducing zero-emission flights. It has been found that satisfaction with a particular transport mode can have a positive impact on subsequent preferences for the same mode (Mokhtarian et al., 2015).

Third, we consider the impact of both environmental attitudes and flight shame. The attitude-behavior relationship has been well documented in the travel behavior context (Kroesen et al., 2017; Kroesen and Chorus, 2020; Molin et al., 2016). In this line, we hypothesize that the favorable attitudes towards zero-emission flights positively influence the choice for this alternative (with less CO_2 emission). We also assume that people who are affected by flight-shaming movements may (or may not) opt for zero-emission flights in some scenarios. As individuals within social networks express heightened concerns about carbon footprints, there might be a normative shift discouraging excessive air travel. This change, propelled by peer influence and a collective consciousness, reflects a broader cultural move towards eco-conscious living. Flight shame is not just a personal sentiment; it is becoming a societal force influencing how we perceive and engage with air travel, emphasizing the alignment between personal choices and environmental responsibility (Cats et al., 2022). We also estimate the role of travel time, cost, and carbon emission on such choices by including them directly in the stated choice experiment. Additionally, we take demographic and socioeconomic variables into account. Regarding demographic and socioeconomic variables, we do not hold specific expectations about the direction of their effects. However, it is well-established that these characteristics generally influence preferences related to mode choice behavior.

4. Method

This section describes the stated choice experiment, details the study sample, explains the measurement and operationalization of variables, and presents the modeling framework.

4.1. The stated choice experiment

In the stated choice (SC) experiment we examine the trade-off travelers make between flying with a zero-emission airplane or traveling by train or car to a relatively distant city (here we calculated attribute levels based on the trip from London to Barcelona which is around 1500 km) and the same trade-off for a trip to a city nearby (we calculated trip attribute levels from London to Amsterdam which is about 500 km). Although we calculated trip attribute levels for London to Barcelona and London to Amsterdam for a trip with 500 and 1500 km distances, respectively, we did not use the names of these origins and destinations in the experiment and survey. In this experiment, we explored which travel mode participants would choose for a long-distance leisure trip to "a city" that is 500 km and 1500 km distant from their residence. Therefore, we used these examples for a better and more precise design of the experiment and did not exemplify them in the experiment for the participants (see Figs. 2 and 3).

Throughout the survey, we attempted to provide some information regarding zero-emission flights that may be introduced by airlines in the future, including how they may operate and how they could reduce carbon emissions. Buses operating over long distances are not considered in the experiment. Even though long-distance bus connections are becoming available between cities in Europe these days, the study area has little tradition of using long-distance buses due to its generally well-functioning railway network. It is still a niche market for long-distance buses, and most travelers will not consider buses for taking a long-distance trip even if the market for buses is growing.

To prepare for the stated choice questions, respondents were asked to select conventional flights, trains, and cars for two distances of 500 km and 1500 km with calculated values (levels) for travel time, travel cost, and CO_2. For the trips from London to Amsterdam (500 km) and London to Barcelona (1500 km), these attribute levels were calculated based on information provided by flight and train ticket websites, an emission calculator website,[1] as well as Google in September 2023.

As for the attributes of travel in the choice experiment, given the earlier discussed objective of this research, only attributes of zero-

[1] https://www.engineeringtoolbox.com/driving-distances-d_1029.html The Engineering Tools website allows users to calculate carbon emissions per person for different travel modes by entering the trip distance or specifying the origin and destination.

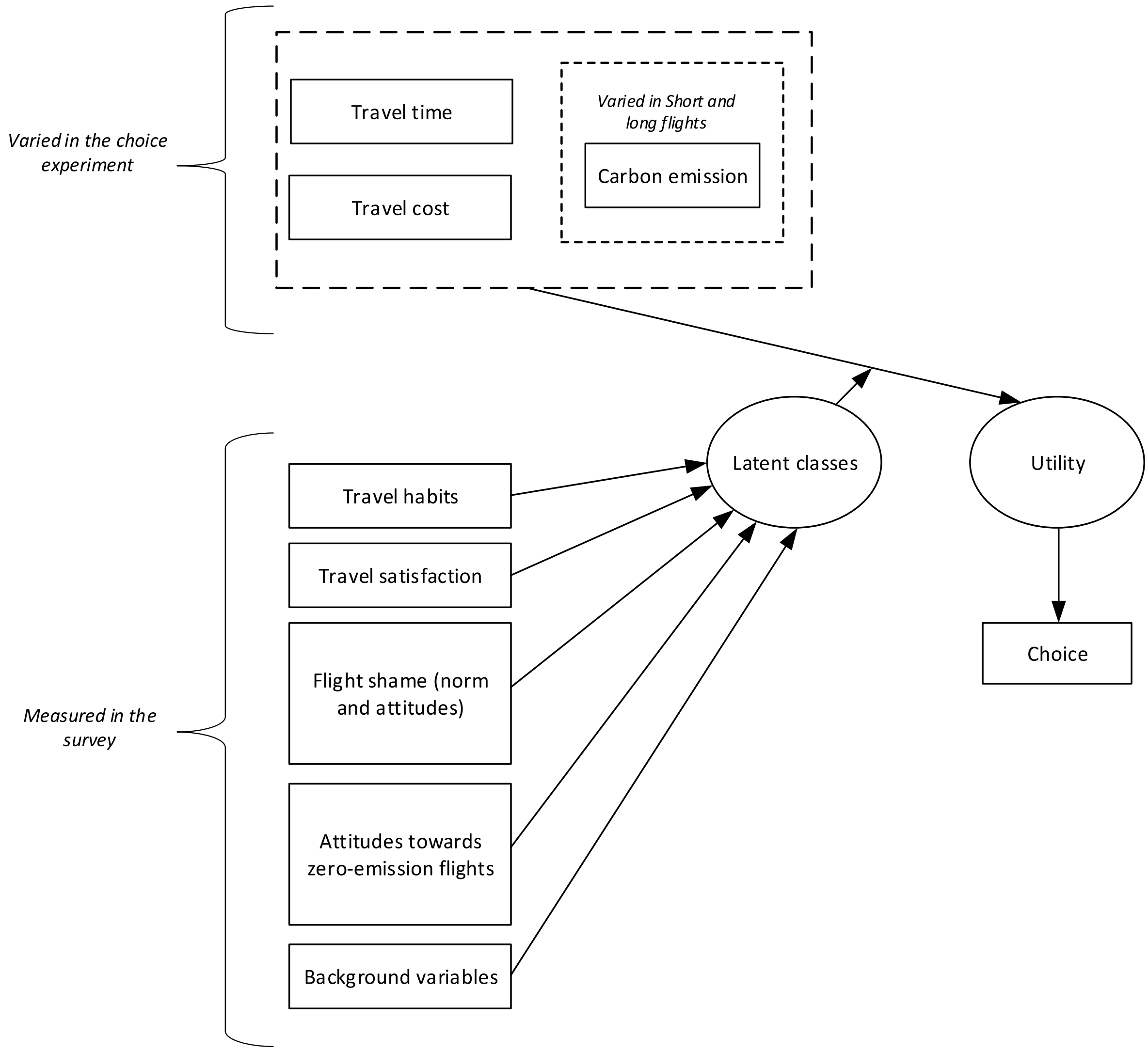

Fig. 1. The modeling framework.

emission flights are varied. The travel time and cost attributes are both varied at three levels, while the CO_2 emission rate is fixed. One may argue that, to understand the value of trade-offs, there should be no particular options that are consistently dominant or consistently less attractive than others. However, we used fixed (true) values for car and train. These fixed values reflect the more stable and predictable nature of these modes over a specified distance, where factors such as time and cost remain relatively consistent. This contrasts with the zero-emission flight option, whose varying attributes across scenarios allow for a more dynamic exploration of consumer responses to a new and fluctuating mode of transport. The assumption is that these fixed values serve as consistent benchmarks against which the varying zero-emission flight option is compared, revealing the threshold at which this new technology can compete.

Considering the 500 km scenario, the travel time by zero-emission flight is 2.45, 3.30, and 4.15 h, while the travel cost is £47, £79, and £111. It was assumed that the CO_2 emissions from zero-emission flights would be less than 2 kg/person in all scenarios of 500 km. Using an orthogonal fractional factorial design, nine scenarios are generated. A choice set of three alternatives is constructed for each of these scenarios by adding two base alternatives, namely car and train. Accordingly, the base alternatives car and train are described by their fixed attribute levels. As shown in Fig. 2, an example choice set scenario for 500 km can be seen. For the 500 km trip (London to Amsterdam), the attribute values (levels) of the train and car are evident in this figure, which are fixed (the same) in all nine scenarios. Even though achieving complete carbon neutrality in aviation is a complex process, this study assumed that airlines would adopt the term "zero-emission flights." The experiment, however, was designed to provide participants with a more realistic scenario in which carbon emissions were estimated to be less than 2 kg per person and less than 4 kg per person for 500 km and 1500 km flights, respectively. These values are not truly zero but are close enough to approximate zero emissions for our participants without misleading them about the concept. This approach allows us to balance the optimistic messaging from airlines about "zero-emission" flights with the practical reality that such flights may still emit small amounts of CO_2. By using 2 and 4 kg/person as proxies, we aim to reflect industry claims while maintaining a grounded perspective on the emissions associated with these flights.

For the 1500 km trip, the same design approach was used. The levels for travel time by zero-emission flight are 3.45, 4.30, and 5.15 h, whereas the levels for travel cost attribute are £79, £198, and £317. For all nine scenarios of the 1500 km trip, the CO_2 emissions from zero-emission flights were assumed to be less than 4 kg/person. An example of the 1500 km choice set scenario is shown in Fig. 3. Different mode choice scenarios including base or current situation (i.e., conventional flights, train, and car) and nine stated choices in the experiment are described in detail in Appendix A (Table A.1 for short distances

Based on the following trip characteristics, which transport option would you choose for a long-distance travel with leisure purpose to a city which is **500** km far from your residential place? (Please note that travel duration by airplane includes 1.30 hours of additional time prior to the flight departure)

Options	**Travel cost**	**Travel time**	**CO_2 emission**
Conventional flight	£ 47	2.45 hours	73.5 kg/person
Train	£ 55	4.40 hours	13 kg/person
Car	£ 106	7.30 hours	83.9 kg/person

S8_Q00 Your choice (choose only one): [Conventional flight; Train; Car]

Now, consider if zero-emission flights with the following scenarios will be provided by the airlines in the future instead of conventional flights, which transport option do you choose for the same long-distance travel with the leisure purpose to the same city which is **500** km far from your residential place? Please note that zero-emission flights run on clean energy like electricity or hydrogen, making air travel less polluting.

Scenario X:
Consider the following zero-emission flight:

Travel costs	£ 79 (a bit more expensive than the conventional flight)
Travel time	4.15 hours (longer than the conventional flight)
$C0_2$ emission	Less than 2 kg/person

Accordingly, your updated choice list is as follows:

Options	**Travel cost**	**Travel time**	**CO_2 emission**
Zero-emission flight	£ 79	4.15 hours	Less than 2 kg/person
Train	£ 55	4.40 hours	13 kg/person
Car	£ 106	7.30 hours	83.9 kg/person

S8_Q06 Which choice would you make for this trip in this situation? [Zero-emission flight; Train; Car]

Fig. 2. A scenario for the 500 km trip in the stated choice experiment.

(500 km) and Table A.2 for long distances (1500 km)).

4.2. Sample

The survey was conducted online through the Prolific platform, targeting individuals residing in the United Kingdom (UK). More detail, Prolific has been chosen as the research subject pool due to its reported high data quality and transparency (Palan and Schitter, 2018), as demonstrated by a previous study (Kong et al., 2020). A random sampling approach, incorporating quotas for, gender, age, education level, and car accessibility, was employed to ensure the recruitment of a relatively representative sample. Data collection took place in November and December 2023.

Conducted as a stated choice experiment featuring nine scenarios, the study engaged a total of 309 participants. Specifically, 154 participants were assigned to scenarios involving a 500 km distance, and 155 individuals participated in scenarios covering a 1500 km distance. This results in a dataset comprising 2781 observations (309 participants multiplied by 9 scenarios), providing a substantively adequate foundation for the choice modeling objectives. For additional information on sample size and essential sociodemographic characteristics, please refer to Table 1, where the corresponding information for the UK population can also be found.

As can be seen, the sample is well-balanced across gender, education levels, and access to car and electric vehicles, demonstrating a reasonable level of representativeness. In terms of age distribution, there is a slight discrepancy between the sample data and the population data, with two age ranges 18–25 years and 45–65 years being characterized by similar percentages. This can be attributed to the limited accessibility to online tools for senior people (65+). Also, according to the UK household statistics,[2] about 20% of UK's population has a household income between £10,000 and £19,999, while this study's data reports almost 7%. However, the other income groups are characterized by relatively similar percentages between this study's data and the UK population data.

4.3. The measures and operationalization of other variables

Travel mode use habits with four conventional modes, car (as a driver or passenger), train, airplane, and bus, for long-distance travel,

[2] https://www.ethnicity-facts-figures.service.gov.uk/work-pay-and-benefits/pay-and-income/household-income/latest/#:~:text=2021%2C%20on%20average%3A-,45%25%20of%20households%20in%20the%20UK%20had%20a%20weekly%20income,of%20less%20than%20%C2%A3600.

Based on the following trip characteristics, which transport option would you choose for a long-distance travel with leisure purpose to a city which is **1500** km far from your residential place? (Please note that travel duration by airplane includes 1.30 hours of additional time prior to the flight departure)

Options	**Travel cost**	**Travel time**	**CO_2 emission**
Conventional flight	£ 79	3.45 hours	131 kg/person
Train	£ 79	12 hours	38 kg/person
Car	£ 247	14.50 hours	251.8 kg/person

S8_Q00 Your choice (choose only one): [Conventional flight; Train; Car]

Now, consider if zero-emission flights with the following scenarios will be provided by the airlines in the future instead of conventional flights, which transport option do you choose for the same long-distance travel with the leisure purpose to the same city which is **1500** km far from your residential place? Please note that zero-emission flights run on clean energy like electricity or hydrogen, making air travel less polluting.

Scenario X:
Consider the following zero-emission flight:

Travel costs	£ 198 (more expensive than the conventional flight)
Travel time	5.15 hours (longer than the conventional flight)
C0$_2$ emission	Less than 4 kg/person

Accordingly, your updated choice list is as follows:

Options	**Travel cost**	**Travel time**	**CO_2 emission**
Zero-emission flight	£ 198	5.15 hours	Less than 4 kg/person
Train	£ 79	12 hours	38 kg/person
Car	£ 247	14.50 hours	251.8 kg/person

S8_Q06 Which choice would you make for this trip in this situation? [Zero-emission flight; Train; Car]

Fig. 3. A scenario for the 1500 km trip in the stated choice experiment.

Table 1
Sample distributions (N = 309).

Characteristic	Category	Sample (%)	The UK population (%)
Gender	Male	48.5	49
	Female	51.5	51
Age (in years)	18–25	9.1	11.1
	25–45	47.2	32.5
	45–65	33.7	33.7
	65 +	10.0	22.7
Level of Education	Primary school	0.9	0.1
	High school	33.7	30.1
	College	5.5	51.3
	University	59.9	
Income	Less than £[a]10,000	3.6	6
	£10,000–19,999	6.8	20
	£20,000–29,999	16.5	19
	£30,000–39,999	14.6	14
	£40,000–49,999	15.5	11
	£50,000–59,999	11.3	8
	£60,000–69,999	8.4	6
	£70,000–79,999	7.8	4
	£80,000 and more	15.5	12
Access to car	Yes	84.5	78
	No	15.5	22

[a] £ = British Pound.

were measured using 4 mode-specific statements. For example, it was asked: "In the past 12 months, approximately how many long-distance trips (>100 km) did you make with a car (as a driver or passenger)?" The respondents had to report the number of trips. The level of travel satisfaction with the four above-mentioned modes was also measured on a five-point Likert scale ranging from (1) very unsatisfied to (5) very satisfied. Of note, another answer option named not applicable was also included in case respondents have not had experience of travel with a specific mode. This overall satisfaction was asked as follows: "How much is your overall satisfaction with using the following transportation alternatives (car, train, airplane, and bus) for your long-distance travel (for leisure purposes) (>100 km)?" the descriptives of travel habit and satisfaction are shown in Table 2. For trips that exceed 100 km, people

Table 2
Descriptives of travel habits and satisfaction.

Mode	Travel habit (>100 km) (number)		Travel satisfaction (range: 1–5)	
	Mean	SD	Mean	SD
Car (as a driver or passenger)	9.31	26.56	4.25	0.86
Train	2.68	5.46	3.77	1.09
Conventional flights	2.21	3.45	3.98	0.92
Bus	0.76	3.78	2.96	1.14

use cars over trains and airplanes. Furthermore, the level of satisfaction tends to follow the order of mode use as well. In other words, people who use a particular mode are more satisfied with it. The factor was constructed via computing an average sum score (i.e. by taking the sum of the items and dividing by the number of items).

As described in Table 3, conventional flight-shaming statements such as "Others encourage me to reduce flying by airplane" and "I feel guilty when I fly to a destination" were measured by seven statements. The level of agreement or disagreement with each of the statements was rated on a five-point Likert scale ranging from (1) strongly disagree to (5) strongly agree. An exploratory factor analysis (principal axis factoring) was applied to explore which statements loaded on the same factor. The result of this factor analysis reveals that one factor including all statements is extracted. Cronbach's alpha also shows that this factor is reliable (alpha = 0.842).

As shown in Table 4, attitudes towards zero-emission flight were measured by six statements (e.g., "I think that zero-emission flights can reduce climate change"). An explanation of zero-emission flights was also provided before evaluating such statements: "As climate concerns continue to escalate, airlines are aiming to develop eco-friendly airplanes with the goal of producing net zero emissions to address global warming. Considering this, how much do you agree or disagree with the following statements?" The same answer battery was used here ranging from (1) strongly disagree to (5) strongly agree. Another PCA, with the same approach mentioned before, was applied to explore which statements sufficiently loaded as indicators of this attitude. This factor analysis also resulted in one factor containing all statements. Cronbach's alpha also shows that this factor is reliable (alpha = 0.831). Again, the factor was constructed via computing an average sum score.

4.4. Modeling framework

A systematic discrete choice modeling approach was employed to better capture behavioral responses (i.e., the choice between zero-emission flight, train, and car). We began with separate multinomial logit (MNL) models for short and long-distance scenarios. The next step involved testing a combined MNL, considering distance (short vs. long) as an explanatory variable in the model. Subsequently, we examined the potential improvement of these models by testing the latent class choice model (LCCM), taking heterogeneity among individuals into account to overcome MNL limitations (Hensher et al., 2015). As expected, the LCCM performed better than the MNL models. Moreover, based on model comparisons, a combined LCCM also better fits the data compared to two separate LCCMs. Therefore, for the sake of parsimony in result interpretations, a combined LCCM is presented in this study. The basic formulation of the LCCM is overviewed as follows.

To capture the inherent heterogeneity in traveler preferences for choosing options among zero-emission flights, train, and car, we employ an LCCM, a robust statistical framework that allows for the identification of distinct segments within the population (Hensher et al., 2015). This modeling approach is particularly well-suited for our study, as it

Table 3
Flight shame statements: means, standard deviations, and factor loadings.

Items	Mean	SD	loading
People in my social network (friends, peers, family members) have reduced their flights.	2.44	0.90	0.496
Others encourage me to reduce flying by airplane.	2.08	0.87	0.679
Climate activists have influenced me to reduce my flights.	2.29	1.10	0.675
People who are important to me want me to stop taking airplanes for unnecessary trips.	2.06	0.90	0.765
When I am going to fly I fear negative reactions from other people.	1.74	0.82	0.771
I feel guilty when I fly to a destination.	2.10	1.10	0.661
I rather do not tell others when I travel by airplane for a holiday.	1.71	0.81	0.598

Table 4
Statements regarding attitudes towards zero-emission flights: means, standard deviations, and factor loadings.

Items	Mean	SD	loading
I think that zero-emission flights can reduce climate change.	3.68	0.90	0.658
I would be more inclined to choose an airline that offers zero-emission flights over traditional airlines with higher emissions.	3.52	1.00	0.755
I would pay extra for zero-emission flight options.	2.61	1.08	0.588
Zero-emission flights promote sustainability.	3.62	0.82	0.692
I would choose a zero-emission flight option even if it involves additional travel time.	2.78	1.08	0.645
Zero-emission flights are a step towards a cleaner, greener future.	3.86	0.79	0.729

recognizes that individuals may exhibit varied preferences concerning zero-emission flights. The LCCM posits that there are unobserved classes within the population, each characterized by unique patterns of preferences. In our context, these latent classes represent different segments of travelers with different attributes influencing their choices. The model assumes that individuals within each latent class make choices based on a set of observed variables.

Standard statistical tests determine the number of segments needed to classify the population, capturing heterogeneity. Model fit statistics like the Akaike Information Criterion (AIC) or the Bayesian Information Criterion (BIC) can be used to assess the goodness of fit and aid in selecting the appropriate number of latent classes. Class membership is probabilistic, allowing individuals to possess characteristics of each class to varying degrees based on their membership probabilities. The models are estimated using LatentGold, a statistical software package.

Within the LCCM framework, it is presupposed that individuals are implicitly categorized into a distinct set of Q classes. The primary behavioral model revolves around a logit model, specifically addressing discrete choices among J_i alternatives (Hensher et al., 2015). This model pertains to individual i within T_i observed choice situations in the SC, as expressed in Equation (1):

$$Prob[choice\ j\ by\ individual\ i\ in\ choice\ situation\ t|class\ q] = \frac{\exp\ (X_{it,j}\beta_q)}{\sum_{j=1}^{J_i} \exp\ (X_{it,j}\beta_q)} \tag{1}$$

The probability of a particular choice made by an individual can be articulated in various formulations. For ease of expression, we use y_{it} to represent the specific choice made. Thus, the model, as outlined in Equation (2), is presented as follows:

$$P_{it|q}(j) = Prob(y_{it} = j|class = q). \tag{2}$$

Assuming class assignment as a given, we postulate the independence of T_i events. Within this assigned class, the contribution of individual i to the likelihood is expressed as the joint probability of the sequence $y_i = [y_{i1}, y_{i2}, \ldots, y_{iT}]$, as detailed in Equation (3):

$$P_{i|q} = \prod\nolimits_{t=1}^{T_i} P_{it|q}. \tag{3}$$

Nevertheless, the class assignment remains unknown. Here, let H_{iq} represent the prior probability of class q for individual i (posterior probabilities will be considered later). Different formulations can be employed for this purpose. One notably convenient form is the MNL model presented in Equation (4):

$$H_{iq} = \frac{\exp\ (z_i'\theta_q)}{\sum_{q=1}^{Q} \exp\ (z_i'\theta_q)}, q = 1, \ldots, Q, \theta_Q = 0, \tag{4}$$

In this equation, z_i refers to a set of observable characteristics (or covariates) that factor into the model for class membership.

The likelihood pertaining to individual i is determined by the expectation across classes of the class-specific contributions, as outlined in Equation (5):

$$P_i = \sum_{q=1}^{Q} H_{iq} P_{i|q}. \quad (5)$$

The log-likelihood (LL) for the sample is presented in Equation (6).

$$ln\, L = \sum_{q=1}^{Q} \ln P_i = \sum_{i=1}^{N} \ln\left[\sum_{q=1}^{Q} H_{iq}\left(\prod_{t=1}^{T_i} P_{it|q}\right)\right]. \quad (6)$$

5. Descriptive results

In Fig. 4, various modal shares are depicted based on different price and time scenarios in the data. It is important to acknowledge that this description lacks insights from behavioral modeling perspectives and does not take into account the influence of other covariates. We reveal the primary behavioral patterns using the LCCM in the subsequent section.

Scenarios 1 to 9 (S1-S9) represent a spectrum ranging from fast and economical zero-emission flights to slower and more expensive ones (see Appendix A). The base scenario describes the current choice between conventional flights, trains and cars. Examining the 500 km case (Fig. 4a), it is apparent that the preference for train travel (55.8%) surpasses that of conventional flights (36.4%) in the base scenario. Upon introducing zero-emission flights, a discernible trend emerges wherein individuals opt for zero-emission flights in economic scenarios, particularly in the initial scenarios. In the first scenario (S1), the share of zero-

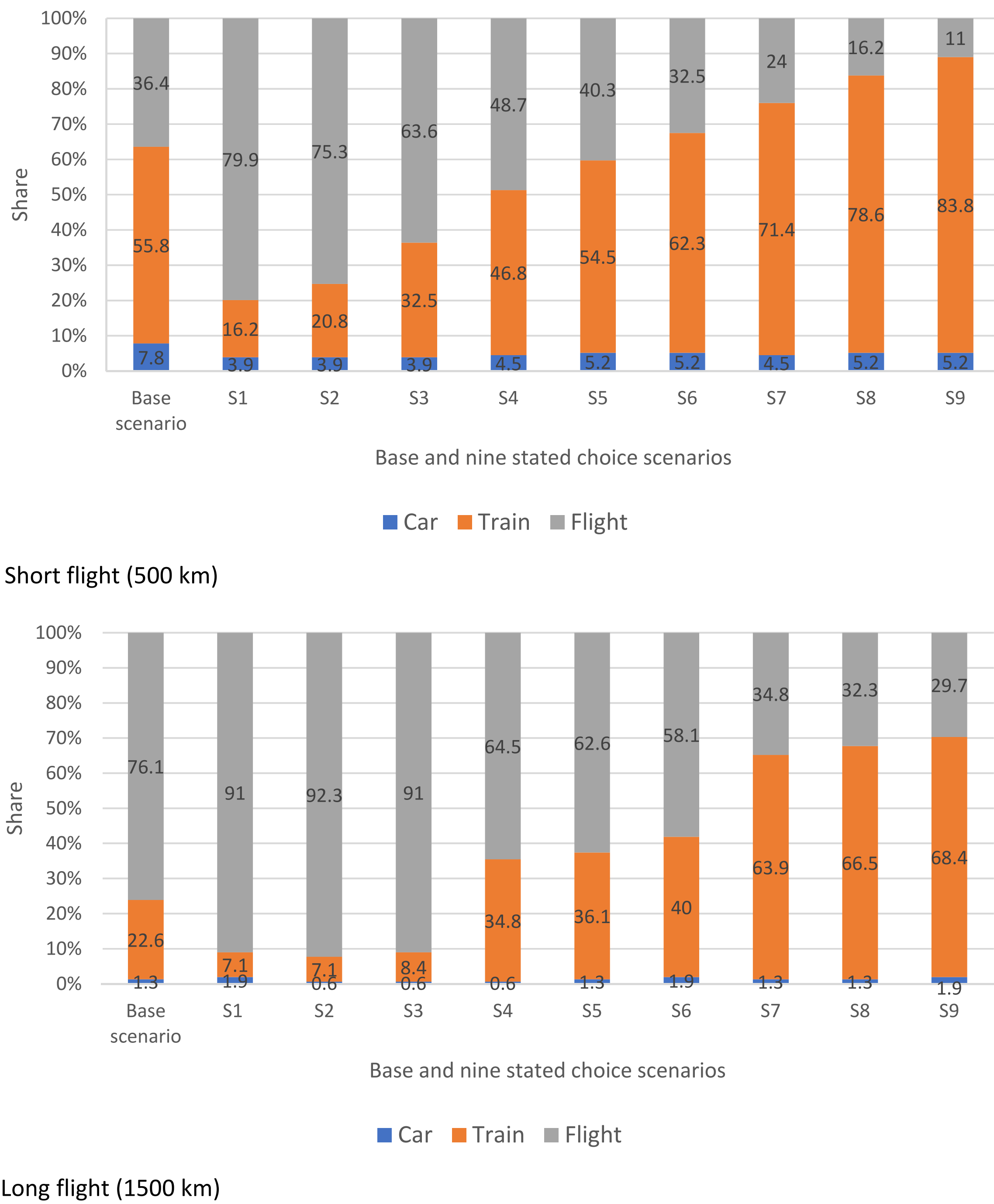

Fig. 4. Transport modal shares in different scenarios. Scenarios 1 to 9 (S1-S9) represent a spectrum ranging from fast and economical zero-emission flights to slower and more expensive ones (see Appendix A). The base scenario describes the current choice between conventional flights, trains and cars.

emission flights reaches approximately 79.9%, causing the share of train travel to decrease from 55.8% to 16.2%. However, beyond scenario 4 (S4), where flight ticket prices rise and air travel time increases significantly, the dominance shifts back to train travel.

In the case of a 1500 km journey (Fig. 4b), the anticipated outcome is observed, with the share of flights (76%) surpassing that of train travel (23%) in the base scenario. Upon the introduction of zero-emission flights, a discernible pattern emerges, indicating a preference for zero-emission flights in economically favorable scenarios, especially in the early scenarios. In the first scenario (S1), the share of zero-emission flights peaks at around 91%, leading to a reduction in the share of train travel from 23% to 7%. However, beyond scenario 6 (S6), marked by an increase in flight ticket prices and a significant rise in air travel time, the dominance shifts towards train travel.

6. Latent class choice model

As previously mentioned, a combined LCCM based on 2781 observations was chosen as the focal model for the study. Regarding model identification, in traditional dummy coding, one category is omitted (coded as 0) to prevent issues with collinearity, leading to q−1 sets of free parameters. However, in our model, we implemented effect coding in LatentGold, which provides an alternative solution for coding categorical variables that resolves these issues while retaining interpretive benefits across all levels (see Vermunt and Magidson, 2013, p18). In effect coding, each level of a categorical variable is coded such that parameter estimates reflect deviations from the grand mean, rather than from an omitted reference category. This approach distributes information across all categories equally and ensures that the intercepts across alternatives sum to zero, which is a built-in feature of effect coding. Consequently, this coding structure inherently avoids perfect collinearity by design. As a result, the model is properly identified, as evidenced by the fact that the intercepts do indeed sum to zero across the classes, which is expected with effect coding. Effect coding also facilitates the interpretation of each parameter estimate as a measure of deviation from the overall mean rather than from a specific base level, which can provide a clearer insight into class preferences across alternatives.

As described in Table 5, the decision to opt for a model with three classes was influenced by its lower BIC and the fact that each class comprised a minimum share size exceeding 10%. Examining the BIC, solutions with more classes show lower values. However, the minimum class sizes in the solutions with 4 and 5 classes are quite small. Consequently, the solution with 3 classes is selected.

As depicted in Table 6, when it comes to the main SC attribute, the latent classes are statistically different from each other in terms of intercepts, travel cost, and whether it is about short or long-haul flights. The classes are not statistically different from each other in terms of travel time (*Wald-test = 1.52, p-value = 0.82*). The interpretation of coefficients, especially intercepts, and their signs and magnitudes across classes can provide valuable insights into understanding class preferences. As an illustration, consider that Class 2, with an intercept of 8.91, exhibits a stronger inclination towards zero-emission flights when contrasted with Class 1 (intercept = 5.69) and Class 3 (intercept = 3.88). Table 7 also describes how different covariates in the model are statistically different across the three classes. At a 10% significance level, gender, income, flight shame, and attitudes towards zero-emission flights were found to be statistically different across classes.

In general, the classes can be interpreted as follows.

Class 1 – *Moderate preference for zero-emission flights.* The first class, constituting 46.19% of the sample, represents individuals with a moderate preference for zero-emission flights. They exhibit a moderate sensitivity to increases in travel costs associated with zero-emission flights. A rise in prices is likely to prompt a shift in their choice from airplanes to trains, as opposed to cars. When it comes to travel time, this group displays the least sensitivity compared to other classes, although this difference lacks statistical significance. In the context of long-haul flights, they show an increased likelihood of choosing zero-emission airplanes. However, in the face of a significant price increase, they are more inclined to opt for cars over trains. Contrastingly, for short-haul flights, there is a noticeable shift towards trains if there is a substantial increase in ticket prices. This group is skewed to females and individuals from lower-income households. Despite having the lowest score in flight shaming norms, they exhibit the most favorable attitudes towards the benefits of zero-emission flights within all classes.

Class 2 – *Zero-emission flights' lovers.* The second class, constituting 36.60% of the sample, comprises individuals who strongly favor zero-emission flights and have the lowest market share for cars. They demonstrate the highest sensitivity to increases in travel costs associated with zero-emission flights. A surge in prices is likely to lead to a shift in their transport choice, from airplanes to both trains and cars. Travel time does not significantly differentiate individuals in this class from other classes. Across various classes, this group holds the lowest share for zero-emission flights in the context of long-haul flights. It may encompass more females and individuals from lower-income brackets compared to those in class 3. However, concerning flight shame norms, this class has the highest norm influences compared to other groups. In other words, individuals who experience guilt when flying with conventional flights are more likely to belong to this class. Moreover, this group believes that zero-emission flights can contribute to reducing climate change.

Class 3 – *Limited preference for zero-emission flight.* This third class, comprising 17.21% of the sample, consists of individuals with a lower preference for zero-emission flights and trains compared to

Table 5
LCCM comparisons.

Class #	LL	BIC(LL)	Number of parameters	L^2	df	Minimum class size
1	−1883.372	3812.611	8	2131.122	301	Accepted
2	−1397.134	2891.734	17	1158.645	292	Accepted
3	−1164.429	**2477.926**	26	693.237	283	**Accepted**
4	−1059.718	2320.102	35	483.813	274	Rejected
5	−1006.686	2265.639	44	377.749	265	Rejected

Note.
LL (Log-Likelihood): A measure of how well the model explains the data. Higher (less negative) values indicate a better fit.
BIC(LL) (Bayesian Information Criterion): A statistic used to compare models. Lower values are better because they indicate a more parsimonious (simple and effective) model.
Number of Parameters: The number of factors used in the model. More parameters allow for more flexibility but may overcomplicate the model.
L^2: A measure of how much of the variability in the data is left unexplained by the model. Smaller values are better.
Df (Degrees of Freedom): A technical term representing the amount of information available to estimate the model.
Minimum Class Size: The smallest number of data points in a class for the model. If this is too small, the model might not be reliable. We set a threshold of 10%, corresponding to approximately 40 data points.

Table 6
The results of the latent class choice model.

		Class1		Class2		Class3		Overall					
R^2		0.57		0.58		0.69		0.66					
Class size		0.4619		0.366		0.1721							
	Choice	Class1	z-value	Class2	z-value	Class3	z-value	Wald	p-value	Wald (=)	p-value	Mean	Std. Dev.
Intercept	Car	−6.84	−0.694	−11.02	−1.111	5.28	1.124	196.22	0.000	8.08	0.088	−6.287	5.6038
	Train	1.14	0.232	2.10	0.424	−9.17	−0.987					−0.2775	4.0776
	Zero-emission flights	5.69	1.154	8.91	1.791	3.88	0.833					6.5645	1.8997
Predictors	Choice	Class1	z-value	Class2	z-value	Class3	z-value	Wald	p-value	Wald (=)	p-value	Mean	Std. Dev.
Costs													
	Car	−0.0028	−0.539	0.0153	2.998	0	0.011	427.08	0.000	48.18	<0.001	0.0043	0.0084
	Train	0.0208	6.346	0.0093	3.328	0.0002	0.038					0.013	0.0078
	Zero-emission flights	−0.0179	−6.532	−0.0246	−7.522	−0.0002	−0.086					−0.0173	0.0084
Time													
	Car	−0.0008	−0.131	0.0061	1.031	−0.0062	−0.543	43.639	0.000	1.52	0.820	0.0008	0.0045
	Train	0.0036	1.170	−0.0001	−0.026	0.0144	0.638					0.0041	0.005
	Zero-emission flights	−0.0028	−0.927	−0.006	−1.934	−0.0082	−0.721					−0.0049	0.0021
Distance (Long = 1, Short = 0)	Car	5.901	0.605	2.172	0.223	−2.673	−1.495	199.30	0.000	113.94	<0.001	3.0609	3.1105
	Train	−8.443	−1.717	−1.483	−0.304	−0.460	−0.131					−4.5224	3.6497
	Zero-emission flights	2.542	0.521	−0.689	−0.141	3.134	1.758					1.4615	1.6475

Table 7
LCCM results across covariates.

Intercept	Class1	Class2	Class3	Wald	p-value
	−0.718	−0.001	0.718	0.957	0.620
Covariates (scale)					
Gender (Female = 1, Male = 0)	0.295	0.240	−0.536	5.265	0.072
Education (Ordinal from primary school to PhD)	0.052	−0.076	0.024	0.749	0.690
Income (Ordinal from low to high)	−0.027	−0.135	0.162	12.414	0.002
Car trips_habit (Number)	−0.005	0.000	0.005	2.879	0.240
Train trips_habit (Number)	0.044	−0.022	−0.021	4.069	0.130
Air_trips (Number)	0.014	0.034	−0.048	1.104	0.580
Bus_trips (Number)	0.038	0.049	−0.087	0.680	0.710
Car satisfaction (Ordinal 1–5)	−0.057	0.020	0.037	0.609	0.740
Train satisfaction (Ordinal 1–5)	0.047	−0.124	0.077	2.720	0.260
Air satisfaction (Ordinal 1–5)	0.053	−0.117	0.063	2.449	0.290
Bus satisfaction (Ordinal 1–5)	0.049	0.080	−0.129	1.417	0.490
Flight_shame_mean score (Ordinal 1–5)	−0.254	0.316	−0.062	5.550	0.062
Zero emission_attitude_mean score (Ordinal 1–5)	0.271	0.140	−0.411	6.439	0.040

other classes. In regular circumstances, they exhibit the highest car share compared to other groups. This group, skewed towards higher-income individuals, is not particularly sensitive to a rise in ticket prices for zero-emission flights. This lack of sensitivity can be attributed to the higher income profile of the individuals in this group. Predominantly male, this group is characterized as unsustainable, with the lowest levels of flight shame norms and the least favorable attitudes towards zero-emission flights. Surprisingly, when it comes to long-haul flights (1500 km) versus short-haul flights (500 km), individuals in this class are more likely than other groups to choose zero-emission airplanes. However, for short-haul flights, they are more inclined to switch to cars in the event of a price increase.

7. Discussion and conclusion

We analyzed potential shifts in travel behavior in response to the introduction of zero-emission flights. A stated choice experiment using a sample from the UK general public was conducted to assess preferences for flights, trains, and cars based on travel time, cost, and carbon emission scenarios. Covariates, such as attitudes towards zero-emission flights, flight-shaming norms, and sociodemographic factors, were incorporated into a latent class choice model. The exploration into individual preferences regarding zero-emission flights unfolds a captivating narrative, revealing complex dynamics shaped by cost considerations, distance sensitivity, and distinct subgroup behaviors.

As we explore the findings, clear patterns begin to emerge, highlighting the relationship between travel choices, sustainability attitudes, and economic factors.

Recognizing the diversity among individuals provides a comprehensive view of the wide range of preferences and attitudes toward zero-emission flights. Similar to findings in previous studies (Rains et al., 2017; Goding et al., 2018; Veisten et al., 2024), there is an overall interest in adopting zero-emission flights. However, distinct subgroups show varying sensitivities to travel costs and distances, underscoring the need for targeted interventions and policies.

The classification into three distinct groups provided a better understanding of traveler preferences. Class 1, with a moderate preference for zero-emission flights, shows a balance between environmental concerns and economic considerations. They lean towards sustainable options but show flexibility based on cost factors. Targeted policies could focus on offering incentives for this group, encouraging a gradual shift towards zero-emission travel.

Class 2, the zero-emission flights' lovers, presents a paradox. While exhibiting the highest sensitivity to cost, their strong preference for zero-emission flights suggests a deep commitment to environmental values. Policymakers should harness this environmental consciousness by implementing measures to alleviate the economic burden associated with sustainable travel, potentially through subsidies or tax incentives.

Class 3, characterized by a limited preference for zero-emission flight, highlights the challenge of engaging individuals with higher income profiles. Despite economic advantages, this group demonstrates resistance to adopting sustainable options. Policies here could involve targeted awareness campaigns, emphasizing the broader societal and environmental benefits of zero-emission flights, potentially shifting attitudes over time.

The finding that people are more sensitive to ticket prices than to travel time challenges some conventional assumptions about what drives travel choices. This economic prioritization suggests a practical lens through which people approach sustainable travel, emphasizing the pivotal role of affordability in steering decisions. The revelation that travel choices tend to remain consistent even if zero-emission flights take longer than conventional airplanes challenges preconceived notions about the importance of travel time duration in mode choice decision-making. This suggests resilience among individuals in opting for sustainable aviation options, even when faced with longer travel durations.

Our findings on the importance of travel costs align with existing literature, indicating that individuals, particularly men and those with higher incomes, are less sensitive to ticket prices for long-haul flights. Rains et al. (2017) found that travelers are willing to pay a 13% premium for biofuel-powered commercial air travel. Similarly, Rice et al. (2020) showed that a greater reduction in greenhouse gas emissions correlates with an increased willingness to pay higher ticket prices. However, our study reveals that, on average, significant increases in zero-emission flight ticket prices might increase a shift toward train travel.

The identification of a group (class 3) with less sustainable choices, characterized by unfavorable attitudes, flight shame norms, and a propensity for car travel over trains, marks a distinctive profile. Intriguingly, this group, predominantly male and high-income-oriented, displays a paradoxical inclination towards zero-emission flights in short and long-haul scenarios. This unexpected shift underlines the complexity of their preferences and the potential for transformative change in specific contexts.

Noticing that this less sustainable group tends to switch to cars for short-haul trips reveals an interesting dimension. While their preference for zero-emission flights increases on longer journeys, shorter distances lead them to favor cars and trains, highlighting how sustainable choices depend on context.

The findings of our study on the preference for zero-emission flights reveal a significant phenomenon: attitudes and norms play a more substantial role in shaping individuals' choices than their established travel habits and satisfaction with current travel modes. Specifically, we observed that people's longstanding travel habits and overall satisfaction with existing long-distance travel options did not significantly influence their mode choices once zero-emission flights were introduced. Instead, it was the individuals' attitudes towards zero-emission flights and their sensitivity to flight-shaming norms that emerged as key determinants in shaping their preferences. However, Xu et al. (2022) highlighted that although there is generally a positive perception of the benefits of sustainable aviation fuel, their study uncovered a limited awareness of its use. Interestingly, while respondents showed a favorable attitude toward sustainable aviation fuel, most were unwilling to pay extra for carbon-neutral air travel (Xu et al., 2022).

This phenomenon can be theoretically explained through the lens of the Theory of Planned Behavior (TPB) (Ajzen, 1991) and the broader context of sustainable behavior decision-making. According to TPB, individual behavior is influenced by three primary factors: attitudes, subjective norms, and perceived behavioral control. In the context of our study, attitudes towards zero-emission flights represent the individual's overall evaluation of this sustainable travel option. The positive or negative attitudes formed contribute significantly to the intention to choose zero-emission flights. Flight-shaming norms, on the other hand, align with subjective norms in TPB, reflecting the perceived social pressure or approval regarding the choice of travel modes. The prominence of flight-shaming norms in influencing mode choices underscores the growing social awareness and stigma associated with high-carbon travel options (Gössling et al., 2020). Individuals, being socially influenced, are more likely to align their choices with the prevailing norms and societal expectations.

The limited impact of established travel habits and satisfaction with existing modes on mode choices post-introduction of zero-emission flights can be attributed to a paradigm shift in values and preferences towards sustainable practices. Individuals, motivated by a desire to reduce their carbon footprint and align with societal expectations, might exhibit a cognitive restructuring that places greater importance on environmentally friendly options, such as zero-emission flights.

Norm-shifting campaigns in other industries can offer lessons for aviation policymakers. For example, the promotion of electric vehicles (EVs) has successfully reshaped norms around transportation for traditional car enthusiasts (Bjerkan et al., 2016). This transformation was driven by a combination of subsidies, investments in infrastructure like charging networks, and marketing campaigns framing EVs as a socially responsible choice. Similarly, recycling became a widespread norm through public awareness efforts, investments in infrastructure such as curbside recycling programs, and educational initiatives (Tumu et al., 2023). In the food industry, campaigns highlighting the environmental and ethical benefits of plant-based diets have gradually influenced consumer behavior and industry norms (Tobler et al., 2011). These examples reveal a common formula for successful norm-shifting: public awareness campaigns, regulatory support, and infrastructure improvements. Applying these principles to zero-emission flights could involve fostering a cultural narrative that prioritizes sustainable air travel.

The positive influence of environmental values and flight-shame norms on the propensity to engage in zero-emission flights is promising from a policy-perspective but also highlights a potential risk. If the aviation industry is able to successfully market flights as zero-emission, even though they retain a large climate impact (because of non-CO_2 effects), especially those people who are environmentally concerned will be drawn into making travel choices that may be less sustainable than the (baseline) alternative(s) that would considered by this group, e.g. not traveling or traveling by train. This means that, even if it becomes possible to realize (near) zero-emission flights (in terms of CO_2) in the future, awareness should be raised about possible non-CO_2 effects.

These findings move us beyond traditional assumptions, revealing a complex mix of preferences shaped by economic factors, sustainability attitudes, and journey length. The policy implications are significant, calling for an approach that takes the diverse nature of individual choices into account. Key considerations for promoting a more sustainable future in air travel include designing interventions that address affordability, encouraging sustainable options for long-haul travel, and tailoring strategies for specific traveler groups.

Policies should prioritize making zero-emission options economically competitive, ensuring that sustainable travel aligns with broader economic considerations. Simultaneously, targeted interventions should address the specific needs and attitudes of distinct traveler groups, acknowledging the diverse factors that influence their choices. By marrying economic viability with environmental stewardship, policymakers can pave the way for a more sustainable and conscientious future in the realm of transportation.

7.1. Limitations and future research direction

The current study has certain limitations that need acknowledgment. To provide a more comprehensive understanding, future research should employ a more intricate stated choice experiment, varying carbon emission rates across different types of airplanes, from current models to those powered by sustainable fuels. In our study, we simplified by assuming two carbon emission rates per person for short and long-haul flights, recognizing that real-world zero emissions are unlikely. Therefore, in our experiment, we assumed airlines would promote such flights with a "less than 2 kg/person" and "less than 4 kg/person" approach for 500 km and 1500 km scenarios.

Our experimental design focused on specific origin-destination pairs, potentially limiting flexibility and introducing bias by not reflecting the full variability of global travel patterns. Preferences for zero-emission flights may differ between shorter regional trips and longer international ones due to variations in cost, travel time, and perceived environmental impact. Future studies should consider a broader range of distances, including intercontinental flights, to capture more comprehensive traveler preferences. The study also focused solely on leisure trips, which may bias results toward travelers with more scheduling flexibility and environmental considerations. Business travelers often prioritize time and convenience, while those traveling for study may have distinct constraints. Future research should examine how trip purpose influences preferences by incorporating it as an experimental variable and using qualitative methods like interviews to explore the unique priorities of different traveler segments. Finally, the interplay between origin-destination characteristics and trip purpose should be explored. Factors like regional infrastructure, cultural attitudes, and economic conditions may influence preferences. Expanding the scope to include diverse scenarios will help develop better and generalizable insights into preferences for zero-emission flights. It is important to note that behavioral responses to zero-emission flights may differ among people from different countries due to factors like infrastructure, availability of alternative modes, economic status, and cultural norms. Conducting a global or region-based study could offer valuable insights into these variations. Countries with varying public transport infrastructures compared to the UK may show different modal shift responses under zero-emission flight scenarios. In nations with less developed train networks, zero-emission flights could see greater adoption in economic scenarios, with cars being the preferred mode for shorter distances. Conversely, in countries with well-established high-speed rail systems, the share of train travel may increase, especially in scenarios where zero-emission flights are slower or more expensive. We acknowledge the role of coach services in Europe—particularly in the UK, where they both complement and compete with the rail network. However, we believe that their combined complementary and substitution effects could neutralize their overall impact in the context of this study. Nonetheless, we recognize that a deeper exploration of how coach services interact with rail options could provide additional insights for future research.

The sample revealed minor discrepancies in age and income distributions (especially regarding low-income groups and older populations). Older individuals may have a higher propensity to fly, while low-income groups could be more price-sensitive and more likely to switch to trains in less economic zero-emission flight scenarios. As a result, caution is advised when generalizing the findings to these population groups.

It would indeed have also been interesting to ask respondents how much they trust the “zero emissions” claim. For comparison, electric cars are often marketed as “zero emission,” but it has become clear that this applies only to exhaust emissions. Indirect emissions, such as those from electricity generation and battery production, remain potentially concerning. This could make respondents more cautious about other so-called “zero emission” offerings.

On the technological front, there is currently considerable uncertainty about the performance features of zero-emission, electric, or battery-powered airplanes. Regular updates will be necessary to stay abreast of changes in travel speed, battery size, charging capabilities, and the cost and availability of aviation fuels. Continuous updates to supply-demand studies in the coming years will be essential to reflect these evolving technological dynamics.

CRediT authorship contribution statement

Milad Mehdizadeh: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maarten Kroesen:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Mirco Peron:** Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A.1
Choice scenarios for short flight experiment (500 km).

Scenario	Options	Travel cost	Travel time	CO_2 emission
Base	Conventional flight	£ 47	2.45 h	73.5 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S1	Zero-emission flight	£ 47	2.45 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S2	Zero-emission flight	£ 47	3.30 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S3	Zero-emission flight	£ 47	4.15 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S4	Zero-emission flight	£ 79	2.45 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S5	Zero-emission flight	£ 79	3.30 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S6	Zero-emission flight	£ 79	4.15 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S7	Zero-emission flight	£ 111	2.45 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person

(continued on next page)

Table A.1 (*continued*)

Scenario	Options	Travel cost	Travel time	CO_2 emission
	Car	£ 106	7.30 h	83.9 kg/person
S8	Zero-emission flight	£ 111	3.30 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person
S9	Zero-emission flight	£ 111	4.15 h	Less than 2 kg/person
	Train	£ 55	4.40 h	13 kg/person
	Car	£ 106	7.30 h	83.9 kg/person

Table A.2
Choice scenarios for long flight experiment (1500 km).

Scenario	Options	Travel cost	Travel time	CO_2 emission
Base	Conventional flight	£ 79	3.45 h	131 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S1	Zero-emission flight	£ 79	3.45 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S2	Zero-emission flight	£ 79	4.30 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S3	Zero-emission flight	£ 79	5.15 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S4	Zero-emission flight	£ 198	3.45 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S5	Zero-emission flight	£ 198	4.30 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S6	Zero-emission flight	£ 198	5.15 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S7	Zero-emission flight	£ 317	3.45 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S8	Zero-emission flight	£ 317	4.30 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person
S9	Zero-emission flight	£ 317	5.15 h	Less than 4 kg/person
	Train	£ 79	12 h	38 kg/person
	Car	£ 247	14.50 h	251.8 kg/person

Data availability

Data will be made available on request.

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