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LETTER

Estimating passenger emissions from airfares supports equitable climate action

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Abstract

Air travel generates a substantial and growing share of global greenhouse gas emissions. Reduction efforts partly rely on estimates of emissions per passenger, which may be used for carbon budgets, offsets, or taxes. Aircraft emissions are typically allocated to individual passengers through space-based allocation dependent on seating arrangements by travel class. However, the operation of aircraft depends on profitability, which benefits from high fares from late bookings, often by business and high-income travellers. Fare-based allocation recognises the economic drivers of airline emissions by allocating the aircraft emissions proportionally to the paid airfares. In this article, we compare space-based passenger emissions, which differ only by class, with fare-based passenger emissions, which depend on the fare paid by the individual traveller. We extract space-based allocation factors from widely used emission calculators and derive fare-based allocation factors from airfares for domestic travel in the US. We find that the space-based allocation factors reflect the difference in average expenditure by travel class but not the difference in expenditure between travellers. With fare-based accounting, the most expensive economy trips have similar emissions to space-based premium trips, while less expensive premium trips have similar emissions to space-based economy trips. We find that a tax on fare-based instead of space-based emissions leads to a more evenly distributed impact on low-fare and high-fare travellers whilst achieving the same reduction in airline revenues. We conclude that fare-based emissions accounting better reflects the drivers of airline emissions and supports more equitable climate action.

1. Introduction

Aviation contributes a growing share of approximately 2.4% of global anthropogenic CO_2 emissions (Lee *et al* 2021) and the sector is very difficult to decarbonise (Schäfer and Waitz 2014, Schäfer *et al* 2019). The Carbon Offsetting and Reduction Scheme for International Aviation by the International Civil Aviation Organization (ICAO) aims to offset the growth in air travel emissions, but even if successful, does not come close to aligning aviation with globally agreed emission reductions (Larsson *et al* 2019, Gössling and Lyle 2021). Other efforts to reduce aviation emissions, including commitments by the International Air Transport Association (IATA 2021), often rely on the extensive use of low-carbon fuels, the supply of which faces major social, environmental, technical, and economic challenges (Staples *et al* 2018, Næss *et al* 2021). As a result, reducing demand for air travel is a key strategy for meeting climate change targets (Bows-Larkin 2015, Klöwer *et al* 2021).

Estimates of the emissions per airline passenger play a major role in emission reduction efforts for aviation. They are used for company greenhouse gas reporting (Hill *et al* 2021), emission offset schemes (Atmosfair 2016, Myclimate 2019), and the analysis of travel emissions at various levels and scales (Chester and Horvath 2012, Larsson *et al* 2018, Van Ewijk and Hoekman 2021). The estimation of the emissions of a single traveller can be summarised as a three-step procedure. First, the calculation of the aircraft emissions based on the aircraft's fuel efficiency, fuel type, and travel distance. Second, the allocation of some emissions to freight (passenger planes often carry freight in the cargo hold, such as international mail). Third, the assignment of the remaining emissions to individual passengers using allocation factors. The present study focuses solely on the third step and investigates how the choice of allocation method influences carbon accounting and taxation.

The conventional approach to allocating emissions to individual passengers is based on passenger space requirements, which are often differentiated by travel class and adjusted for aircraft occupancy rates (Jardine 2009). In widely-used emission calculators, the premium class passengers are assigned 1.3–2.9 times more emissions per unit of distance than the economy class passengers (Bofinger and Strand 2013, Atmosfair 2016, ICAO 2018, Myclimate 2019, Hill *et al* 2021). Space-based allocation observes that the smaller space requirements of economy seating imply a larger number of travellers on a plane and hence lower average emissions per passenger. This logic is valid when assuming the flight occurs irrespective of the demand for air travel. However, the decision to operate a flight is based on profitability, which in turn depends on revenues from airfares.

Fare-based allocation differs from space-based allocation by assigning emissions proportional to airfares instead of seating space. Airfares vary widely because airlines maximise revenue by charging more for late bookings, often by business travellers willing to accept higher prices (Williams 2022). The practice of intertemporal price discrimination is a fundamental part of airline yield management strategy. Passengers that pay high fares contribute more to airline profitability by generating more revenue at the same operational cost. Fare-based allocation is shaped by the relative differences in airfares between passengers on the same flight (defined here as a unique combination of origin, destination, airline, and quarter) but independent of the differences in average airfares between travel routes, airlines, or seasons.

In this article, we argue that allocation choices for aviation emissions are not a mere technicality, but have profound implications for the equitability of climate policies. We show the consequences of space-based and fare-based allocation for the distribution of emissions across passengers based on widely used emissions calculators and fare data for US air travel, and discuss the implications for carbon accounting and offsetting. We estimated the impacts of space- and fare-based carbon taxes on the number of travellers and airline revenue. We evaluated the taxes assuming that high-fare (and typically high-income) passengers should reduce their travel at least as much as other travellers. The next section explains the methods and data, followed by a discussion of the results, including a reflection on the potential implementation of a fare-based carbon tax. The article wraps up with conclusions and recommendations.

2. Methods

2.1. Allocation factors

We analysed the impact of space-based and fare-based allocation on passenger emission estimates for a representative US flight. For both allocation methods, we estimate a dimensionless allocation factor that describes the distribution of emissions among the passengers on the flight. The average allocation factor across methods and travel classes is normalised to 1. For the space-based allocation factors, we first collated the relative space requirements by travel class cited in the methodological documentation for emission estimates by the UK government (Hill *et al* 2021), the World Bank (Bofinger and Strand 2013) and two online emission calculators (Atmosfair 2016, Myclimate 2019). We derived the allocation factors from the relative seat sizes and the prevalence of each travel class on an average plane. For a consistent comparison with the fare-based allocation factors, we derived the prevalence of the travel classes from the fare data.

For the fare-based allocation approach, we first estimated and normalised the fare distribution for flights in the Airline Origin and Destination Survey (DB1B) database (BTS 2020). The DB1B includes datasets for tickets, which describe itineraries consisting of one or more flights, and coupons, which describe individual flights. The data includes airports of origin and destination, travel class, and fare per unit of distance. The data is continuously collected through the passenger origin-destination survey, in which all large US-certificated air carriers are legally mandated to participate. A full description of the data collection procedure is available in the relevant legislation (Legal Information Institute 2019).

We combined the ticket and coupon datasets to identify the airfares per unit of distance for a specific quarter and unique combinations of the airport of origin, airport of destination, and airline, which we refer to as 'flights' throughout the article. We cleaned the dataset to ensure a more representative sample. First, we excluded airports outside of the US. Second, consistent with previous analyses, we truncated fares below $20 or above $9998, removed tickets with more than four coupons, and removed one-way trips with more than two coupons (Borenstein n.d.). Third, we removed bulk fare bookings because they are not representative of individually booked tickets. Finally, we excluded observations with fare data flagged as questionable by the data provider.

We removed first class fares (0.6% of the sample) because of the occurrence of anomalously low fares. We simplified and relabelled the travel classes: we applied the term 'premium' to restricted and unrestricted business class and 'economy' to restricted and unrestricted coach/economy class. We do not use the term 'business class' to avoid confusion with passengers travelling for business purposes, which are often equated with business class for practical purposes (Brons *et al* 2002), but this is undesirable in our study. We removed entries with an unknown travel class. We did not consider the potential effect of cancellations and frequent flyer schemes on revenue and profitability because the dataset only considers the airfares as stated on the ticket and only flights that were actually taken.

We calculated a representative industry-wide fare distribution for both travel classes by averaging the values in each quantile of the fare distributions of the flights in the sample. First, we calculated the fare distributions for all combinations of origin, destination, operating carrier, and fare class. We excluded combinations with less than 100 data points to ensure a sufficient sample size for each distribution. Second, we normalised each fare distribution by dividing the values by the average fare for the relevant flight. Third, we took the value for each quantile in all normalised distributions and averaged these to calculate the representative distribution for the US aviation market. We also calculated the 5–95 percentile values to capture uncertainty. We estimated distributions by quarter to reduce seasonal effects.

The representative industry-wide distribution shows the extent to which, on a typical flight and for each travel class, some passengers pay more than other passengers. The 5–95 percentile distribution shows the extent to which the level of price discrimination differs between flights. Our results do not describe the differences in average fares between carriers because they are not relevant to our allocation approach, which starts from the total aircraft emissions and not the total expenditure for the flight. The difference in average fares was eliminated from the data by normalising the distributions for each flight. The results we show are only for the first quarter of 2019 but the distributions for the other quarters of 2019 are almost identical. Supporting information table 1 shows the descriptive statistics and supporting information table 2 shows the results of the comparison between quarters.

2.2. Carbon tax modelling

We modelled the short-term reduction in economy and premium travellers in response to carbon taxes on space-based and fare-based emissions. For each travel class, we divided the representative fare distribution into deciles to create ten separate markets and calculated the demand response for each market. The fare-based tax is a fixed percentage of the ticket price for all travellers on the same flight. For illustrative purposes, the tax was set at 20% of the ticket price. The equivalent space-based tax charges each passenger the same amount of tax (see supporting information) and was set at a level that yields the same tax revenue in the case of perfectly inelastic demand. Consistent with prior calculations, we focused on the allocation of emissions and taxes between passengers on the same flight, which cancels out differences between routes, airlines, or seasons.

We calculated the impact of taxation based on the price elasticity of demand. In the main scenario, we followed recommendations to separately model the demand response in economy and premium class (Brons *et al* 2002) and applied the median values from a review of price elasticities of demand for short/medium-haul travel in economy (-1.5) and business (-0.7) (Gillen *et al* 2007). We ran two alternative scenarios to check the robustness of the main scenario findings. In the first, we assumed the elasticity ranges from -0.7 to -1.5 but correlates with expenditure instead of travel class because high-income travellers with low price elasticities might be purchasing the most expensive fares in each travel class. In the second, we assigned the same elasticity (-1.1) to all travellers irrespective of class or expenditure. The assumptions are further explained in the supporting information.

We estimated only the short-term demand response based on current airfares. In the long term, airlines should be expected to adjust their offerings to optimise profits, for instance by adjusting the aircraft technology, seating arrangements, flight schedules, service levels, and yield management strategy.

3. Results and discussion

3.1. Impact of allocation

Figure 1(a) shows the fare-based allocation factors for a representative US domestic flight (see methods) and the space-based allocation factors based on the seat size estimation in a representative calculator (ICAO 2018). For both allocation methods, the average allocation factor across travel classes is 1. Figures 1(b) and (c) are analogous to figure 1(a) but show the ranges of potential allocation factors for each travel class separately. The ranges are based on the minimum and maximum values derived from five emission calculators (Bofinger and Strand 2013, Atmosfair 2016, ICAO 2018, Myclimate 2019, Hill *et al* 2021) and the fare values within the 5–95 percentile range in the fare distributions for the flights in our sample.

Figure 1(a) reveals both agreement and disagreement between the space- and fare-based allocation methods. The average allocation factor by travel class differs just 1%–5% between the allocation methods, suggesting that the choice of method does not

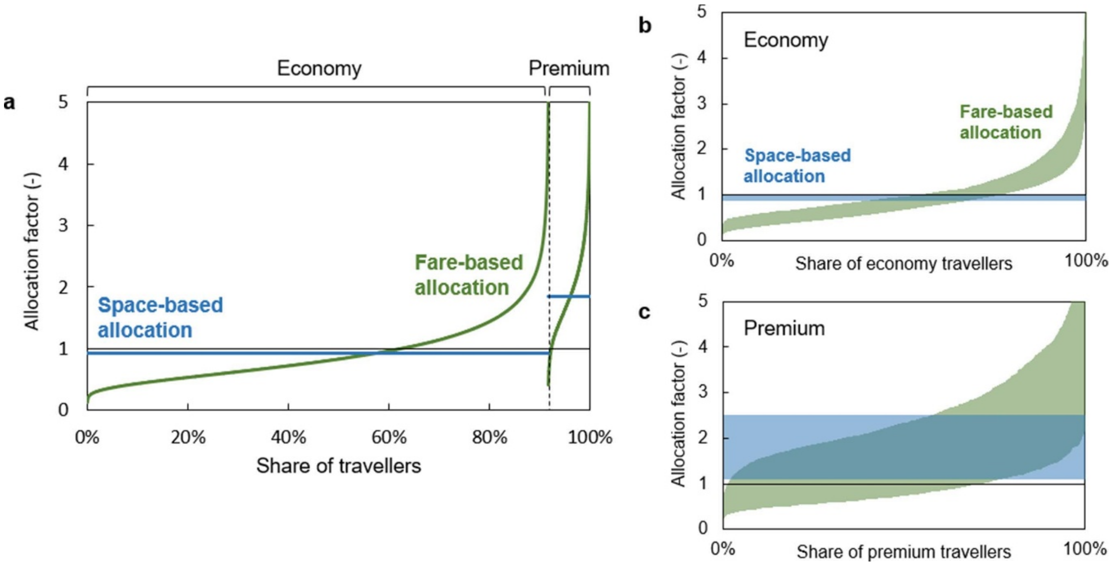

Figure 1. The allocation factors show the distribution of emissions among the passengers under space-based allocation, which differs only by class, and fare-based allocation, which differs by individual passenger. The distribution is discontinuous because of the difference between economy class (92% of passengers) and premium class (8% of passengers). The average allocation factor across methods and classes is 1. Chart 1a shows the values for a representative US flight and emissions calculator and chart 1b (economy class) and 1c (premium class) show the ranges based on the differences between various emission calculators and the 5–95 percentile range of fares in our sample.

significantly affect the total allocation of emissions to each travel class. However, within each travel class, the choice of allocation method has a major impact on the distribution of emissions among individual passengers. In economy class, the bottom 10% of fare-payers are allocated just 3.8% of the fare-based emissions for economy travellers, whereas the top 10% of fare-payers are allocated 23% of the emissions for economy travellers. In premium class, the distribution is slightly flatter and the corresponding fractions are 4.5% and 19%.

Fare-based accounting blurs the distinction between the travel classes. The allocation factors of the most expensive economy trips are similar to the space-based allocation factors of premium trips, while less expensive premium trips have similar allocation factors to space-based economy trips. Of the economy class travellers, 14% have a fare-based allocation that is closer to the space-based allocation factor of 1.85 for premium than the space-based allocation factor of 0.92 for economy. These high-fare paying travellers play a major role in driving airline emissions but the traditional space-based emission calculators hide this. At the same time, 24% of premium travellers have a fare-based allocation factor that is closer to the space-based allocation factor of economy than premium.

Figures 1(b) and (c) show that the variability in the allocation factors is smaller for economy than for premium. The relatively large ranges in premium class are probably due to the aggregation of a wider variety of seat sizes and service levels (despite removing first class, see methods). The figures also show that the agreement between space- and fare-based allocation factors is much lower for economy than for premium. For economy class, only 8% of the fare-based range overlaps with the space-based range, which confirms that the allocation method has a major impact on the passenger emission estimates. For premium class, 56% of the fare-based factors overlap with the space-based factors. In conclusion, the consequences of the choice of allocation method are substantial even when considering the variability in fares and calculators, but mostly for economy class, which accounts for the majority of travellers.

3.2. Targets and offsets

The implementation of fare-based allocation would increase the emission estimates for high-fare paying travellers, who tend to be travelling for business purposes (Williams 2022). Corporate emissions, when they include scope 3 emissions from business travel, would likely increase under fare-based accounting. Consequently, a corporate commitment to achieve net zero would require more travel reduction or emission offsetting. This effect could be particularly relevant for the service industries, for which travel tends to be a large contributor to their overall emissions (Huang *et al* 2009). At the same time, leisure travellers who book early would face lower emission estimates than with space-based allocation, which could affect their reduction efforts and the cost of purchasing voluntary carbon offsets for their flights.

3.3. Carbon taxes

Figure 2 shows the normalised airfares and space- or fare-based taxes by travel class and the tax-induced reduction in passengers by fare decile. The results are

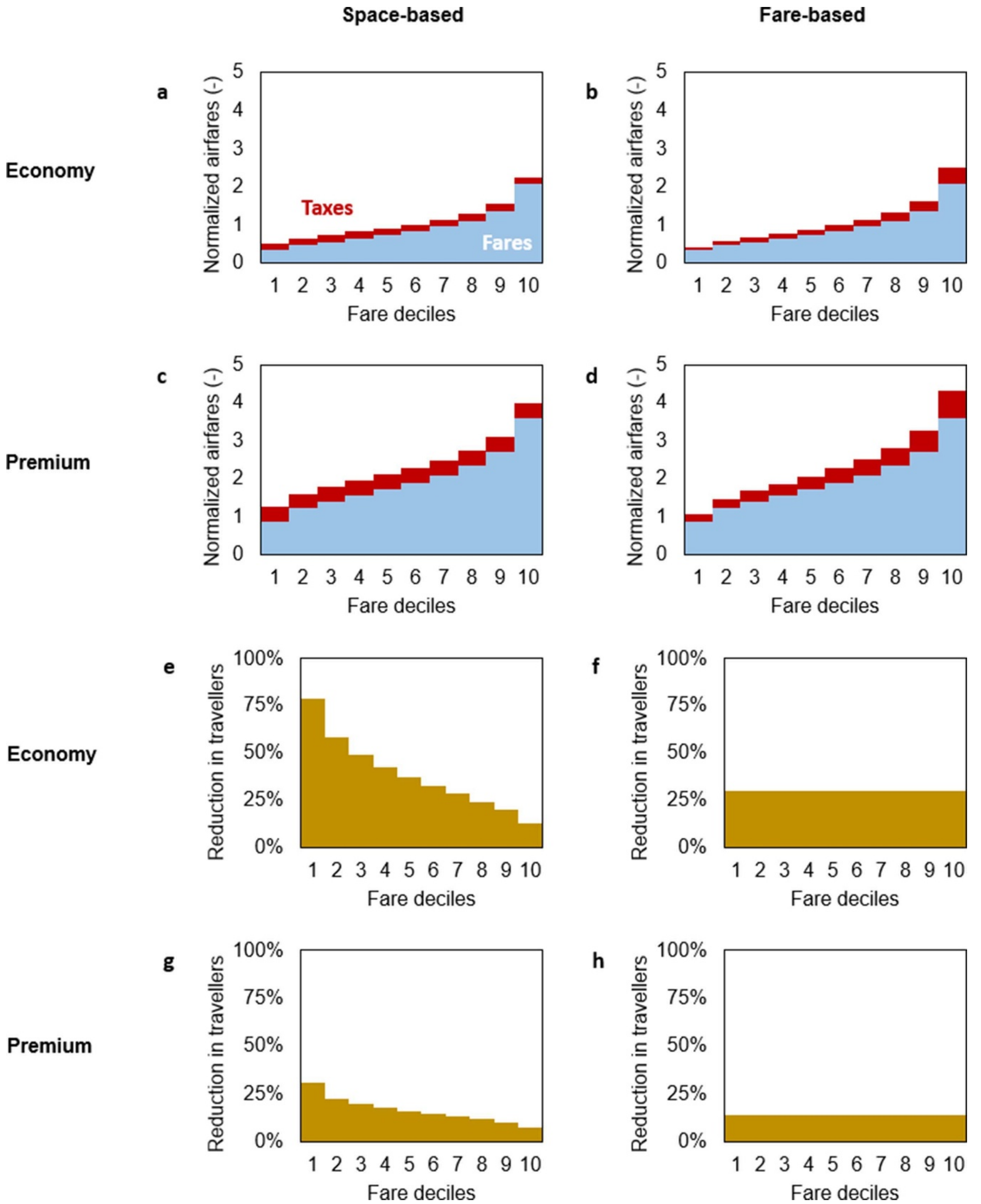

Figure 2. Charts 1(a)–(d) show the distribution of economy and premium airfares (blue), normalised to average 1 across all passenger on a flight, and the space-based and fare-based taxes (red), which are equivalent but differently distributed among the fare deciles. Charts 2(e)–(h) show the reduction of flights for each decile under the two allocation schemes, based on a price elasticity of −1.5 for economy and −0.7 for premium.

for the main scenario with a class-specific price elasticity of demand (see methods). The space-based tax is at the same level (in absolute terms) for all fare deciles in economy (1a) or premium (1c); the fare-based tax is proportional to the economy fare (1b) or premium fare (1d). In economy class, the space-based tax leads to a demand reduction of 79% for the bottom decile but just 13% for the top decile. In premium class, the corresponding reductions are just 31% and 8% because the tax is smaller compared to the fare. In contrast, the tax on fare-based emissions leads to the same response across all fare deciles within a travel class, which may be considered more equitable, but the reduction is much larger in economy (30%, figure 1(f)) than in premium (14%, figure 1(h)) because of the lower price elasticity of demand in premium class.

The space-based tax achieves a higher reduction in the number of travellers than the fare-based tax (38% versus 30% in economy and 16% versus 14% in premium) because the space-based tax deters a larger number of low-fare payers. However, since these low fare-payers contribute less to revenue, the total reduction in revenue is the same for both types of taxes—30% in economy and 14% in premium. Since the revenue rather than the number of travellers drives emissions, the choice of allocation method is unlikely to influence the overall effectiveness of the tax, but it does affect the equitability of the impact. The fare-based tax might be preferable because it shares the burden more equally between low and high-fare-payers, who are likely to be low- and high-income travellers respectively, whilst achieving the same pressure on airlines.

The results from the alternative scenarios, which featured fare-dependent and constant elasticities (see methods), suggest that the findings from the main scenario are robust. In both alternative scenarios, the space-based tax led to a much higher reduction in demand for low fare-payers compared to high-fare payers. The demand reductions were hardly different between economy and premium, which is different from the main scenario, but this provides further evidence that the fare-based tax may have a more equitable impact than the space-based tax. In the first alternative scenario, the revenue reduction was not exactly the same for the two taxes but was still very close. Altogether, the alternative scenarios show that even under substantially different assumptions for the price elasticity of demand, the fare-based tax is likely to have a more equitable impact. The detailed results for all scenarios are provided in supporting information tables 3–8.

Our analysis has several limitations. First, the figures we present are for illustrative purposes only because the analysis is based on fare distributions for two simplified fare classes. Second, high fares may have higher profit margins than low fares, but the analysis focuses on revenue. The fare-based tax may hurt profit more than revenue and thus be more effective at reducing emissions than suggested by the revenue reduction alone. Third, a national or regional tax can lead to a shift in aviation towards nearby tax-exempt airports, partly offsetting the gains from domestic reductions in aviation (Borbely 2019, Falk and Hagsten 2019). In our analysis, border effects should be small because the US has few airports close to competing airports in other countries. Fourth, travellers that forego aviation may choose alternative modes of transport, or spend on different goods altogether, partly offsetting the gains from reduced flying (Hofer *et al* 2010). These rebound effects tend to be limited because most products and services have lower emissions per unit of expenditure than aviation (Berrill *et al* 2020).

3.4. Implementing a fare-based carbon tax

The feasibility of a fare-based tax depends on the public support for targeting expenditure. Moreover, the tax requires knowledge of the paid airfare as well as of the airfares paid by other passengers. The latter can be known only after the ticket sales have ended but could be estimated through a model with generic predictors for airfares based on the typical cost factors for flights, which are mainly flight distance and aircraft seat capacity (Swan and Adler 2006). Relevant other parameters, or even a full or partial price distribution, may be derived from fare data, such as the frequently updated DB1B database used for the present study. In addition, for both fare- and space-based allocation, the total emissions attributable to passengers must be estimated before the passenger allocation and requires data about fuel use and freight load.

In practice, it may be unattractive to estimate taxes or offsets from fare-based emissions because data regarding passenger fare distributions may not be available. A simpler tax would charge a fixed percentage of airfares. Such a policy resembles a value-added tax (VAT) and may still have equity-related benefits compared to a tax on space-based emissions (which would apply the same tax to each ticket) because high-fare payers would pay a higher tax than low-fare payers. However, the tax rate would be uniform across flights and not be based on an initial assessment of the aircraft emissions. As such, the tax would not reflect the flying distance and the aircraft efficiency, the inclusion of which is essential to promote emission reductions by operators (Kito *et al* 2020).

Taxation of aviation is complicated by the Chicago Convention from 1944 (ICAO 1944) and later resolutions by the ICAO (Council 2000), as well as bilateral agreements, all of which promote tax exemptions to stimulate international travel and avoid discrimination between foreign and domestic airlines or services (Tumpel 2020). These agreements do not completely preclude taxation and, despite legal challenges, various countries have instated ticket taxes, including Austria, Germany, France, Norway, Sweden, and South Africa (EC 2019, Larsson *et al* 2019). Such taxes expressly or implicitly put a price on emissions, albeit often a small one, and tend to be differentiated by distance group and travel class. Besides international agreements, aviation tax reform is also held back by concerns over the potential loss of the social and economic benefits of international travel.

Alternative policy instruments include emissions trading, fuel taxes, and a frequent flyer levy. The European Union Emissions Trading Scheme (EU ETS) includes aviation since 2012. The national schemes of the UK, Switzerland, New Zealand, and South Korea also cover aviation. Oesingmann (2022) found no significant negative effect of the EU-ETS on passenger flows, though higher prices for emissions allowances could change this. Fuel taxes carry a lower administrative burden than ticket taxes (OECD 2019) and offer more flexibility for airlines to reduce emissions. Norway and Japan implemented fuel taxes (Larsson *et al* 2019) and González and Hosoda (2016) found the Japanese tax to be effective at reducing emissions. Whereas ticket taxes have potential distributional advantages (Keen and Strand 2007), emissions trading and fuel taxes have the benefit of directly targeting emissions.

A frequent flyer levy (Chapman *et al* 2021) would introduce a charge per flight that increases with the number of flights taken by a traveller. Similar to a tax on fare-based emissions, the levy targets high-income and business travellers and shields low-income travellers, but based on the frequency of flight instead of expenditure. Both measures may create undesirable burdens for travellers who have low incomes but, for whatever reason, need to fly often or book late (Büchs and Mattioli 2022). In principle, a frequent flyer levy could reflect both the number of flights taken, as well as the flight-specific emissions, whether space-based or fare-based, but this would be challenging to implement. The most effective strategy to reduce emissions from aviation is not the implementation of a single policy but rather a policy mix, which can be more economically efficient (Keen and Strand 2007) and could promote both technological change and demand reduction for a systemic transition towards sustainable aviation (Gössling and Lyle 2021).

4. Conclusions

Climate action on air travel, including personal or corporate reduction efforts, emission offsets, and carbon taxes, currently relies on space-based allocation of emissions to individual passengers based on the seating arrangements on the aircraft. We argue that fare-based allocation more accurately reflects the drivers of aviation emissions because it targets high fares that drive profitability and thus the operation of flights. With fare-based allocation, late bookings of expensive tickets, often by business or high-income travellers, are assigned more emissions. Fare-based allocation would likely increase the estimates of corporate emissions, as well as the reductions or offsets required to meet corporate emission targets, but reduce the estimates for leisure travellers. A tax on fare-based instead of space-based emissions may be more equitable because it would impact the number of high-fare and low-fare-payers more uniformly whilst reducing airline revenue to the same extent. More broadly, we argue for greater attention to allocation in emissions accounting, which may be overlooked as a mere technicality but can play a pivotal role in achieving equitable climate action.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/shitiz88/Airline_Emissions.

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