nature energy

Article

https://doi.org/10.1038/s41560-024-01561-3

Understanding the large role of long-distance travel in carbon emissions from passenger travel

Received: 30 April 2023

Accepted: 22 May 2024

Published online: 02 July 2024

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Zia Wadud[1,2] ✉, Muhammad Adeel[3] & Jillian Anable[1]

Long-distance passenger travel has received rather sparse attention for decarbonization. Here we characterize the long-distance travel pattern in England and explore its importance on carbon emissions from and decarbonization of passenger travel. We find that only 2.7% of a person's trips are for long distance travel (>50 miles one-way), but they account for 61.3% of the miles and 69.3% of the greenhouse gas (CO_2 equivalent) emissions from passenger travel, highlighting its importance for decarbonizing passenger transport. Long-distance travel per person has also been increasing over time, trending in the opposite direction to shorter-distance travel. Flying for leisure and social purposes are the largest contributors to long distance miles and emissions, and these miles are also increasing. Overall, per capita travel emissions have started decreasing slowly from 2007, but are still higher than in 1997. We propose a new metric—emissions reduction sensitivity (% emission reduced/% trips altered)—to understand the efficiency of travel demand related initiatives to reduce greenhouse gas emissions. Long-distance travel—especially flying—can offer orders of magnitude larger emissions reduction sensitivity compared with urban travel, which suggests that a proportionate policy approach is necessary.

The transport sector accounts for 30% of global energy use[1] and 37% of global carbon dioxide emissions[2]. Despite its large share in national emissions[3], transport has been one of the most difficult sectors to decarbonize[4]. For example, between 1990 and 2019, emissions from other end-use sectors in the United Kingdom were reduced by 44% while those from transport were reduced by less than 5%, leaving transport with an increasingly larger share of emissions over time[3]. The majority of national transport emissions come from passenger travel in developed economies (specifically, 61.4% in the United Kingdom[5]), underlining the importance of passenger transport, especially in the context of any ambitious decarbonization strategy (such as the United Kingdom's net-zero target by 2050). The decarbonization efforts are often technology focused (namely, electrification, energy efficiency improvements and fuel switching), yet technologies alone will not be enough: passenger travel demand reduction and behavioural changes are also necessary to achieve a net-zero society[6–8]. As such, understanding passenger travel patterns is crucial for reducing energy use and greenhouse gas (GHG) emissions.

Long-distance travel (LDT) constitutes a small portion of all passenger trips but contributes to a large share of miles travelled and carbon or GHG emissions[9,10], yet estimates for these are rare[11,12]; even rarer is any study on the evolution of LDT over time. Also, flying—an important mode for LDT—is often considered separately in strategies to decarbonize passenger transport[13]. However, understanding these LDT elements is important for effective and efficient GHG mitigation from the passenger transport sector.

[1]Institute for Transport Studies, University of Leeds, Leeds, UK. [2]School of Chemical and Process Engineering, University of Leeds, Leeds, UK. [3]Centre for Transport and Society, University of the West of England, Bristol, UK. ✉e-mail: Z.Wadud@leeds.ac.uk

https://doi.org/10.1038/s41560-024-01561-3

In this Article, we use England as a case study and combine several nationally established surveys—such as the National Travel Survey (NTS)[14] and International Passenger Survey (IPS)[15]—to characterize LDT for England residents. Unlike the relatively well-endowed literature on determinants of LDT and demand modelling (primarily air travel[16–20]), or LDT and daily travel[21], the focus of this study is twofold. First, we examine the role of LDT in the context of overall passenger travel and GHG emissions (expressed as CO_2 equivalents (CO_2e)) by spatial coverage, mode and journey purposes, and how they have evolved over the past 20 years, from 1997 to 2017. Second, we propose a new metric—emissions reduction sensitivity—to understand the relative decarbonization potential of travel-demand-focused emissions reduction strategies for LDT and urban travel. While there are various definitions of LDT (Methods), a cut-off of 50 miles (one-way) is adopted in this study.

Distribution of domestic versus international trips

Figure 1 shows the distribution of per capita trips (one-way), mileage and GHG emissions at different distance bands for domestic, international and combined travel. On average, an England resident made 782.5 trips in 2017 (excluding short walks <1 km) within Great Britain, covering 6,471 miles and emitting 1,139 kg of CO_2e (using 100-year global warming potential (GWP); Methods). These data come from the NTS, which covers only domestic travel. On the other hand, the NTS and IPS data together show that, on average, only 3.1 international trips are undertaken annually per capita, yet those trips account for 5,406 miles and emit 1,646 kg of CO_2e. Combining domestic and international travel, an average England resident makes 785.6 trips, covers 11,877 miles and emits 2,785 kg of CO_2e over a year. This clearly shows that both travel miles and CO_2e emissions for passenger travel are vastly underestimated (by 45.5% and 59.1%, respectively) if they are calculated from only national travel surveys and fuel sales, which often do not consider LDT, especially international travel, in most countries.

The very few international trips (0.4% of all trips), which are all long distance (LD), constitute a large share of all passenger miles (45.5%) and an even larger share of total CO_2e emissions (59.1%) because of the highly carbon-intensive modes in play for international trips, primarily aviation. On the other hand, domestic travel—although dominated by car travel (75.9% of domestic trips and 78.6% of domestic miles)—has some low-carbon alternatives such as rail and coaches for longer distances and buses, walking and cycling for short trip distances. Given this dominance of international travel emissions in a resident's travel profile, it is questionable to exclude international travel-related emissions when calculating the carbon footprint of passenger travel, as is the current practice (in particular, the UK and other nationally determined contributions do not include international aviation emissions).

Combining domestic and international travel (Fig. 1), an average England resident makes 21.5 long distance (LD) trips over 50 miles (one-way) a year covering 7,278 miles and emitting 1,929 kg of CO_2e in the process. This means that LDT accounts for only 2.7% of annual trips per capita yet is responsible for a staggering 61.3% of all passenger miles travelled and 69.3% of GHG emissions from personal travel. The large majority (85.5%) of the LD trips are still conducted within the island of Great Britain using a combination of modes, but the few international LD trips (3.1 per capita, 14.5% of LD trips) contribute substantially to both LD miles (74.3%) and LD emissions (85.3%).

Modal analysis of LDT

As shown in Fig. 2a–c, an England resident flies only 2.9 times a year (0.36% of all trips) on average, but flying is the largest contributor to total passenger miles (5,255 miles, 44.2%) and CO_2e emissions (1,534 kg, 55.1%). Given the small geographical area, flying is not popular for domestic destinations in England and nearly all flights are to or from international destinations, which naturally falls within the LDT category, too. The flying emissions include radiative forcing due to emissions at high altitude and contrail formation.

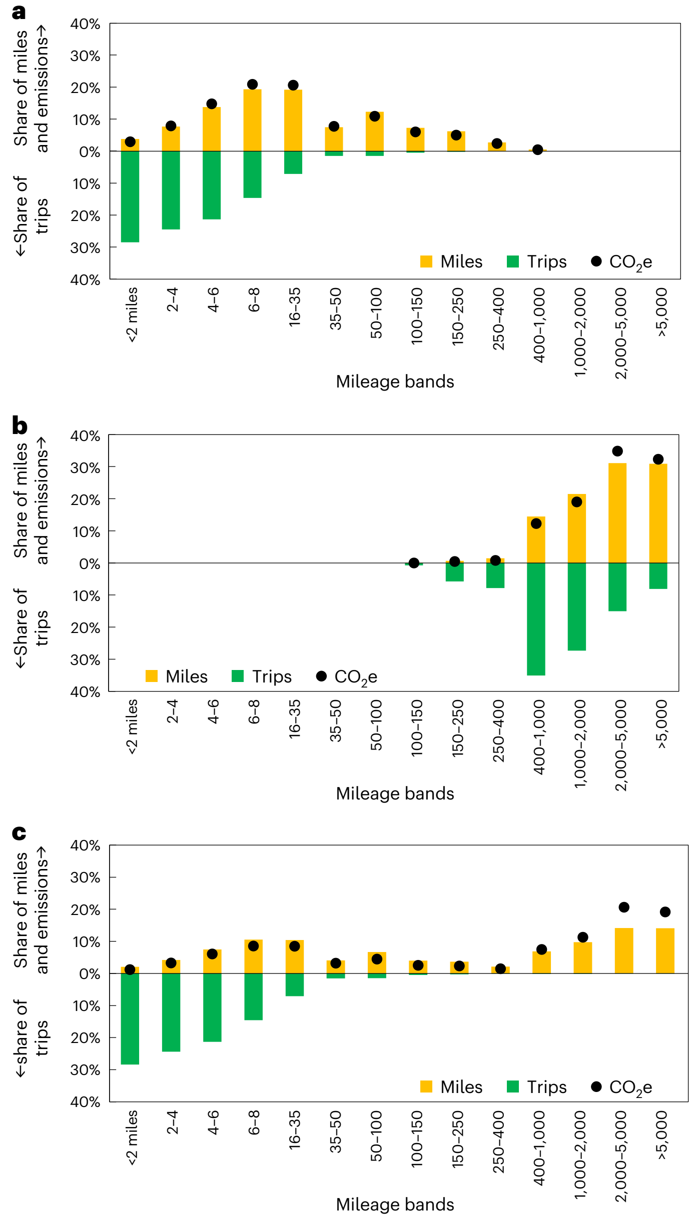

Fig. 1 | Shares of annual trips, miles and emissions per capita in 2017 by trip distance bands. a–c, Trips are shown across domestic (**a**), international (**b**) and both trips (**c**). The shares are within respective types of trips; for example, in **b**, 37% of international trips fall within the 400–1,000 mile range, but this represents only 1.2 trips per capita, which is a very small share of all trips, almost invisible in **c**.

The largest number of trips are undertaken by cars (594.4 per capita), which represent three-quarters (75.7%) of all trips made (Fig. 2a), confirming the dominance of car as a transport mode in England. Yet, car travel accounts for a similar share (43.5%) of all passenger miles as aviation (44.2%), and a relatively smaller—but still large—share (36.8%) of CO_2e emissions from all passenger travel (Fig. 2b,c). On average, an individual takes only 14.1 LD car trips a year (1.8% of all trips), but that represents 1,478 miles (12.4% of all mileage) and 9.3% of all emissions, whereas its 580.3 shorter-distance trips (below 50 miles) cover 3,693 miles (31% of all miles) and 27.5% of all CO_2e emissions. Higher occupancy for LD car trips make their emissions to mileage performance slightly better compared with shorter-distance trips.

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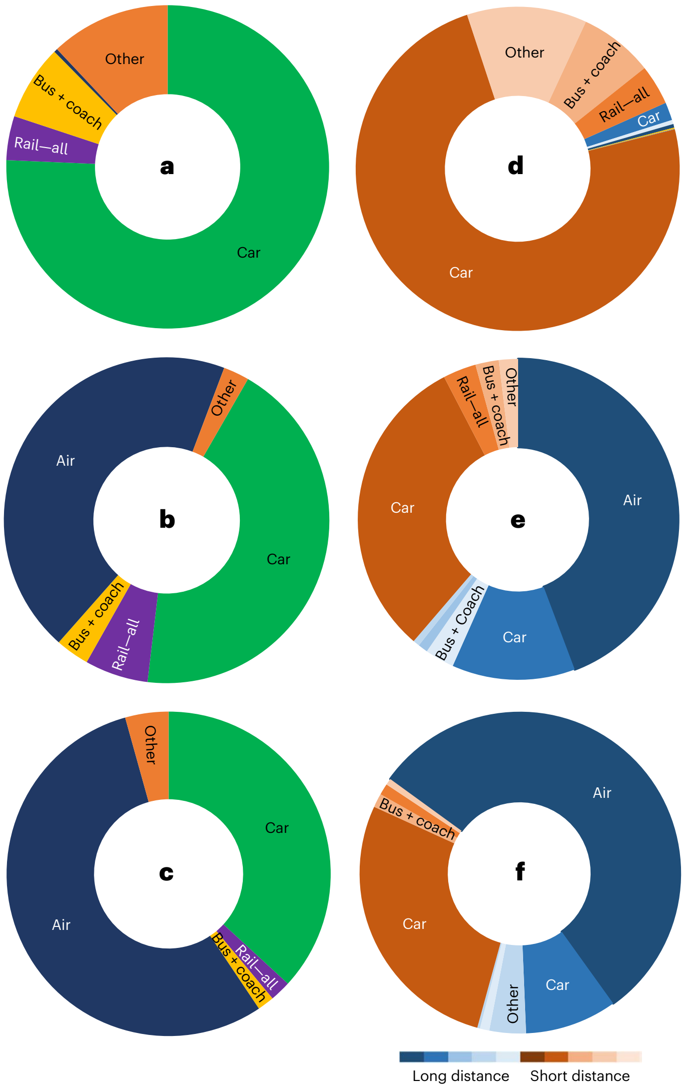

Fig. 2 | Shares of trips, miles and CO_2e emissions per capita by mode. a–f, Trips are shown by mode of travel (**a**–**c**) and across short- and long-distance groups by mode of travel (**d**–**f**). The charts show a disproportionately large contribution of air travel (**a**–**c**) and LDT (**d**–**f**) to miles and emissions.

Within the LDT segment of the travel profile, car is still the most frequently used mode (65.6% of LD trips), followed by rail (3.3 trips, 15.2%), flying (2.9 trips, 13.3%) and bus and coach (0.9 trips, 4.3%). However, this picture changes when mileage and emissions are considered: air travel contributes 72.2% of LD miles and 79.5% of LD emissions (Fig. 2d–f).

Considering the respective modes of travel, LDT covers 2.4% of trips, 28.6% of miles and 25.3% of CO_2e emissions by car; 15.5% of trips, 55.3% of miles and 53.6% of CO_2e emissions by rail (excluding underground); and 18.9% of trips, 75.1% of miles and 74.7% of CO_2e emissions by coach (Supplementary Table 1). This shows, unsurprisingly, that a larger share of miles in rail and coach travel is for undertaking LDT.

LDT by journey purposes

When international travel is taken into account, leisure (holidays, day trips and recreational activities), social (visiting friends and family) and commute purposes account for similar share of trips in a person's travel profile: 16.7%, 14.8% and 17.0% of the total respectively (Fig. 3a). However, the mileage shares can differ vastly: 39.6%, 23.6% and 11%, respectively (Fig. 3b). Emissions also follow a similar pattern: 43.2% for leisure, 23.6% for social and 10.7% for commute trips (Fig. 3c). This clearly shows that commuting trips, which are often the target of local sustainable transport and emissions reduction initiatives, are responsible for a relatively small share of miles and emissions; this is due to the generally shorter distances of commutes and relatively more frequent use of less carbon-intensive modes (such as public transport, walking and cycling) for this purpose. Business travel, on the other hand, accounts for 3.3% of all trips but 8.3% of all miles and 9.2% of all emissions, indicating they are more carbon intensive on average. The rest of the travel—dominated by various escort and shopping purposes—constitute nearly half (48.3%) of total yearly trips but only 17.4% of all miles travelled and 13.2% of all GHG emissions (Fig. 3a–c).

Out of the 7,278 LD miles a year, leisure and social purposes account for 6,056 miles, that is, a dominant 83% of all LD miles (Fig. 3e). On average, an England resident makes 13.9 LD leisure and social trips, which accounts for only 1.8% of all trips (64.5% of LD trips) on a per capita basis, but 50.7% of all miles and 58.6% of all CO_2e emissions. These LD trips are primarily for holidays and visiting friends and family and show that these potentially discretionary trips are responsible for a disproportionately large amount of mileage and emissions. Within the leisure sector, holidays are particularly carbon intensive: only 0.7% of all trips are LD holiday trips but are responsible for 30.3% of all miles and 37.2% of all emissions (Supplementary Table 2). In comparison, shorter-distance (<50 miles) leisure (including holidays) and social visits account for 29.7% of all trips covering 12.5% of all miles and 8.2%

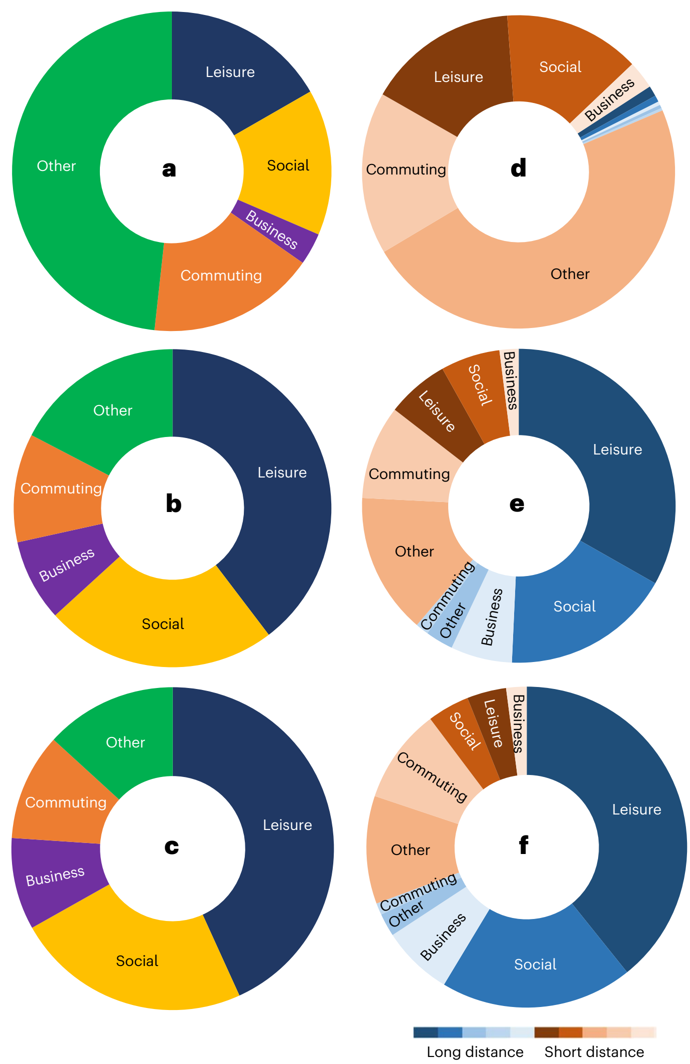

Fig. 3 | Shares of trips, miles and CO_2e emissions per capita by journey purpose. a–f, Trips are shown by purpose (**a**–**c**) and across short- and long-distance groups by purpose (**d**–**f**). The images show the large role of leisure and social trips in miles and emissions.

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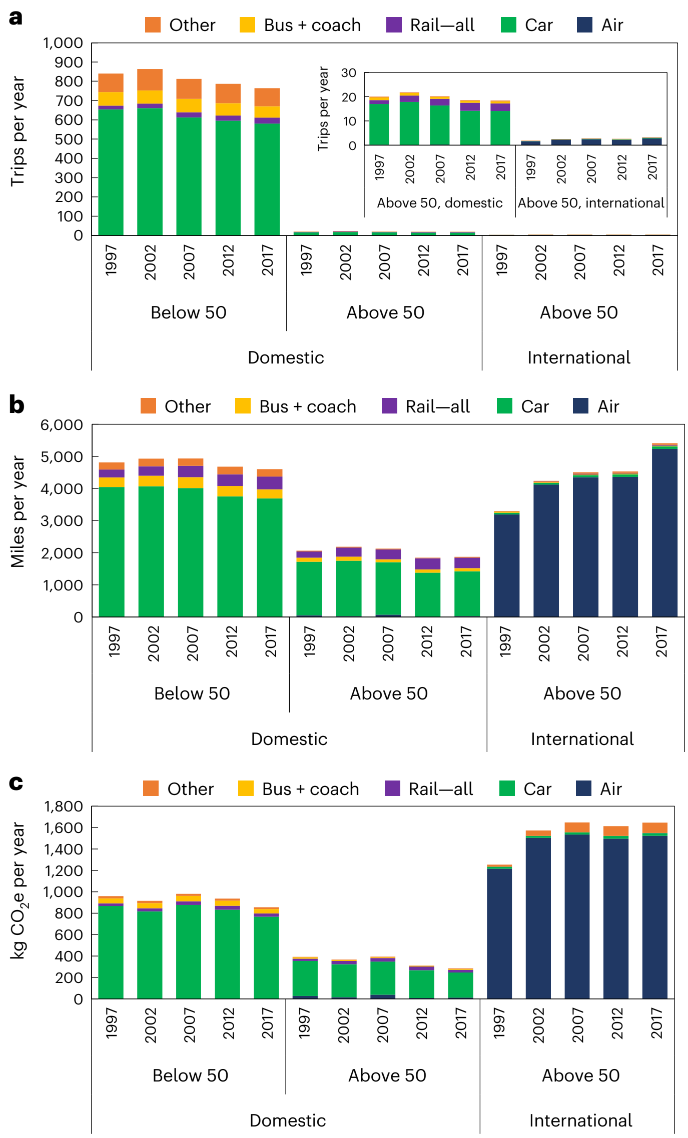

Fig. 4 | Trends in short- and long-distance trips by mode. a–**c**, Trips are shown by trips per capita (**a**), miles per capita (**b**) and CO_2e emissions per capita (**c**) between 1997 and 2017 by travel mode (inset in **a**: international trips). This shows that the domestic trips, miles and emissions are decreasing, while their international counterparts are increasing. 'Peak car' for domestic travel is also visible.

of all emissions. Travelling for business is the next largest contributor to LD trips, miles and emissions.

Although the car is still the dominant mode for undertaking LD leisure and social trips, flying dominates for mileage and emissions. Holidays and social visits are the most popular reasons for flying, followed by business.

Temporal analysis of LDT

Per capita domestic short- and long-distance trips and mileage have been falling since 2002 (Fig. 4a,b). Similar trends are observed for domestic car trips and mileage, too, lending support to the 'peak car' hypothesis[22–24] that car use in the Western economies has already plateaued. However, over the same period, international LD trips and mileage have continued to increase in England, most likely aided by the liberalization of air transport in the late 1990s leading to a proliferation of low-cost carriers and growing income and immigration[25,26]. This means that a fall in the total number of trips per capita could not stem the growth in total miles per capita, which continued to grow (but for a slight dip in 2012). As such, it is clear that 'peak car' domestically has not resulted in 'peak travel' when international travel is included.

Between 1997 and 2017, an average England resident travelled fewer domestic miles for business purposes, with a larger reduction in LD miles compared with shorter-distance miles (Fig. 5b). On the other hand, per capita LD international mileage for leisure purposes has increased by 47% during that period, backed by an increase in travel frequency, although LD domestic mileage for leisure remained relatively stable. The greatest increase in mileage was due to international travel for social visits—from 556 miles per capita in 1997 to 1,601 miles in 2017, a 188% increase; the frequency of these trips went up, too. Average miles per international trip for both social and leisure trips show a decreasing trend, suggesting that the increases in these mileage are results of more frequent flying of relatively shorter distances, probably facilitated by the rise of low-cost airlines (which do not fly very long distances and often cater for regional holiday destinations) and growth of immigration from nearby European countries, which possibly leads to more frequent visits to the immigrants' relatively nearer home countries[26]. Hence, LD leisure and social trips are not only a large share of miles and emissions now, but travel demand for these purposes has also been growing.

Overall emissions per capita for personal travel shows a gentle concave downward trend with a peak around 2007 (an 8% decrease between 2007 and 2017, but still a 7% increase between 1997 and 2017; Supplementary Fig. 1). This indicates that emissions for passenger travel may have peaked on a per capita basis. This is primarily driven by a substantial reduction in emissions from domestic car travel (Fig. 4c): reduction in domestic miles, more fuel-efficient vehicles (despite a proliferation of sports utility vehicles) and dieselization (with lower carbon emission intensity compared with petrol), combined with some increase in demand in the rail transport sector after privatization in the 1990s. However, emissions from international LDT continue to increase (albeit at a slower rate than LDT miles, probably due to improvements in engine efficiency and higher load factors for flights). Nonetheless, England's population grew by 14% during 1997–2017; therefore, aggregate emissions from passenger travel have increased slowly during these 20 years, although they appear to have stabilized around 2007 (Supplementary Fig. 2).

Emissions reduction sensitivity

Recent research[6–8] suggests that reducing travel demand and changing travel behaviour (for example, shift to low-carbon modes) are crucial in decarbonizing the transport sector. However, the disproportionate role of aviation and car modes presents a dilemma for demand-focused emissions reduction strategies. As Fig. 2 shows, both modes are responsible for nearly equal amount of overall mileage and somewhat comparable emissions, yet these arise from very different levels of trip making. Travel-behaviour-related emission mitigation strategies primarily focus on controlling or shifting short-distance car travel in urban areas, for example, by improving public transport, walking and cycling facilities, by controlling car parking or by pricing road usage[27–29]. Yet, due to the enormous quantity of short-distance car trips, very large-scale changes in these trips are needed for these policies to make a substantial dent in emissions.

We examine this further through a thought experiment involving several demand-focused strategies to reduce CO_2e emissions, which is summarized in Table 1. As Table 1 shows, a modal shift strategy of switching all car trips under 8 miles to walking and bicycles (strategy A) can potentially reduce total emissions by 9.3%, but it requires a change in 55.1% of all trips and 75% of all car trips undertaken now—a very large disruption in existing travel behaviour. On the other hand, switching all LD car trips to rail (strategy D) can achieve an overall reduction of 5.2%, disrupting only 1.8% of all trips, indicating a rather large decrease in emissions with respect to the number of trips affected.

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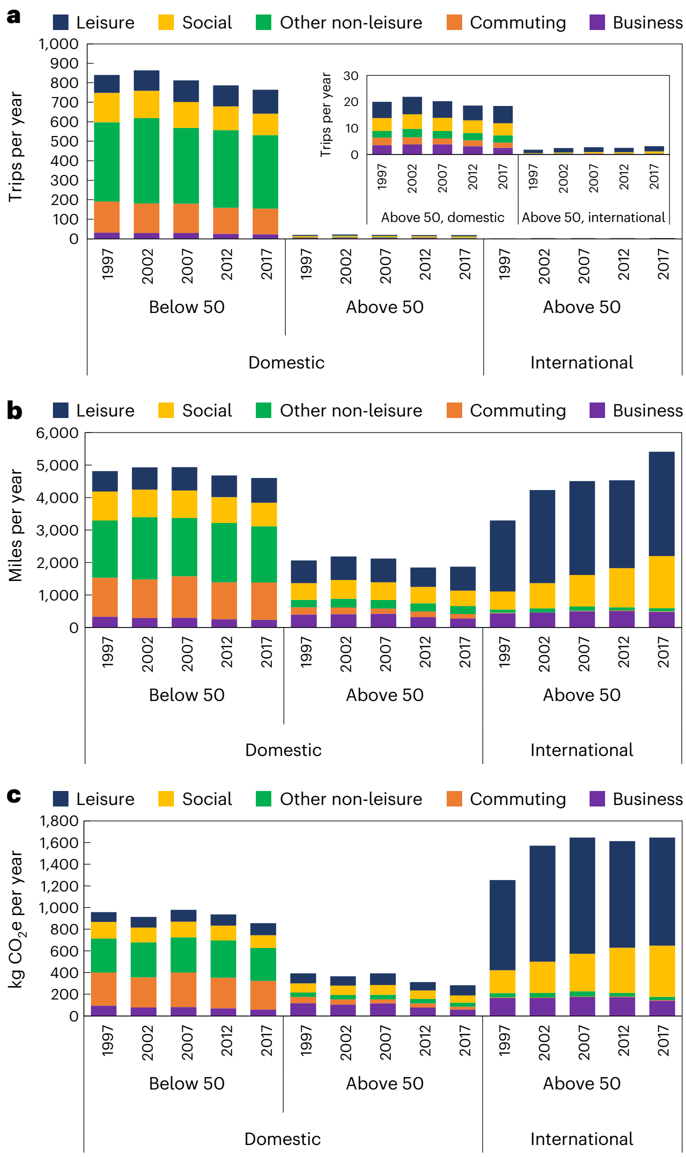

Fig. 5 | Trends in short- and long-distance trips by purpose. a–c, Trips are shown by trips per capita (**a**), miles per capita (**b**) and CO_2e emissions per capita (**c**) between 1997 and 2017 by travel purpose (inset in **a**: international trips). This shows the growing share of social and leisure travel.

To compare the efficiency of these diverse strategies in terms of their emissions reduction potential and alterations or substitutions needed in current trip making, we propose a new metric, emissions reduction sensitivity with respect to trips altered—ERSTA in short—defined as below:

$$\text{ERSTA} = \frac{\text{per cent reduction in emissions}}{\text{per cent trips altered}}.$$

As such, it is the ratio between (1) the emissions that would be saved if a subset of trips were to be substituted by alternative modes, destinations, behaviours or curtailed completely and (2) the proportion of total trips that these represent. The metric identifies where the maximum amount of emissions savings can be secured from the smallest number of trip alterations and is a function of not only the emissions intensity of the original and shifted modes or destinations (in g/pass-km or g/pass-mile) but also the share of emissions, miles and trips for the original and altered modes or destinations. Comparing two strategies, a larger value of ERSTA would suggest a relatively larger reduction in emissions compared with altered trips, indicating a greater efficiency. An inverse metric—trip alteration sensitivity to emissions reduction (TASER), defined as the ratio of per cent altered trips to per cent reduction in emissions—may sometimes also be useful to stakeholders involved in decarbonizing travel.

For the aforementioned two strategies, shifting car LDT to rail (strategy D) has an order of magnitude larger ERSTA compared with modal shift to walking and cycling (strategy A). Similarly, shifting all aviation trips under 1,000 miles to rail can reduce emissions by 5.6%, disrupting only 0.17% of all trips (strategy E). Taking driving holidays within Great Britain instead of flying abroad (strategy F) can reduce mileage by 20.9% and emissions by 27.6%, but affects only 0.22% of all trips. More restrictive policies that target frequent flying and discourage more than one return flight per person per year (for those who fly now, strategy L) can reduce emissions by 33.9%. The emissions reduction sensitivities are clearly very high for these strategies (Table 1).

It is important to note that, while the ERSTA or TASER metric captures the alterations in the numbers of trips, it does not differentiate between the type of changes required; some of the strategies may include foregoing trips completely, while others may only include a modal shift. Also, the efforts needed from the policymakers or the willingness of the travellers to make the changes are not captured. For example, the marginal utility of the only LD holiday trip in a year will probably be more than the marginal utility of the 200th short car trip, indicating that people may be less keen to give up that LD holiday trip than switching to bicycles for some of the short trips. Addressing these aspects to the proposed metric will be a useful avenue of future research.

Discussion

International travel and emissions (especially aviation), which are all LD in nature, clearly account for a very large share of mileage and emissions for a passenger's travel profile, and excluding them in national emissions accounting leaves these emissions to be addressed by the unpredictability of international negotiations (for example, the limited inclusion of aviation in the European Emissions Trading Scheme[30] or the recent non-binding emissions reduction aspirations by the International Civil Aviation Organization[31]). Personal carbon budgets or carbon trading are also increasingly being discussed as a policy lever to reducing travel demand and carbon emissions[32–34], and any such approach requires the full attribution of travel-related emissions (including aviation) to the respective travelling population. All these point towards the need for including international aviation emissions in carbon accounting for passenger travel[35,36]. The UK Government's intention to include international travel emissions in its carbon budget from 2033 is a step in the right direction; however, more is needed internationally to harmonize this approach.

Air transport's impact on global warming remains a source of uncertainty. Using a higher CO_2 multiplier for air transport's radiative forcing than that suggested by the Department for Business, Energy and Industrial Strategy (BEIS) and used in this study (Methods) increases the aviation (and leisure and social travel) share of CO_2e emissions even further (Supplementary Figs. 3 and 4). Recent studies[37] suggest that, given the urgency of the climate change problem, 20-year GWP should be considered as an alternative to 100-year GWP, and aviation's impact becomes even larger using this metric. Further, estimation of international aviation emissions requires reevaluation in the national emission accounting framework given that the current approach of using bunker fuel sales substantially underestimates the emissions by UK residents (Supplementary Fig. 10).

Our finding of a disproportionately large share of mileage and emissions from LDT (2.7% trips, 61.3% miles and 69.3% emissions) is not unique. In the Netherlands and Flanders region (Belgium) the ratio was 1–2%:44–45%:48% in 2013 (ref. 10), and in Germany it was 1.7%:46.3% for trips and miles in 2018 (ref. 38). The LDT cut-off was 62.1 miles (100 km)

Table 1 | Mitigation potential of different modal shift and technological policy options

	Policy options	Reduction in miles (%)	Reduction in emissions (Em) (%)	Disrupted trips (Tr) (%)	Emissions reduction sensitivity[a] = Em/Tr
A	All car trips under 8 miles shifted to walking and bicycle	0.0%	9.3%	55.05%	0.17
B	All car trips under 8 miles shifted to walking and cycling, all car trips 8–16 miles shifted to electric bicycles	0.0%	16.9%	66.75%	0.25
C	Half of all LD car trips shifted to rail	0.0%	2.6%	0.90%	2.88
D	All LD car trips shifted to rail	0.0%	5.2%	1.80%	2.88
E	All flying trips under 1,000 miles shifted to rail	0.0%	5.6%	0.17%	33.2
F	All holidays involving flying abroad shifted to domestic holidays by car (300 miles one-way)	20.9%	27.6%	0.22%	122.9
G	All holidays involving flying abroad shifted to domestic holidays by rail (300 miles one-way)	20.9%	30.2%	0.22%	134.5
H	All holidays involving flying abroad halved, the rest shifted to domestic holidays by car (300 miles one-way)	7.9%	12.2%	0.11%	108.3
J	Reduce business flying trips by half	2.0%	2.6%	0.02%	129.8
K	Stop all business flying trips	4.1%	5.2%	0.04%	129.8
L	Maximum one return trip abroad is permitted per person per year[b]	27.4%	33.9%	0.21%	158.3
M	All car trips shifted to electric, using current grid mix for upstream emissions	0.0%	21.1%	0.0%[c]	–
N	50% fuel replacement with sustainable aviation fuel (with a 70% emissions reduction potential over replaced fuel on a lifecycle basis)[d]	0.0%	19.3%	0.0%	–

[a]The proposed emissions reduction sensitivity with respect to trips altered (ERSTA) score calculates the ratio of percentage changes in emissions to percentage alterations in the trips. It is clear that measures targeting flying have very large scores, few orders of magnitude larger than the short-distance measures. For measures involving car travel, those involving LDT have a larger reduction sensitivity. [b]Those who do not fly in a given year continue to have zero flights. [c]Assuming EVs have the range to replicate all petroleum car trips without any disruptions. [d]This is an optimistic estimate using ref. 49; it is likely that the reduction on the basis of radiative forcing will be less given the non-CO_2 effects at high altitude.

in both of these studies, and at this threshold, our recalculated ratio would be 2.1%:58.9%:67.8% (Supplementary Fig. 5). This shows that UK residents have a slightly larger share of LD trips, but those trips cover substantially larger shares of miles and CO_2e emissions than their European counterparts. It is likely that the geography-related differences in travel patterns (due to an island and/or edge location) and a more diverse population in England with ties to other countries are responsible for the rather large difference in LD miles. In a 'net-zero' society, reducing GHG emissions from all types of passenger trips (along with emissions from other transport and end-use sectors) is important; however, the oversized contribution of LDT requires special attention for both calculating emissions and devising mitigation policies. Yet, for travel-behaviour-related approaches, LDT also offers the opportunity to reduce the emissions with the least disruption in the number of trips. Among the strategies considered, those addressing LD car trips are at least an order of magnitude more efficient that those addressing urban car trips. Strategies involving flying are another order of magnitude more efficient in terms of the least disruption to the trips for an average England resident.

Flying internationally for leisure and social purposes has emerged as a crucial segment because of both its large share in mileage and emissions footprint and its continued growth over the past two decades compared with other travel purposes and modes. Post-COVID-19 international travel statistics also show that these two segments are still thriving[39]. While social flights abroad can be personally important and unavoidable for those with families abroad, holidays abroad are generally perceived as discretionary in nature, as opposed to the generally non-discretionary nature of commute trips. Indeed, the number of flights taken is also closely related to income, indicating that many flights are luxury rather than necessary activities[40–42]. Choice experimentation studies show that people are more willing to give up flying compared with other transport- and domestic energy-related means to reduce emissions to meet a carbon budget at a household or personal level[28]. Specifically, targeting flying for leisure and social purposes can bring about a disproportionately large reduction in emissions. Yet, despite the high emissions reduction sensitivity for flying-related measures in general, there are few initiatives in this area, especially in comparison with behavioural (and technical) measures around surface transport. This reveals a mismatch between policy investments and potential returns.

Technological solutions such as energy efficiency[43] or low-carbon technologies (for example, electric cars[44,45]) or renewable fuels (for example, biofuels[46]) have attracted the most attention in reducing energy use and GHG emissions from the transport sector. While this study focuses on the travel demand side of emissions and its mitigation, there is an interaction between demand and technologies (or fuel), too. For instance, shifting all car trips to electric vehicles (EVs) now can reduce total passenger travel-related emissions by 20.1%, but this would still require 32.9 million cars[47] to be switched to EVs (despite the growing EV sales, only 0.75 million vehicles are currently fully electric in the United Kingdom[48]). On the one hand, using optimistic estimates[49], a 50% blend of sustainable aviation fuels with jet fuel could reduce emissions by a similar amount (19.3%) with little disruption in travel patterns (Table 1), although the scale of alternative fuel production required (given the mileage it needs to support) will probably be prohibitive and the viability is presently uncertain due to the availability issues of the feedstock and potential competition with food production. This again shows the role of LDT, especially aviation, to reduce emissions further and with fewer disruptions in overall trips. On the other hand, new road vehicle technologies such as automated vehicles could substantially increase car travel demand in future[50], especially for LD trips[51]; as such, decarbonizing car travel need not be de-prioritized and a careful balancing act is needed.

The data fusion approach used in this study has allowed the estimation of the LD trips, mileage and emissions only at some broad category level. These averages mask potentially large variations among the population. For example, the top 1% car travellers in England travel seven times as much as the average car travellers for domestic travel[52].

Similarly, there are large equity concerns in air transportation, as only one-fifth of the fliers in the United Kingdom are known to take around three-quarters of all the flights[53]. Spatial difference may also exist, for example, urban residents are known to fly more than rural residents[17]. As such, an important area of future research is to understand the distribution of these LD trips, miles and emissions among the population in order to better target a policy for a particular group of travellers (say, frequent fliers) or a particular type of trip (for instance, holiday trips abroad and short city breaks) or to better understand the equity implications of a particular policy. Given that traditional, nationally representative household travel surveys often underestimate LDT, especially international travel, it is also important to improve the data collection procedure[54,55].

Conceptually, the emissions reduction sensitivity metric can also be expanded in future to include other non-travel consumption. The Emissions Reduction Sensitivity to Consumption Substitution could measure the ratio between (1) the emissions that would be saved if a subset of products or services were to be substituted by those with lower per-unit carbon intensity and (2) the proportion of total products or services that this subset represents. The metric can then be used to identify where the maximum amount of emissions savings can be secured from the smallest number of changes in the demand for a product or service and identify the strategies with the largest return.

Methods

LDT definition

There is a lack of agreement on the definition of LDT in literature; however, most studies use one or the other of the following four criteria: longer spatial distance, longer duration of travel, occurrence with a low frequency and with a lack of regularity, or overnight stay at a non-home location[11]. The last of these criteria is more common in tourism literature, whereas the first few are used more in mobility studies[56]. The threshold for the distance definition varies from country to country: in the United Kingdom's NTS and the United States' National Household Travel Survey it is 50 miles, while in European surveys they are often longer (100 km, or 62.1 miles)[12]. While devising a consistent definition can be useful—especially for harmonization and comparison across countries—in this study, the NTS cut-off of 50 miles one-way is used to define LDT. The exact definition and cut-off will affect the numerical results, however, our key conclusions on the role of LDT in emissions and decarbonization will likely hold for any reasonable definition of LDT. A higher cut-off will increase the share of air transport within LDT miles and emissions but decrease the LDT share of trips, miles and emissions from all travel (Supplementary Fig. 5).

Data sources

The main sources for travel data for this analysis are the NTS[14] for domestic travel and IPS[15] for international travel. We use year 2017 microdata for both for our main analysis and then 1997–2017 surveys at 5-year intervals for temporal analysis. Supplementary Notes 4 and 5 list the data sources for each of the variables of interest and sample sizes for the underlying travel statistics.

Domestic travel within Great Britain is measured through the NTS. Its respondent households are selected through multistage stratified random sampling to be representative of travel patterns in England. All household members complete their weekly trip diaries noting every trip detail (trip purpose, length, modes used and accompanying passengers), alongside responding to an interview detailing other socio-demographic (gender, income, household size and area) and vehicle-related information among which vehicle characteristics (make, model, fuel type and fuel economy) are of particular interest here. All trips starting in England and ending within Great Britain (domestic trips) are recorded. A trip is defined as a one-way course of travel with a single main purpose and can have multiple stages if the mode of travel changes[57]. We retain this one-way definition of a trip.

LD trips in NTS are recorded for an additional week to account for their smaller frequency of occurrence. However, studies have shown that LDT reported in the main diary are more likely to be accurate and reliable[58]. So, we have used 1-week's main travel diary for this analysis. Short walks (walking trips <1 mile) are excluded from this analysis as they do not contribute to the emissions but have disproportionally high impact on trip rates because of their frequent occurrences. Weights are added to each record to cover impacts of non-response, sampling and coverage errors, these weights have been applied while deriving the totals or averages. This study used the 'Special Access License' version[14] of the dataset, with more details compared with the regular version. NTS is a rolling survey, whereby different households are surveyed at different times over the year. This is especially important for calculating annual averages for LDT, which is known to exhibit a seasonal pattern.

International travel from the United Kingdom, all of which are LD, are carried out by air, train (Eurostar), cars or coaches via ferries or Le Shuttle or sea cruises. IPS is the only national survey in the United Kingdom that collects data regarding international travel to and from the United Kingdom[59]. It interviews a large sample of international travellers across most of the international points of arrival and departures (airports and seaports) in the country. As such, it is an intercept survey. Recommended weights are also applied for IPS records for the results to be representative[60]. Unlike NTS data, some IPS data required further processing to obtain travel distances and trip rates for some modes. These are described in detail in Supplementary Notes 6–8. For cruise travel, cruise destinations data by Cruise Lines International Association (CLIA)[61] was used.

Data fusion strategy

Since the survey respondents are different in IPS and NTS, an individual-level analysis is not possible, and group-wise averages are used for analysis across trip distance bands, modes or purposes. Further disaggregation was avoided (for instance, travel by age, mode, purpose and distance band) since there would be very few responses in many smaller subgroups for the averages to be consistent and meaningful across surveys and years. Some of the variables are not available across the two surveys as well (for example, income). As such, the analysis was done on an average per capita basis and heterogeneity in the travel profile could not be ascertained.

Given the very different objectives of these surveys, the data elements often do not correspond to each other and some harmonization is necessary to get a consistent set of definition across two surveys. A common set of categories was created for each data element (mode, purpose and distance band) across surveys and survey years. These harmonizations are presented in Supplementary Note 6.

Once the categories are harmonized, domestic and international travel miles per capita were calculated separately by purpose, mode and of travel distance bands. Details of these calculations are presented in Supplementary Notes 7 and 8. Both IPS and NTS use weights corresponding to each observation, and these weights are applied to estimate aggregates or averages. The mileage calculations were then validated against the data providers' aggregate mileage measures. Finally, both mileage values were added to get the total of domestic and international miles per capita. Supplementary Fig. 6 explains the data fusion flowchart.

Emissions calculation

CO_2e emissions factors used in this study uses radiative forcing for 100-year GWP. CO_2e emissions are calculated at a trip level when microdata are used from NTS and IPS using the ASIF (Activity-Structure-Intensity-Fuel) framework of Schipper and Marie-Lilliu[62] using trip distances and carbon intensity (emissions factors) of the modes used for the trips. For car-based trips from NTS, the CO_2 factor is derived from household vehicle information directly (for 2007–2017 surveys) and multiplied by 1.01 (ref. 63) to include the

https://doi.org/10.1038/s41560-024-01561-3

warming effects of other pollutants (for example, N_2O) and get CO_2e. Load factor (occupancy) for private vehicles is calculated from individual trip data of NTS; hence, the estimates already include the effect of often higher occupancy of car LDTs compared with shorter car trips. Several regression analyses are carried out to calculate emissions factors for missing records for different years (Supplementary Note 9). For pre-2007 survey data, when vehicle emissions factors were not fully reported for all individual vehicles in NTS, BEIS emissions factors[63–65] were used by engine size and fuel type (Supplementary Note 10). These are also for CO_2, but were multiplied to get CO_2e. Since all of these private car emissions factors are based on laboratory testing using standard drive cycles, an emission uplift factor is used to realistically estimate on-road emissions. The uplift factors vary between years, and we used BEIS[66] to get the uplift factors. For the few EVs in NTS, upstream emissions (grid) are considered.

For trips undertaken via rail, aviation, cruise, coaches and buses, and ferries, BEIS average emissions factors are used, where possible with some differentiated factors[63]. For example, for air trips, BEIS emissions factors for long-haul flights (>2,000 miles long) and short-haul flights (<2,000 miles) were used. For air travel particularly, radiative forcing due to non-CO_2 emissions (for example, water vapour at high altitude) is especially important and the relevant emissions factors were used.

For international travel, mode-specific emissions factors over time were computed through a linear backcasting of European Environment Agency emissions factors[67] for air, rail and sea travel. Supplementary Notes 10 and 11 describe all emissions factors in further detail. Supplementary Note 12 presents a comparison with national aggregate emissions and explains any differences.

Data availability
The data used in this study are all publicly available; Supplementary Table 3 lists the data sources. Source data are provided with this paper.

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Acknowledgements

The authors thank S. Cairns and M. Morgan for stimulating discussions. All three authors also acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions, grant reference number EP/R 035288/1. The NTS special licence microdata were kindly provided by the Economic and Social Data Service (ESDS) through the UK Data Archive at the University of Essex, Colchester.

Author contributions

Z.W.—writing, study design, review of analysis and funding acquisition; M.A.—writing, data collection and data analysis; J.A.—funding acquisition, and review and editing.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41560-024-01561-3.

Correspondence and requests for materials should be addressed to Zia Wadud.

Peer review information *Nature Energy* thanks Lisa Aultman-Hall, Jeffrey LaMondia, Tobias Kuhnimhof and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.