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Spatial-temporal variation of CO₂ emissions from private vehicle use in Japan

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E-mail: longyinutokyo@gmail.com and liyuancolour@gmail.com**Keywords:** micro-survey, greenhouse gases emissions, transport sector, spatial-temporal patternsSupplementary material for this article is available [online](#)**Abstract**

The transport sector is a major contributor to anthropogenic climate change through the emissions of large amounts of greenhouse gases from fossil fuel combustion. Private vehicles account for almost half of the transport energy demand, and are thus a major target for climate change mitigation efforts. However, emissions from private vehicles can have large variability due to various geographic, demographic and socioeconomic factors. This study aims to understand how such factors affect private vehicle emissions in Japan using a nationally representative survey of household energy consumption ($n = 7370$) for 2017. The results indicate a large temporal and spatial variability in private vehicle emissions. Annual emissions show three peaks associated with major holiday seasons in winter and summer. Some of the more noteworthy spatial patterns are the higher emissions in prefectures characterized by low population density and mountainous terrain. Income, city size and the fuel-saving driving behavior all have a significant effect on emissions. The results indicate the need for sub-regional and socioeconomically-sensitive mitigation efforts that reflect the very different emission patterns, and the factors affecting them. The strong effect of city size, which is often much more clear-cut than between prefectures, suggests that it is more appropriate to approach transport decarbonization in Japan at the city level.

1. Introduction

The transport sector is a major source of greenhouse gases (GHGs) emissions globally. The sector has been reportedly responsible for emitting 7.0 GtCO₂eq yr⁻¹ in 2010 [1], accounting for approximately 23% of total energy-related GHG emissions globally (approximately 6.7 GtCO₂eq yr⁻¹) [2]. However, by 2018 transport-related GHG emissions increased to 8.0 GtCO₂eq yr⁻¹ and accounted for 24% of energy-related GHG emissions [3], even under the aggressive promotion of low carbon transport technologies. Undoubtedly transport-related GHG emissions could increase at even faster rates compared to other energy end-use sectors in the absence of aggressive actions, especially when

considering the emissions from the booming global trade and supply chains [3–5]. However, the implementation of effective transport-related GHG emission mitigation measures has been challenged by both the constant growth in passenger and freight activity, and the burgeoning demand for mobility and private vehicle ownership in many countries (and particularly emerging economies) [6]. There are concerns that these phenomena could indeed outweigh ongoing emission mitigation efforts [3, 7]. For example, it has been estimated that without aggressive mitigation policies, transport-related GHG emissions may exceed 12 GtCO₂eq yr⁻¹ by 2050 [2].

When disaggregating emissions from the transport sector, it is estimated that private vehicle use accounts for 46%–48% of the total transport-related

GHG emissions [8, 9]. According to the International Energy Agency, private road vehicle emissions in 2018 stood at 3.6 GtCO₂eq yr⁻¹, which was 1.2 GtCO₂eq yr⁻¹ higher than emissions from road freight vehicles and 2.7 GtCO₂eq yr⁻¹ higher from aviation emissions [3]. Unsurprisingly, controlling the GHG emissions of private road vehicles has been at the forefront of climate change mitigation efforts through very diverse technological, socioeconomic, behavioral, and policy approaches [2, 6, 10, 11].

However, various geographic, demographic, behavioral and socioeconomic factors may affect GHG emissions from private vehicles, and consequently the type, promotion, adoption and overall effectiveness of such measures. For example, in many national contexts the GHG emissions of private vehicles are significantly correlated with demographic and socioeconomic factors such as population, age and income [12, 13]. At micro-levels (e.g. households, individual users), transport-related GHG emissions per household member is often significantly correlated with increases in living standard [14], or other household characteristics via private car ownership, use and efficiency [15–19]. At macro levels (e.g. neighborhood, city), population density in residential areas seems to have a significantly negative effect on private vehicle ownership [19, 20] and the associated GHG emissions. Furthermore, urban form may also influence private car ownership and related GHG emission by influencing households to shift travel choices and behavior [17, 21, 22].

The above imply both a need for obtaining a good understanding of the factors affecting private vehicle emissions, as well as for designing and implementing targeted emissions mitigation measures [17, 23]. In this respect it is important to generate fit-for-purpose evidence at appropriate resolutions that can offer sufficient insights to relevant decision-makers of who, where and how should be targeted. However, there is often a lack of datasets with appropriate resolution and quality to enable the estimation of the temporal and spatial variability of transport-related GHG emissions, as well as understanding the factors affecting this variability [17, 18].

Japan is a highly industrialized country where the transport sector still remains a major source of GHGs emissions, accounting for 17%–19% of national emissions in the past five years [24, 25]. Nearly half of these emissions are from private vehicles, which accounted for 45.9% of total transport-emission in 2019 [25]. As a result, the transport sector, and particularly private vehicles, are a major focus of GHG emissions reductions efforts in the Japanese Intended Nationally Determined Contribution (INDC) to the Paris Agreement [26]. However, despite the numerous studies on private vehicle emissions in Japan, there are still three major knowledge gaps. First, although some studies have discussed the emissions of (and mitigation potential from) private vehicle

[9, 18], such studies have seldom used high quality and resolution micro-level data at the national level due to their unavailability. Second, the demographic, geographical, and socioeconomic determinants of transport emissions have usually been discussed separately [27–31], with no comprehensive synthesis to understand their different effects on private vehicles emissions. Third, the past studies have largely ignored emission seasonality, again due to the lack of datasets with appropriate temporal resolution [32, 33].

To resolve these knowledge gaps, the aim of this study is to provide a comprehensive analysis of the spatial and temporal characteristics of GHG emissions from private vehicle use in Japan, as well as the factors affecting them. We use 7370 micro-level surveys (i.e. at household scale) for the year 2017, which is the most recent year for which such is data available at the moment. More broadly, Japan offers a very interesting case study to explore this interface, considering that private vehicle use and emissions are not uniform owing to the very diverse geographical and socioeconomic factors across the country. For example, private vehicle use is more prevalent outside of the major cities that have good public transport systems, with the residents of rural and mountainous areas being particularly dependent on private vehicle use [27]. At the same time, the Japanese population is rapidly shrinking (as in many parts of the developed world) [34], especially in such small cities and remote areas, which may have important ramifications for private vehicle use and emissions [35].

Section 2 outlines the methodology of the study. Section 3 presents the spatiotemporal variations of emissions from private vehicles (section 3.1) and the factors affecting them (section 3.2). Section 4 puts the main findings into perspective and their implication for emission mitigation from the transport sector.

2. Methodology

2.1. Household-level emissions from private vehicles

A well-established body of literature has analyzed the emissions associated with private vehicle use in different parts of the world, through for example approaches as diverse as the driving force analysis method [36, 37], the conventional Impact of Population, Affluence, and Technology model [38–42], or the extended Stochastic Impacts by Regression Population, Affluence and Technology (STIRPAT) model [36, 43–45]. Such methods can be used to decompose the effects of different driving forces for macro-level data, and are particularly suitable for time-series data and capturing annual variation.

However, it is not always clear through such approaches what influences consumption behavior at the household level, including for private vehicle use [46, 47]. For example, some of the factors influencing household-level GHG emissions from private vehicle

use such as travel distance, engine size, and use frequency, can vary regionally [48], and thus not captured well in top-down studies. Furthermore, regional emission patterns may vary greatly within a single year due to climatic factors and seasonal activities (e.g. holidays) [49]. In this sense, understanding the temporal and spatial variation of GHG emissions from private vehicle use can be arguably as important as estimating the overall level of emissions [32, 50].

In this study, we use the ‘Survey Results on Japan Household Carbon Emissions’ to estimate the household-level emissions from private vehicle use, and their spatiotemporal variability. This one-off (and not recurring) survey was conducted in 2018 by the Japanese Ministry of Environment to understand patterns of energy use and carbon emissions from the household sector for the period between March 2017 and April 2018. During this survey [51], a representative sample of 9507 Japanese households was surveyed across the 47 prefectures of Japan⁵. Some of the variables included in this survey were household-level car use (e.g. use frequency, driving distance, car types), basic household characteristics (e.g. city, income, household size) and monthly fuel consumption (including both gasoline and diesel consumption), which collectively allow for a spatial and temporal analysis of car use patterns. For this study we exclude households that did not own a private car at the time of the survey, resulting in a sample of 7370 households.

It should be noted that the aim of the aforementioned survey was to capture all types of energy consumption at the household level. However, in this paper we analyze only the transport-related module, and thus we exclude households not owning private vehicles as mentioned above. However, it is not possible to ascertain whether the spatial distribution of the households considered in this study is similar to the distribution of private vehicles in Japan.

The carbon emissions generated from private vehicles in Japan are mainly due to the combustion of gasoline and diesel [52]. Although, electric vehicles can also have indirect carbon emission due to power generation, the penetration of electric vehicles at the point of the survey was rather low in the country (only 1% of new sold private vehicles are electric) [7]. Similarly hydrogen vehicles also had very low penetration rates at the time of the survey, despite ambitious targets [53]. For this reason, in this study, we only consider direct carbon emissions due to direct fossil fuel use.

⁵ According to the information provided by the MOEJ that undertook the survey the households are randomly sampled from both the Basic Resident Register Information and through an internet survey. In case of bias for urban areas the sample number was adjusted by prefecture and city level (MOEJ, 2018). Therefore, the sampled households follow a similar spatial distribution to the distribution of households and population.

The carbon emissions from the combustion of liquid fossil fuels from private vehicle transport in prefecture i and month j can be expressed as:

$$C^i = \sum_j^{n=1} (g_j^i * E_g + d_j^i * E_d) \quad (1)$$

where g represents the household-level gasoline consumption and d the diesel consumption for transport, E_g refers to the emission intensity of gasoline and E_d the emission intensity of diesel. The thermal conversion factors of gasoline and diesel are 33.36 MJ l^{-1} and 38.04 MJ l^{-1} , respectively. The emission intensities are 18.71 tC TJ^{-1} for gasoline and 18.79 tC TJ^{-1} for diesel. Emission intensities are derived from the Ministry of Environment Japan (refer here: <https://ghg-santeikohyo.env.go.jp/calc>).

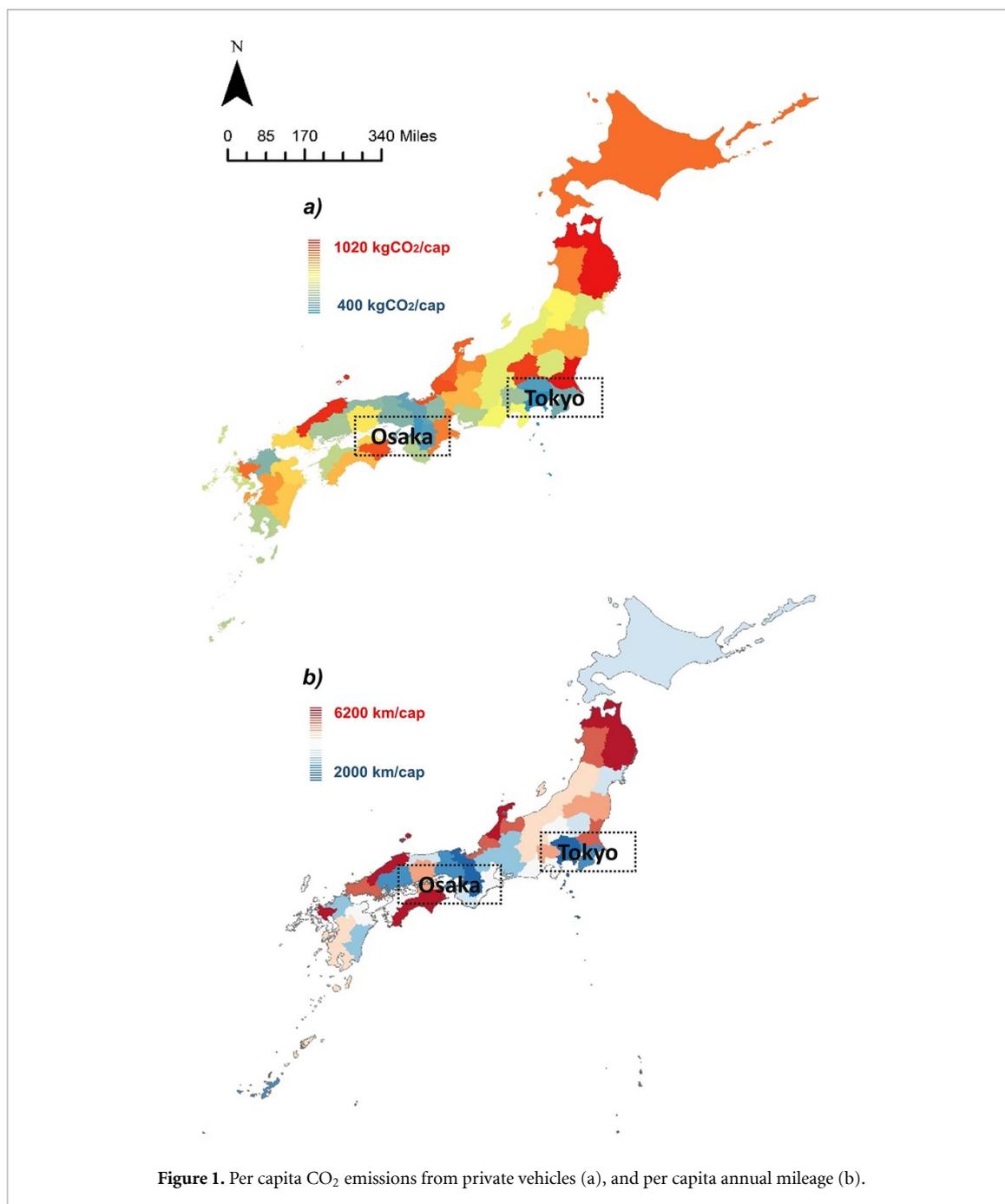
2.2. Factors affecting emissions from private vehicles

To further understand the patterns of household-level carbon emissions from private vehicle use, we explore the effects of some of the primary factors expected to affect their temporal and spatial distribution, including: (a) household size, (b) age, (c) vehicle fuel efficiency, (d) travel distance, (e) fuel-saving behavior (e.g. driving habits such as gentle acceleration/deceleration and fuel conservation while driving), (f) income, and (g) location (prefecture and city size). The equation can be expressed as follows:

$$\begin{aligned} & \text{CO}_2 \text{ emissions per household (per capita)} \\ & = \beta_0 + \beta_1 \text{size} + \beta_2 \text{age} + \beta_3 \text{fuel_efficiency} \\ & \quad + \beta_4 \text{Traveldistance} + d_{\text{Ecosense}} + d_{\text{Income}} \\ & \quad + d_{\text{City}} + \varepsilon. \end{aligned} \quad (2)$$

All of these variables were included the household survey that is used in this study as outlined below (section 2.1) (a) size is the number of people in each household; age is the average household age; fuel_efficiency is the fuel consumed per kilometer (1 km^{-1}); Traveldistance is the annual average running distance (kilometers); eco-sense is a dummy variable based on two questions concerning driver awareness and adoption of fuel-conserving practices during driving (e.g. accelerating the car slowly and gently); income is the household income according to seven groups (table S1, supplementary material (available online at stacks.iop.org/ERL/17/014042/mmedia)); and city level indicates the type of city the household was within, including large (prefectural capital and cities >100 000 population), medium (population 10 000–100 000), and small (population <10 000) cities.

The factors outlined above are correlated with the carbon emissions from private vehicle use, expressed as the total annual carbon emissions or monthly emissions, both for the entire household and on a per



capita basis (section 3.2). Before conducting the multiple regression analysis, we conducted multicollinearity testing using the variance inflation factor (VIF). All VIF scores were below ten, suggesting a lack of multicollinearity that might lead to inaccurate correlation results [54].

3. Results

3.1. Spatio-temporal variations in private vehicle emissions

Figure 1 presents the geographic distribution of average annual travel distance and emissions from private vehicles across the 47 prefectures of Japan (see figure

s1, supplementary information for a map of Japanese prefectures). The results indicate that households located in prefectures that do not contain major cities such as Iwate, Aomori, Ishiyama, Kochi, Tokushima, Saga, and Shimane tend to have the highest annual average travel distances and CO₂ emissions from private vehicles (indicated in red colors in figure 1). Conversely low average per-capita travel distances and CO₂ emissions are estimated in prefectures such as Tokyo, Kanagawa, Chiba, Osaka, Kyoto, and Hiroshima, which contain large cities with good public transport networks and dense populations [25]. This is reflected also quite well in the relatively lower ratio of using cars when people are going out (figure 2(a)) [55]. Figure 2(c) gives out the spatial

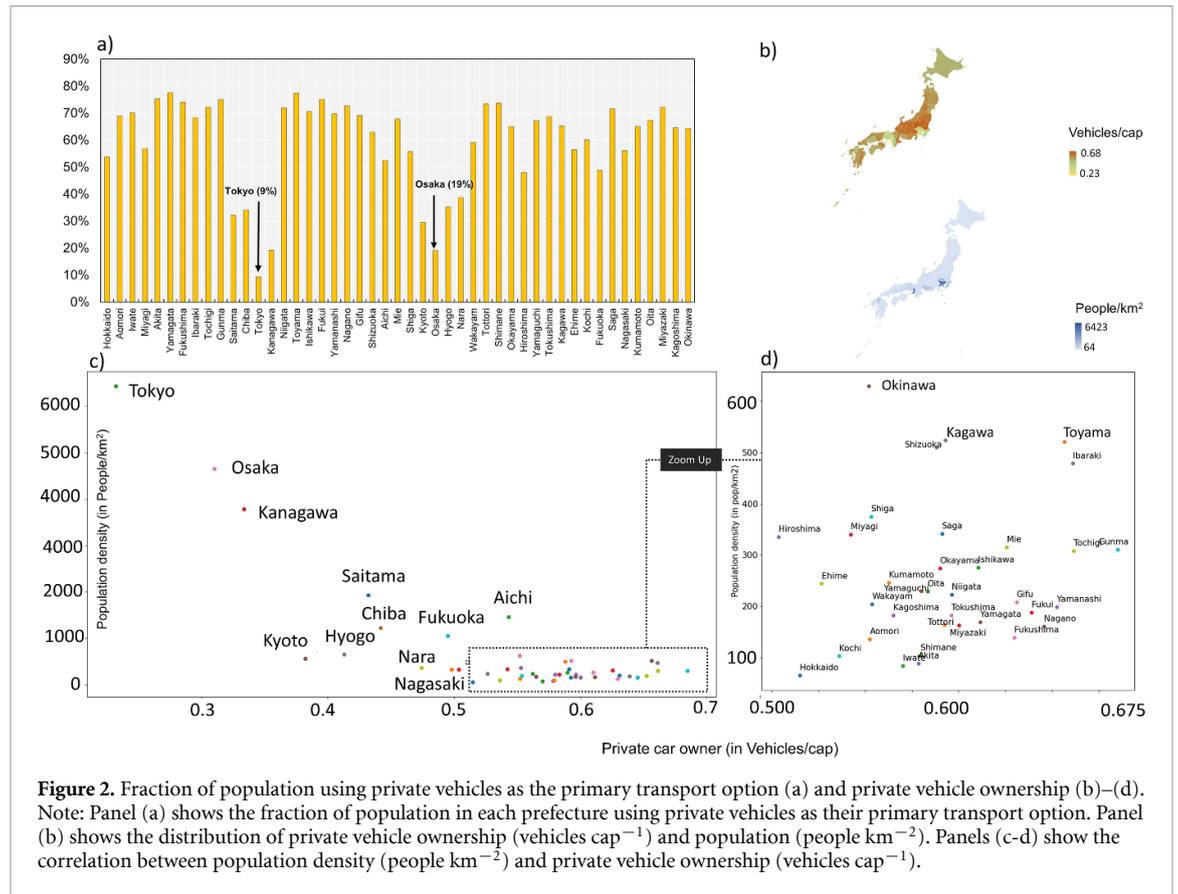


Figure 2. Fraction of population using private vehicles as the primary transport option (a) and private vehicle ownership (b)–(d). Note: Panel (a) shows the fraction of population in each prefecture using private vehicles as their primary transport option. Panel (b) shows the distribution of private vehicle ownership (vehicles cap^{-1}) and population (people km^{-2}). Panels (c)–(d) show the correlation between population density (people km^{-2}) and private vehicle ownership (vehicles cap^{-1}).

distribution of car ownership by per capita and population density. Then figure 2(c) shows correlations between population density and private car ownership, which indicate high car ownership (>0.6 car per capita $^{-1}$) only in prefectures with low population density (<1000 people km^{-2}), and figure 2(d) zooms up the prefectures which obtain higher car ownership (>0.5 car per capita $^{-1}$).

Beyond distance travelled and vehicle ownership, some geographical features such as the prevalence of mountainous terrain can also affect the emissions from private vehicle use. A clear such example is Gunma prefecture (just north of Tokyo), 70% of which is covered by mountainous terrain [56]. In this case carbon emissions are quite high (figure 1(a)) despite the relatively moderate travelled distance (figure 1(b)).

Apart from spatial heterogeneity, there is also temporal heterogeneity in emissions from private vehicle use (figure 3). At the national level, we can observe three emission peaks from private vehicle use in May, August, and December, with the peak in August being the highest (figures 3(a) and (c)). All three peaks coincided with the major holiday periods in Japan, i.e. the Golden Week (May), the Obon Festival (Aug), and New Year holiday (Dec-Jan). Similar patterns are also largely visible when looking these temporal patterns at the prefecture level (figure 3(a)).

Interestingly, emissions patterns exhibit lower seasonality for some prefectures in the northeastern part of Japan such as Iwate, Aomori, and Akita,

(in figure 3(a)), which are generally in the higher end of the emissions spectrum regardless of the season. This constant rate of emissions implies the central role of private vehicles for the daily lives of residents in these prefectures. In contrast, emissions from prefectures such as Tokyo, Hokkaido, and Tohoku are relatively stable throughout the year, and are at the lower end of the spectrum (figure 3(a)).

When looking both regional and monthly differences from figures S1 and 3(b), for prefectures such as Hokkaido and Gunma we estimate much higher emissions than other regions, due to much lower population density in the former case or geographical features (e.g. mountainous terrain) in the latter case. As explained above, the northeastern area is remote from the metropolitan areas of Tokyo and Osaka, resulting in lower population density and less developed public transportation systems. Therefore, behaviors of using private cars are comparatively stable as well as high in these areas. In contrast, lower emissions were observed for Saitama, Tokyo, and Kanagawa, which are located in the Tokyo metropolitan area.

Figure 3(b) shows boxplot of the distributions, which is for comparing the temporal difference across Japan. Besides, the emissions from each region by prefecture are given out in table S2. According to figure 3(b), although the emissions were slightly higher in August, the general variation trend did not significantly change. Therefore, there were monthly

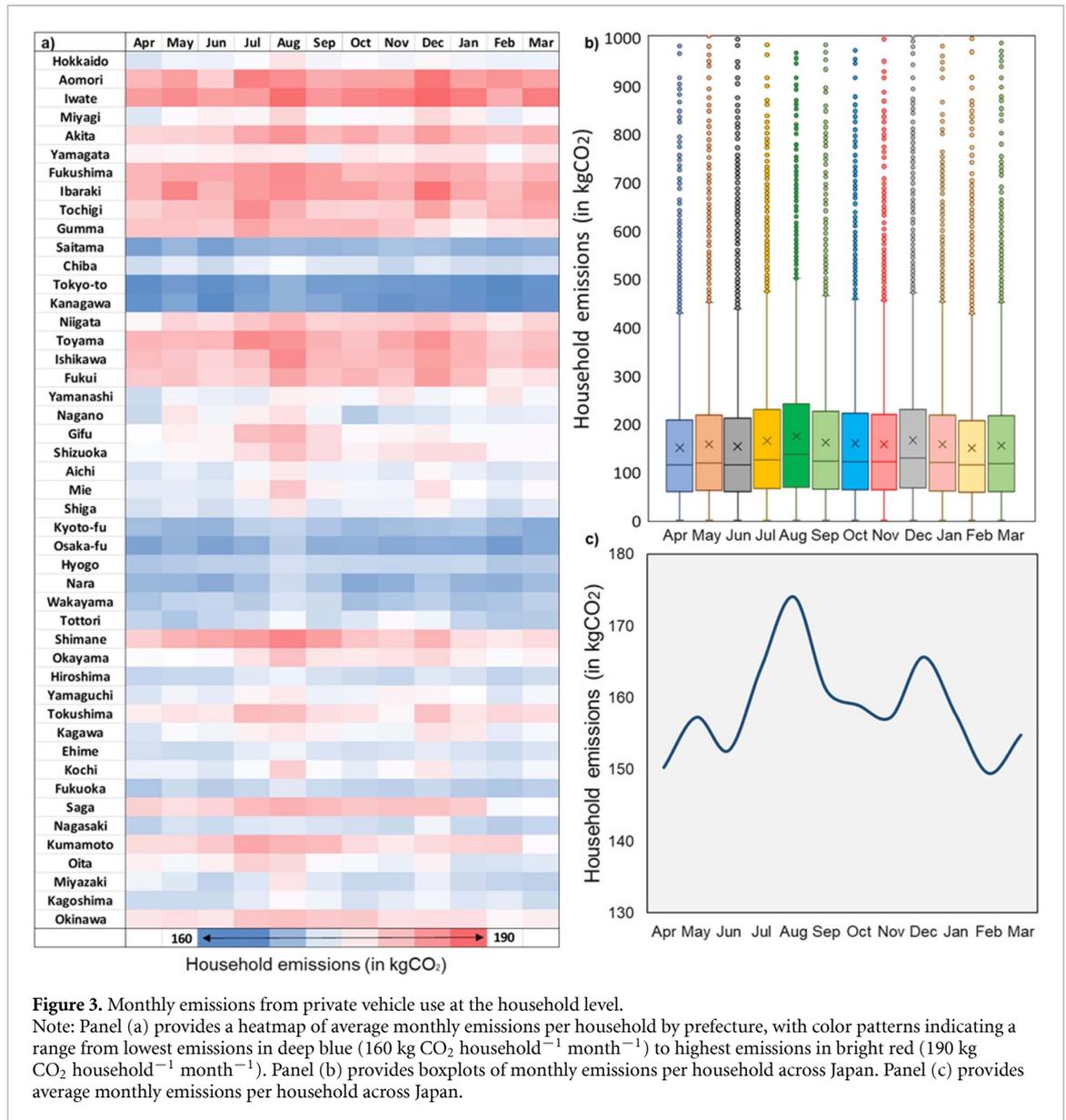


Figure 3. Monthly emissions from private vehicle use at the household level.

Note: Panel (a) provides a heatmap of average monthly emissions per household by prefecture, with color patterns indicating a range from lowest emissions in deep blue (160 kg CO₂ household⁻¹ month⁻¹) to highest emissions in bright red (190 kg CO₂ household⁻¹ month⁻¹). Panel (b) provides boxplots of monthly emissions per household across Japan. Panel (c) provides average monthly emissions per household across Japan.

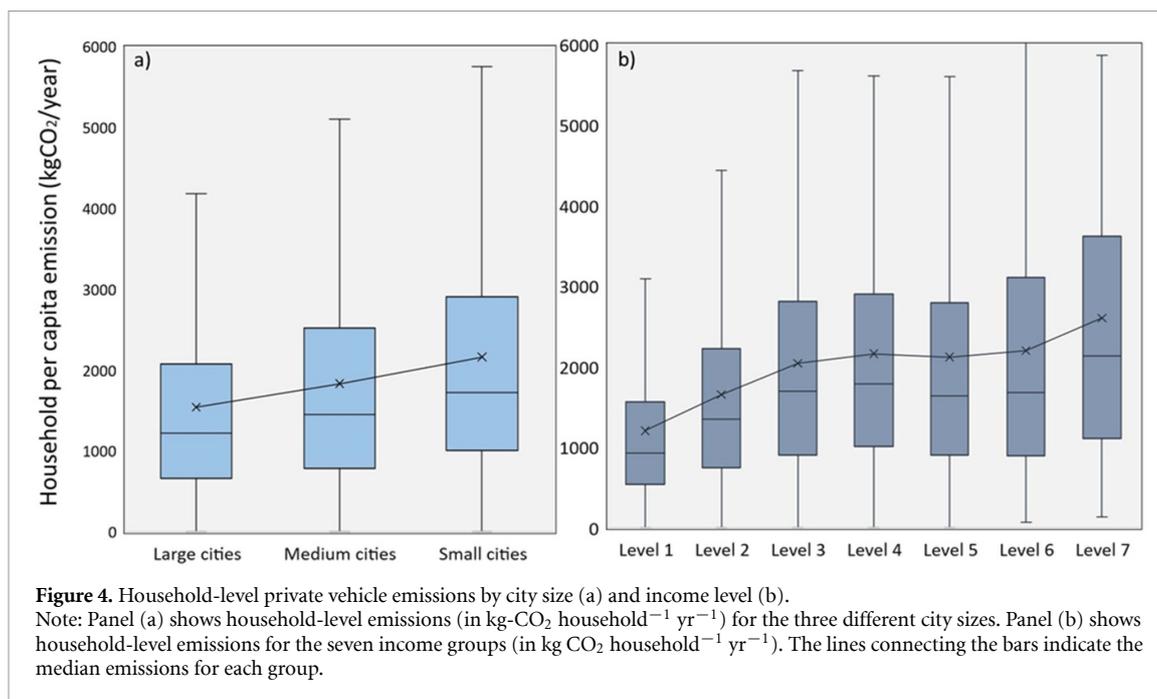
variations, but they were not notable. However, according to the grouping of samples by region, Tohoku and Hokuriku exhibited higher private car emissions, which was consistent with figure 1(a) from a prefecture perspective. From these observations, the regional differences were greater than the monthly disparity. There were notable variations in the emissions between the regions of Japan, and regional impacts should be considered when exploring the driving forces of private car emissions. Last, although seasonal variations were not a primary source of emission disparity, they could be taken as a secondary reference for the implementation of seasonal emission control measurements.

3.2. Factors affecting emissions from private vehicle use

Below we explore the factors underpinning the differences in emissions patterns. Figure 4 outlines the per-household emissions from private vehicle use by

city size and income level. Emissions seem to increase as the city size decreases, with emissions from large cities often being below 2 tCO₂ household⁻¹ yr⁻¹, while emissions from smaller cities sometimes exceeding 5 tCO₂ household⁻¹ yr⁻¹. At the same time, private vehicle emissions increase with income level. Figure 4(b) suggests, that as the income level increases, the overall emissions from private vehicle use not only increases.

To further understand how different factors affect private vehicle emissions, table 1 provides the results of seven regression models that identify the factors with the greatest influence on CO₂ emissions from private vehicle use (see section 2.2). Models 2–7 consider the regional fixed effects. The results of the regression analysis suggest that city size, household size, eco-sense, income level, engine displacement, and travelled distance were all significantly correlated with the annual CO₂ emissions from private car use, regardless of whether the results are expressed per



household (table 1) or capita (table s3, supplementary information).

First, the results indicate clearly that city size has a significant negative effect on emissions both per household and per capita, with the emissions significantly decreasing as the city size increases (by 18%–19%). Second, total household size has a positive effect on emissions, with the total emissions at the household level and per capita being higher from larger households (by 24% on average) (tables 1 and S3 supplementary information). Third, we observe a significant negative correlation between emissions and fuel-saving driving behavior, with households using such practices having lower emissions (by 8%).

4. Discussion

4.1. Implications of spatial and temporal emission variation for mitigation strategies

Several studies have discussed the correlation between city size and emissions from private vehicles [20, 32, 57–59]. Such studies have suggested that energy consumption and associated emissions from private transport vehicles are lower in larger cities, partly due to the well-established public transport systems or the high fees associated with parking [25]. Our results for Japan are similar, as the estimated household emissions from private vehicles (a) are lower in prefectures that are parts of mega-cities (e.g. prefectures in the regions of Kanto and Kinki) (figure 1), and (b) increase with decreasing city size (figure 3). Thus the results from this bottom-up analysis of survey data are consistent with other studies that have used top-down methods in Japan [12, 13, 60]. In more detail our results range between 0.4–1.0 tCO₂ cap⁻¹ yr⁻¹, which is similar to findings

from the National Environmental Institute of Japan (NIES) (0.2–1.2 tCO₂ cap⁻¹ yr⁻¹) [61] and peer-reviewed studies (0.3–1.4 tCO₂ cap⁻¹ yr⁻¹) [12, 62].

Overall although we observe a strong spatial variation in emissions from private vehicle use, we do not believe this is attributed to differences in administrative regulations or fuel intensities. For example, when it comes to economic incentives related to private vehicle ownership, car-related taxation is not very different between regions⁶ (e.g. compared to federal countries such as the US [63]), while the fact that more than 99.5% of the oil products is imported means that the emission intensity across Japan is rather unified [64].

Perhaps the main reasons behind the regional differences on private vehicle emissions are the differentiated residential travel behaviors, which are further triggered by household characteristics (e.g. income), location (e.g. size of city which reflects also access to public transport services) and possibly operational vehicle costs. For example, regarding the latter the operational costs of private vehicles are quite different between Japanese regions, with people living in large cities, such as Tokyo, facing much higher parking costs. This increases driving costs in large cities, reducing the cost-effectiveness of private vehicle transport to many urban households, especially when considering the extensive and reliable public transport systems in most of the large Japanese cities.

⁶ There are nine different taxes related to private vehicles in Japan, which are imposed during purchase (acquisition tax), ownership (usually related to car characteristics) and use (usually related to fuel). Most are levied by the national government, while even those collected by the regional governments have the same levels between regions (www.car-tax.go.jp/).

Table 1. Factors influencing the annual total emissions by region.

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
2. CITY_CLASS	0.318*** (0.0392)	0.305*** (0.0404)	0.306*** (0.0404)	0.319*** (0.0379)	0.346*** (0.0378)	0.370*** (0.0378)	0.212*** (0.0340)
3. CITY_CLASS	0.677*** (0.0541)	0.532*** (0.0557)	0.535*** (0.0557)	0.560*** (0.0507)	0.596*** (0.0503)	0.631*** (0.0502)	0.365*** (0.0468)
Fuel-saving behavior			-0.0886** (0.0434)	-0.1000** (0.0399)	-0.0998** (0.0395)	-0.123*** (0.0393)	-0.159*** (0.0359)
Household size				0.449*** (0.0155)	0.387*** (0.0165)	0.383*** (0.0163)	0.285*** (0.0159)
2. Income_level					0.291*** (0.0419)	0.241*** (0.0417)	0.108*** (0.0369)
3. Income_level					0.547*** (0.0529)	0.466*** (0.0528)	0.214*** (0.0474)
4. Income_level					0.648*** (0.0629)	0.540*** (0.0633)	0.196*** (0.0558)
5. Income_level					0.646*** (0.0824)	0.512*** (0.0827)	0.122* (0.0740)
6. Income_level					0.677*** (0.171)	0.491*** (0.175)	0.160 (0.165)
7. Income_level					1.334*** (0.291)	1.119*** (0.286)	0.474* (0.278)
Car_gas_Engine displacement average						0.129***	0.117***
Distance travelled						(0.0131)	(0.0120) 6.79e- 05*** (2.94e-06)
Constant	1.676*** (0.0277)	1.773*** (0.0630)	1.839*** (0.0706)	0.681*** (0.0766)	0.446*** (0.0758)	0.147* (0.0799)	0.0519 (0.0706)
Prefecture fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7288	7288	7288	7288	7288	7288	7288
R-squared	0.024	0.069	0.069	0.210	0.227	0.238	0.397

Robust standard errors are provided in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Beyond demographic and cost-related features, geographical factors such as the mountainous terrain in some parts for the country further affect emissions [65], with average household emissions being comparatively higher in prefectures in predominately mountainous regions such as Tohoku and Hokuriku, as well as individual mountainous prefectures belonging to highly urbanized regions, such as Gunma prefecture in the Kanto region (figure 1).

As discussed in previous studies, some of the main approaches for mitigating emissions from private vehicles include decreasing car ownership, encouraging a larger switch to public transportation and improving traffic conditions [26, 32, 66]. However, as discussed above our observations suggest a distinct sub-national divide in emissions between prefectures with different urbanization levels and geographical features. In this respect, such initiatives could have a substantial effect in highly urbanized regions with good public transport networks.

Undoubtedly it is important to ensure the continuous reduction of transport-related emissions in

large cities through tested measures such as the ones outlined above. However, arguably the effectiveness of such measures could be questionable in other prefectures where private vehicles are essential for daily life [65]. In these contexts we indeed see higher per household emissions from private vehicles than prefectures containing very large cities, but at the same time we are conscious that it might be difficult to find other feasible alternatives for personal transport. For example, when considering prefectural population and economic situation (See figures s2 and s3, supplementary information), the promotion of public transport may add heavy financial burdens to areas that are less economically developed and are characterized by lower overall population and/or population density, especially when considering the significant further population shrinking expected in these parts of Japan [65]. At the same time, while emission reduction gains would be high on a per household basis, they could end up being much lower on aggregate levels considering the much lower population of such areas [65].

Thus in such contexts it may be more effective for emission mitigation at the household and per capita level to promote measures such as carpooling, limiting larger vehicles (e.g. through the Car Weight Tax) [66] or promoting with special incentives electric or hybrid vehicles [67, 68] (see also points made below), rather than simply ask local residents to reduce car usage. The strong negative correlation between fuel-saving behavior and emissions suggests that raising environmental awareness about driving behavior could possibly help in conserving fuel and decreasing emissions, by both evidence across Japan and other countries [69–71] (see also section 4.2).

Importantly, our results clearly show the effect of city size on emission levels. Overall, a declining city size has a rather strong and statistically significant effect on increasing emissions from private vehicle use (table 1; figure 4). Conversely emission differences are not always clear-cut between prefectures (figure 1). This finding can have important ramifications for regional decarbonization efforts in the transport sector in Japan. Currently, Japan has articulated the target of increasing the share of eco-friendly automobiles, such as hybrid and electric vehicles, to 50%–70% by 2030, while it plans to ban the sale of new gasoline cars in the mid-2030s [72]. However, these ambitious targets are still rather new and lack fine print on how to be promoted effectively considering the geographical differences. To this point, we have demonstrated that if Japan approaches seriously regional decarbonization in the transport sector, then measures for private vehicles could be better suited at the city rather than the prefecture level considering that the emission disparities among cities are more significant than among prefectures.

Currently, most of the related measures are concentrated in large cities such as Tokyo and Osaka, including some of the incentives and subsidies for electric and hybrid vehicles established by the local governments of larger cities such as Tokyo [73]. Based on our results, we suggest promoting transport-related decarbonization technologies (e.g. electric and hybrid vehicles) equally strongly in smaller cities, considering the high transport-related emission intensities and heavy reliance on private vehicles. Considering the heavy reliance on private vehicles and the difficulty in expanding the public transport networks as outlined above, this offers a golden opportunity to curb emissions in smaller cities drastically.

Such findings are different from previous analyses which have focused on larger scales such as the region, state, or prefecture [74–76], but are consistent with the recently increasing focus on city-level mitigation measures in Japan and elsewhere [59, 77, 78]. In fact this finding reflects well, and makes a stronger case, for the increasing attention towards city-level emission mitigation and decarbonization measures in Japan, e.g. the recent Zero Emission Target [79] set by many Japanese cities. Beyond the promotion of

technologies, appropriate incentive should be offered for such vehicles, which are now mostly given in larger cities such as Tokyo [73].

Third, we see strong signs of seasonal emission variation across most prefectures (figure 3). Various on-site air quality modeling studies have identified the close correlation of emissions and meteorological conditions [80–83], but this has been rarely identified through social surveys. Here, we find higher emissions during August and December, which coincide both with the summer and winter vacations, as well as with temperature extremes within many parts of Japan. These results suggest (a) the possibly substantial effect of recreation on private vehicle emissions [84, 85], and (b) the greater need for air-conditioning for cooling and heating respectively during these months [55, 86]. In this sense it might be useful to raise awareness to domestic consumers to both avoid concentrated driving for holidays (e.g. through promotion of domestic destinations with good public network connection) or creating opportunities for renting in affordable prices electric or hybrid vehicles in recreation areas [68] as well as best practices in air-conditioning use [87–89].

4.2. Implications of household characteristics for mitigation strategies

Beyond demographic and geographical features, we also find that some socioeconomic and cultural factors affect emissions from private vehicle use. First, income seems to have an effect on emissions from private vehicle use (table 1; figure 4), despite the relatively high social equality in Japan and the relative low emission differences between income groups [12, 90, 91]. In more detail, the greatest emissions disparities are observed between the highest income group (Level 7) and all other income groups, with this group emitting >18% than the second highest income group (table 1; figure 4(b)). Higher-income groups in Japan have been associated with higher vehicle ownership, higher vehicle use frequency and larger engine displacement (and thus higher emission factors) [92, 93]. In this sense by targeting this higher income group (Level 7) could offer some emission reduction benefits, possibly through measures such as vehicle emissions taxes [94]. However, it is also important to also note the very low prevalence of such households among the general Japanese population (around 1.3% of the total) [95], which means that while on a per capita basis such measures might yield emission benefits, the absolute mitigation benefits could be rather small. One more interesting pattern is that emissions are very similar among income groups in Levels 3–6, which constitute a large portion of the Japanese population (42.9% of the total) [96]. This might offer some important opportunities for designing mitigation measures, but care should be taken considering the large heterogeneities within these groups.

Second, the results suggest the strong effect of fuel-saving driving behavior on emissions, with households exhibiting such behavior having on average 16% lower emissions (table 1). Although there have been some studies employing on-site experiments to link fuel-saving driving behavior with lower emissions [97, 98], our study is one of the few demonstrating this link through the extensive analysis of secondary data. In this sense, raising driver awareness about fuel-saving behavior might be one of the few strategies that can be applied across income groups [99]. However, this would possibly require different messaging [100].

4.3. Limitations

Despite its extensive focus and robust results, this study has two main limitations. First, when using the ‘household’ as the unit of analysis might insert some uncertainties. In particular, the survey data used for this analysis reported the total emissions per household from private vehicle use. This background information reported the household size, but included teenagers and infants. However, the per capita results might be different depending on whether they are estimated on the basis of the total number of household members or only adult household members [101]. In this study, we estimate both the ‘per household’ and ‘per capita’ emission levels using the total household members for the latter. The results show that per capita emissions are positively correlated with household size (table S3, supplementary information), which seems to be a bit counter-intuitive, as we expected that if multiple individuals owned the same vehicle it would lead to decreased per capita emissions [32, 102]. This might point to another demographic factor influencing emissions, namely that households with children might be more likely to adopt a car-dependent lifestyle [103]. If data with better resolution of the household structure become available in the future, then future studies should attempt to elicit the effect of household structure on the per capita emissions.

The second limitation reflects the incomplete information in the underlying dataset about electric vehicles. Due to data constraints in this study, we did not consider indirect emissions associated with electricity generation to power electric vehicles (section 2.1). Future datasets should attempt to capture related information such as electricity consumption for transport and the underlying power generation process (though the latter would require some regional analysis alongside the main power producers in Japan) [104]. Although we expect that the exclusion of electric vehicles in this analysis would have minor effects considering their low penetration (section 2.1), electric vehicles should be included in future studies as they are a major element for meeting the INDCs [105].

5. Conclusions

Transport is one of the most important sources of GHG emissions, and thus a priority sector for climate change mitigation efforts both in rapidly growing and developing countries, as well as developed countries with shrinking populations such as Japan. In this study we conduct a bottom-up analysis of household-level survey data from Japan to identify the temporal and spatial variation of private vehicle emissions in the year 2017, as well as the factors affecting them. The results reveal significant seasonal emission variations and regional disparities, with generally higher emissions in areas with low population and population density (i.e. not located in highly urbanized regions such as Kanto and Kinki), as well as mountainous in regions such as Gunma, Tohoku and Hokuriku. Furthermore, we identify higher emissions during some winter and summer months that contain important holidays (i.e. Golden week, summer and winter holidays), which might be due to recreational driving and/or increased use of air-conditioning due to the temperature extremes in some parts of the country.

We also find that some variability in emissions across income levels. On the one hand low-income (Level 1–2) and high-income (Level 7) groups have clearly differentiated emission levels, which points to high-income groups as potential targets of emissions mitigation measures. Interestingly middle-income groups (Level 3–6) have similar emission patterns, which points to a large fraction of the population with high heterogeneity having similar emissions. This creates both opportunities and challenges for emission mitigation efforts. Fuel-saving driving behavior is negatively correlated with emissions, which further points that the promotion environmentally friendly driving habits can have large emission reduction potential in the future.

Finally, due to the strong effect of city size in emissions (which is often much more clear-cut than between prefectures), it might be more appropriate to approach transport decarbonization in Japan at the city level rather than the prefectural level. In this respect, when policy-makers promote transport-related decarbonization policies in less-populated areas the focus should be more on encouraging technological improvement and related incentive (e.g. EV subsidies) rather than decreasing private vehicle use, which is essential for daily life in these contexts. The prioritization of smaller cities considering their higher emission intensiveness could pay real dividends both for increasing convenience and achieving transport decarbonization in the long run.

Data availability statement

No new data were created or analysed in this study.

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Author contributions

Y Long, A Gasparatos and Y Yoshida designed this study. Y Long collected the data and interpreted the results. Y Long conducted analysis through consultation with Y Yoshida, Y Long and A Gasparatos wrote and revised the paper with input from all authors. A Gasparatos and Y Li supervised the study.

Declaration of conflicting interests

The authors declare no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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