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# Estimation of passenger car $CO_2$ emissions with urban population density scenarios for low carbon transportation in Japan☆

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ABSTRACT

The aim of this study is to quantify the potential reduction of $CO_2$ emissions by passenger vehicles over the long term through the introduction of compact cities. We determined the correlation between population distribution and passenger car $CO_2$ emissions from 1980 to 2005 and simulated passenger car $CO_2$ emissions in 2030 under both compact and dispersed scenarios. We conducted correlation analysis and scenario analysis with the data sets of municipal $CO_2$ emissions of passenger cars, national population census figures, and future population distribution scenarios. Then, we estimated the annual $CO_2$ emissions of passenger cars per capita by mesh cell density category. The results show that the difference in emissions per capita between the compact and dispersed scenarios is roughly 5% in Japanese municipalities as a whole.

## 1. Introduction

Cars account for roughly 20% of all $CO_2$ emissions in Japan. The Japan's Intended Nationally Determined Contribution (INDC) for greenhouse gas emissions is taken as a 26% reduction in GHG emissions by 2030 from 2013 levels. The Japanese cabinet has announced its long-term emissions reduction target of 80% by 2050 compared to 1990 levels. Given these conditions, avoiding climate change will require not only improvements in the fuel efficiency of cars but also reductions in the distances that cars travel.

However, meaningful reductions in the distances that passenger cars travel involve more than just individual effort. Take a person who decides to ride the bus to work instead of driving his or her own car, for instance. If riding the bus means having to catch one of only a few available buses every day or needing to make a much longer commute, the transition from driving to riding would be an unrealistic shift to make for that individual. From the medium- to long-term perspective, people would need to choose new places to live or travel to.

In the society-wide context, these selections coalesce to propel one of the most effective ways of cutting passenger car $CO_2$ emissions: modifying urban structures to create urban land use that eliminate excessive dependence on cars. The practice of controlling urban structures, called “transit-oriented development” (TOD [1]), has gained recognition as a useful method for limiting the amounts of $CO_2$ emissions from passenger cars. That said, observers can only speculate about how making medium- to long-term changes to the urban structures of cities across Japan will impact $CO_2$ emission levels.

Through empirical research, Newman et al. [2] showed that higher land use density correlates to lower gasoline consumption. Critics of the study, however, have argued that the researchers oversimplified the idea of city density into a single value and ignored the various conditions that create differences among countries and cities; due to these and other problems, scholars have cast doubt on the idea that increased density leads to reduced energy consumption [3].

This study, which focuses on cities in Japan, thus formulates correlations between passenger car $CO_2$ emissions by city over a 25-year period (1980–2005) and the population density of each mesh cell for each city to produce estimates of $CO_2$ emission volume by mesh cell size. We also use this input and past demographic data to create two population distribution scenarios for the year 2030. Through scenario analyses that assess the potential of differences emerging under each set of scenario conditions, we aim to identify the ideal population distribution patterns for cutting $CO_2$ emissions and outline the effects of said patterns.

## 2. Materials and methods: an overview of the data used and the analyses performed

The Japanese government conducts sampling studies of car usage and complete censuses of national demographics every five years. Using the following three sets of data, we performed analyses as shown in Fig. 1.

a) Annual passenger car $CO_2$ emissions by municipality at six points in time (1980–2005)

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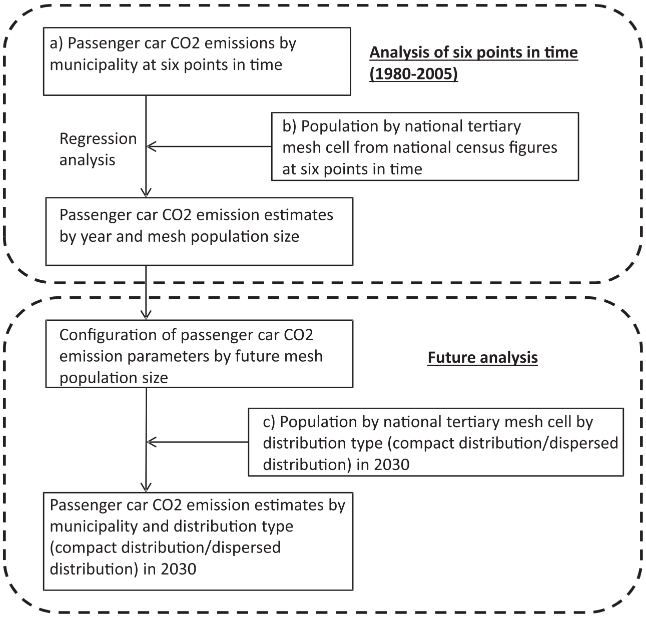

**Fig. 1.** Analysis process.

We created this set of $CO_2$ emission estimates for each municipality with passenger car registration data from Road Traffic Censuses and Vehicle Origin–Destination Surveys, which the Japanese government generally conducts at five-year intervals to investigate the movement of cars throughout Japan. The 1994 and 1999 surveys deviated from this five-year schedule, each occurring one year early. The sampling study data, which covers approximately 2% of all passenger car owners in Japan, describes the travel distance per trip unit on a single weekday and a single non-weekday in the fall. We multiplied this travel distance by the primary unit of emission volume per unit of travel distance by vehicle type, which we determined based on the national figures for travel distance by vehicle type, fuel consumption, and emission factor by fuel type (see Formula 1). Annual emissions by municipality are calculated by aggregation of the emissions by day type, area and vehicle type. The emissions in towns and villages should be paid attention on the uncertainty because the number of samples might be not enough. The process for a) adheres to the approach of Matsuhashi et al. [4].

$$C_{art} = e_t \sum_i d_{arti} \tag{1}$$

$C_{art}$: $CO_2$ emissions by day type (weekday/non-weekday), municipality, and vehicle type.

$e_t$: emission factor by vehicle type (mini cars, small cars, buses, mini freight vehicles, light duty vehicles, passenger-freight vehicles, heavy duty vehicles, specific purpose vehicles).

$d_{arti}$: travel distance per trip unit by day type (weekday/non-weekday), area, and vehicle type.

a: day type (weekday/non-weekday).
r: municipality of vehicle registration.
t: vehicle type.
i: trip number.

b) Population by national tertiary mesh cell from national census figures at six points in time (1980–2005).
This data aggregates national census population figures into a tertiary mesh (a grid that divides the land area of Japan into mesh cells measuring 1 km by 1 km). The Japanese government conducts national censuses every five years.

c) Population by national tertiary mesh cell by distribution type (compact distribution/dispersed distribution) in 2030.

We created two municipal population distribution scenarios for use with identical municipal populations. By applying opposite patterns of population distribution changes that municipalities have experienced in recent years (compact distribution/dispersed distribution) to future conditions via the cohort change ratio method, we constructed two highly probable scenarios. The process for c) adheres to the approach of Ariga et al. [5].

We created our population distribution scenarios based on past demographic data of 2000 and 2005. For classification purposes, we created 36 categories: we first sorted municipalities into twelve "municipality type" categories according to several variables (whether the municipality was inside or outside a metropolitan area, whether the municipality was a "city" or a "town or village," and whether the population of the municipality was growing, shrinking, or stable) and then created three "population distribution" tiers for the twelve categories based on whether the changes in the corresponding population distributions were compact, dispersed, or static. This gave us a total of 36 categories. Next, we determined the population change parameter set for each category, sorting the data by mesh cell population size, gender, and age (at five-year intervals). We used the scope of the Three Major Metropolitan Person Trip Surveys (Tokyo, Keihanshin and Chukyo) to define "metropolitan area" for our study and set the population boundary separating cities from towns and villages at 30,000. To ensure a proper balance among the municipalities, we also set the population change threshold to $+/-3\%$ over five years. For population distribution, we set the threshold for the five-year change in the Gini coefficient of population distribution (calculated based on the cumulative residential area share and cumulative population share for the lowest-density area and moving upward; see Formula 2) to 0.01. We then derived future population distribution patterns by multiplying the data for the corresponding municipality category by the parameters for the appropriate scenario (compact distribution or dispersed distribution).

$$G = 1 - \Sigma_i b_i (p_i + p_{i-1})/10000 \tag{2}$$

G: Gini coefficient of population distribution.

$b_i$: the percentage of the inhabitable land area occupied by the mesh cell with the ith-lowest population density.

$p_i$: the percentage of the total population represented by the cumulative population of the mesh cells with the lowest population densities (from the mesh cell with the lowest population density to the mesh cell with the ith-lowest population density).

The data sets for a) and c) are available on the "Kankyō Tenbōdai" section of the National Institute for Environmental Studies website (http://tenbou.nies.go.jp/).

We analyzed the correlation between past municipal population distribution and passenger car $CO_2$ emissions, operating under the assumption that mesh cell population size (population density) would affect annual per capita passenger car $CO_2$ emissions. As Fig. 1 shows, we first analyzed the correlation between past population distribution and passenger car $CO_2$ emissions based on sets a) and b). We then evaluated the results of that analysis and the possible future population distribution scenarios created by c) in terms of passenger car $CO_2$ emissions. We employed the regression analysis approach for the first step, using population distribution variable to explain the passenger car $CO_2$ emissions variable, and used the results of the first step for the subsequent scenario analysis. Although the Road Traffic Censuses for 1994 and 1999 occurred one year ahead of the conventional schedule, we appropriated the data from the 1994 and 1999 studies as the data for 1995 and 2000, respectively, in order to ensure that our estimates were consistent with the national census data.

## 3. Results and discussion

### 3.1. Past correlations between population distribution and passenger car $CO_2$ emissions

For our analysis, we set up a regression formula where the explained variable was "annual per capita passenger car $CO_2$ emissions by municipality" (annual passenger car $CO_2$ emissions by municipality at six points in time [1980–2005; "a)"] divided by municipal population) and the explanatory variable was "population share by mesh cell population size" (based on population by national tertiary mesh cell from national census figures at six points in time [1980–2005; "b)"]). Fig. 2 shows the statistically meaningful results of our estimates by year.

Fig. 2 show the results of correlation analysis. It illustrates that mesh cells with larger population sizes tend to have lower annual per capita passenger car $CO_2$ emission levels across the board, regardless of the year. Residents of mesh cells with large populations generally enjoy more opportunities to use public transportation and have quick access to stores, hospitals, and other common destinations, making their travel distances shorter and limiting overall car use. Mesh cells with more than 10,000 people are located in three major metropolitan areas such as Tokyo, Keihanshin and Chukyo which have rich network of public transportation. In mesh cells with small populations, however, the data suggests that the scarcity of public transportation options and the considerable distances separating residents from the facilities they need to use on a day-to-day basis contribute to a stronger dependence on cars.

Another facet to examine is change over time. In 1980, the annual per capita passenger car $CO_2$ emissions in mesh cells with large population sizes came out to approximately 0.4 tons, while the same value in mesh cells with small population sizes amounted to 0.6 tons—a relatively minor difference. Looking across our temporal span, however, one can see how the annual per capita passenger car $CO_2$ emissions in small-population mesh cells have increased significantly to a point where the values now dwarf those of large-population mesh cells. The main contributing factors behind this widening gap were economic growth, which led to an increase in car ownership, and the development of larger vehicles. In recent years, as the Figure shows, the annual per capita passenger car $CO_2$ emissions in mesh cells with large population sizes are actually decreasing. In addition to new technologies bringing about improved fuel efficiency levels, people are also exhibiting a growing preference for living in convenient locations and using cars sparingly—a trend especially evident in metropolitan areas [6], where midtown areas are surging back to life and growing numbers of young people are turning away from driving [7].

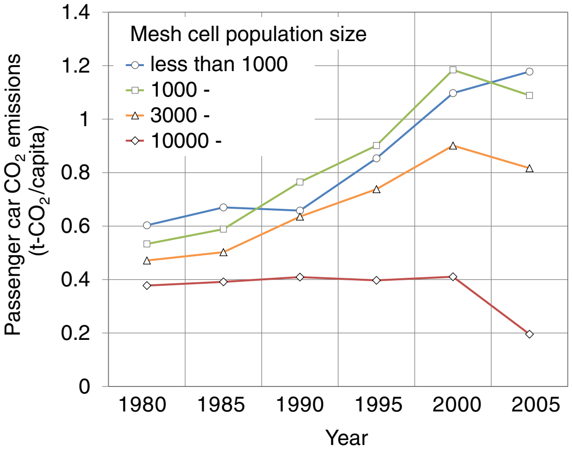

**Fig. 2.** Trends in annual passenger car $CO_2$ emissions per capita by mesh cell population size (regression parameter).

### 3.2. Future correlations between population distribution and passenger car $CO_2$ emissions

Looking at emissions across Japan, passenger car $CO_2$ emission levels seem to be leveling off in recent years. If the Japanese population starts to shrink at a faster rate, though, the effects of that demographic shift—lower population density, reduced public transportation availability, fewer stores, hospitals, and other facilities, and the resulting longer travel distance—could very well prompt another increase in passenger car $CO_2$ emissions. We thus estimated the impact that future changes in population distribution would have on passenger car $CO_2$ emissions. Basing correlation analysis on the passenger car $CO_2$ emissions per travel distance by mesh cell population size for the year 2005, we investigated the annual per capita passenger car $CO_2$ emission levels estimated under the conditions of the different population distribution scenarios.

One example of our findings appears in Fig. 3, which provides an analysis of the population distribution scenarios for Sagamihara City, Kanagawa Prefecture (the administrative district as of December 2008), in 2030 and the corresponding annual per capita passenger car $CO_2$ emissions. Given its location bordering the Tokyo metropolitan area and its population of approximately 700,000, Sagamihara City is a good example of a municipality where variation in population distribution would have a considerable effect on passenger car $CO_2$ emissions. In the compact distribution scenario, the large-population mesh cells of Sagamihara City (especially those with populations of 10,000 or more) constitute a larger share of the total population in 2030 than in 2005; in other words, the scenario suggests that the city would grow more compact and assume a more intensive urban structure. The dispersed distribution scenario, on the other hand, projects that large-population mesh cells would account for a smaller share of the overall population in 2030—a pattern indicative of the sprawl phenomenon. Whereas the annual per capita passenger car $CO_2$ emission level would drop over time (from 2005 to 2030) under the compact distribution conditions, the level would increase under the dispersed distribution conditions. The results of our analysis indicate that differences in population distribution could swing annual per capita passenger car $CO_2$ emissions by nearly 15%.

The effects of population distribution on passenger car $CO_2$ emissions were particularly dramatic in our investigation of Sagamihara City, but our analysis showed that many of municipalities across the country would likely follow the same tendency as Sagamihara City more or less. While municipality size and the municipal population distributions for 2005 – the baseline figures for our scenarios – were different, the compact distribution scenario produced annual per capita passenger car $CO_2$ emissions that were around 10% lower than the estimates that the dispersed distribution scenario generated in many of municipalities. The difference in emissions per capita between the compact and dispersed scenarios is roughly 5% in Japanese municipalities as a whole.

## 4. Conclusions

This study determined passenger car $CO_2$ emission parameters by mesh cell size in Japanese municipalities for the last 25 years based on passenger car $CO_2$ emission data and municipal population distributions. We also applied the 2005 parameters to compact and dispersed population distribution scenarios for the year 2030. By comparing probable conditions in compact cities and non-compact cities, we found that a compact distribution had the potential to reduce passenger car $CO_2$ emissions by approximately 10% relative to a dispersed distribution—a drop that stands to grow even larger as automobile fuel efficiency improves, modal shifts continue to progress, and government initiatives encourage walking and biking instead of driving. One goal for future research would be to evaluate these possibilities through a quantitative approach.

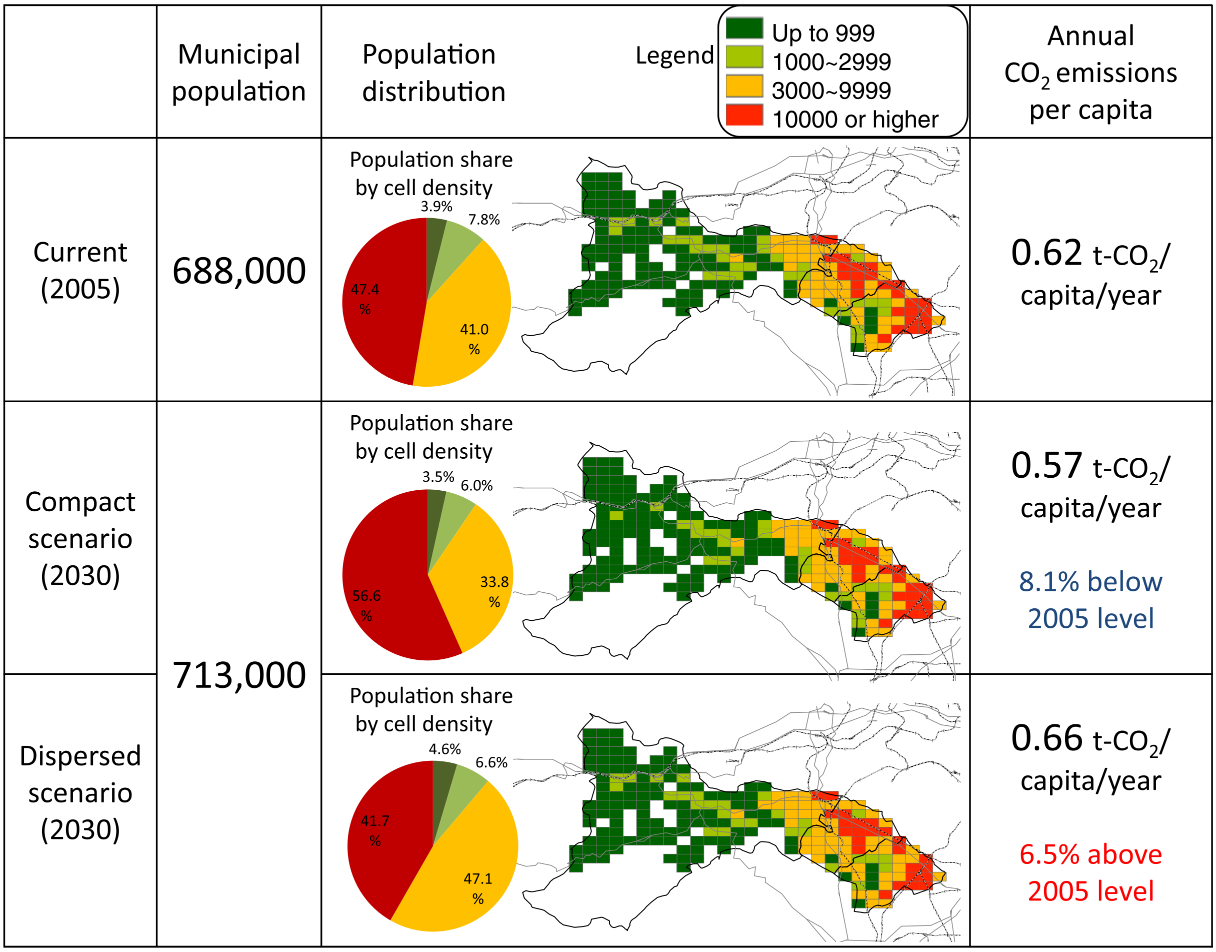

**Fig. 3.** Example of scenario analysis of passenger car CO$_2$ emissions (Sagamihara City, Kanagawa Prefecture).

Population distribution scenarios affect much more than just passenger car CO$_2$ emissions: changes in how a population occupies a given land area also have an impact on things like energy demand, the spatial patterns of waste generation, health, and the ecosystem. As we continue to assess the issues from multiple angles, we hope that our findings will help society account for the full range of factors in identifying the optimal population distribution.

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