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Metro Proximity and Built Environment on Commuting CO_2 Emissions in Shanghai

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Abstract: To explore the impact of geographical location, built environment, public transportation service and individual socioeconomic attributes on commuting carbon dioxide (CO_2) emissions, a survey was conducted in 27 residential compounds of Shanghai in 2016. In this paper, commuting distance was calculated according to a Baidu map application programming interface (API). CO_2 emissions were calculated based on the mode used in each segment of commuting and distance travelled. Through the use of a multiple linear regression model, factors of personal socioeconomic attributes, including gender, occupation and apartment area, were significant to commuting CO_2 emissions. In terms of the public transport service, the distance from compounds to the nearest metro station was found to be a significant factor on CO_2 emissions, whereas the built environment, such as parking space and employment density, had a weak impact in our study. In addition, even when living near a metro station, the top 20% of travellers' CO_2 emissions can account for approximately 80% of the total CO_2 emissions. Hence, policies to reduce those people's commuting CO_2 emissions are worth further exploring.

1. INTRODUCTION

1.1 Transport and emissions

There is growing worldwide concern regarding carbon dioxide (CO_2) emissions due to transport. According to recent statistics from the International Energy Agency (IEA), global CO_2 emissions increased by 38% between the years 2000 and 2017. Since 2010, global emissions have grown at approximately 1% annually, with the rate for China being 2.4% (Zhu & Jiang, 2019; International Energy Agency (IEA), 2019). In 2017, the emissions of the transport sector reached 8 Gt CO_2eq, accounting for one quarter of total global CO_2 emissions and playing a crucial and growing role with respect to world energy use (29% in 2017) and both energy-related and total greenhouse gas (GHG) emissions (more than 21% and 16%, respectively, in 2015) (International Energy Agency (IEA), 2019).

Growth in GHG emissions has continued since the Fourth Assessment Report (AR4) despite more efficient vehicles being introduced (road, rail, watercraft and aircraft) and policies being adopted. The growth rate of energy consumption in the transport sector has been the highest among all the end-use sectors (International Energy Agency (IEA), 2019; IPCC, 2014).

In China, from 1990 to 2016, CO_2 emissions from transport increased from 5.15% to 9.35% of fuel combustion, which is still far below the world average (24.34% in 2016) (International Energy Agency (IEA), 2018).

China's urbanisation is forecast to grow stably over the next 20 years. The growth of China's urban population has been accompanied by a continuous spatial transformation of its cities. Household car ownership, as expected, will continue to increase. From 2010 to 2017, emissions from road transport, mostly for passenger travel, which accounts for approximately three quarters of total transport emissions, increased 3.5-fold in China (International Energy Agency (IEA), 2019). The increase in transport emissions has posed a significant challenge for policy-making in terms of targeting emissions reduction with a high expectation of future economic growth.

1.2 Transit-oriented development (TOD) strategy and travel demand

In response to this challenge, many megacities in China claim to have adopted a green and low-carbon urban transport strategy. Large cities have established highly ambitious plans to construct an extensive urban rail transit system to meet the growing travel demand due to economic and population growth and lessen the dependence on cars. For example, in Beijing and Shanghai, several thousand kilometres of urban transit rail networks have been planned in recently announced master plans.

Transport energy consumption and GHG emissions are highly linked to the dependence on cars in many cities. Transit-oriented development (TOD), which involves encouraging urban development around metro stations, is conceptually a substantially promising approach for reducing car dependence and lowering CO_2 emissions.

Numerous studies have found that TOD residents tend to own fewer cars, drive less and travel by transit more often than those living in non-TOD areas. The key characteristics of a TOD area are mixed land use and high density in areas around metro stations with walk-accessible shopping, pedestrian amenities and lower parking supply to encourage households to walk, bicycle and take public transport (Cervero, Guerra, & Al, 2017; Belzer & Autler, 2002; Calthorpe, 1993).

Through an investigation of the literature relating to empirical studies of TOD planning factors in American cities, Ewing and Cervero (2001) identified that the application of these factors tends to reduce the total number of trips and distances travelled by vehicles. People staying in TOD areas will produce less work and non-work trips made by cars (Nasri & Zhang, 2014) and lower Vehicle Kilometres Travelled (VKT) (Jeihani et al., 2013; Chatman, D., 2006; Arrington & Cervero, 2008). Recent research results in Shanghai demonstrate that rail transit-supported urban expansion can produce important positive outcomes in modal choice and VKT reduction (Chen, F. et al., 2017; Shen, Chen, & Pan, 2016).

1.3 Built environment (BE) and travel demand

Chatman, D. G. (2013), using household survey data within 2 miles of ten metro stations in New Jersey, found that the lower car ownership and use in TODs are mostly credited to land-use factors, other than the metro service. Land-use factors, such as the density and mixture of land use, exhibited a high interrelationship in terms of their effects on reducing car dependence (Newman & Kenworthy, 1989).

Researchers have assessed the effect of development density on travel mode choice and found a positive effect on non-motorised travel (Iseki, Liu, & Knaap, 2018; Loo, Chen, & Chan, 2010; Zhang, 2004; Parsons Brinckerhoff Quade & Douglas Inc. et al., 1995). Considering both ends of a trip, some studies have found that the effect of destination density is more important than the density around the origin (Chen, C., Gong, & Paaswell, 2008; Kwoka, Boschmann, & Goetz, 2015; Shiftan & Barlach, 2002). Deboosere, El-Geneidy, and Levinson (2018) emphasised the importance of access to destinations when analysing average commute times, and Ding et al. (2014) emphasised the density of workplace aspect when analysing work-related VMT.

Considering specifically which particular density form was having an effect, Chen, C., Gong, and Paaswell (2008) found that employment density at the workplace did indeed play a more important role than population density around the home in reducing car use in a commuting trip. However, regarding commuting distance, the study of Ding et al. (2017) showed insignificant results with respect to employment density. One possible explanation could be that high employment density implies a highly concentrated work area and high land rent such that most residents cannot afford to live in such areas.

Cervero and Kockelman (1997) examined the TOD-built environment of the San Francisco Bay Area and found that land-use mixture significantly reduced travel demand and increased the utilisation of non-motorised modes of transport. A recent study examined the relationship of various travel outcomes and neighbourhood built environment characteristics in rail-based station areas in eight U.S. metropolitan areas and found that it is the land-use diversity that was most associated with travel modes. Furthermore, car use is associated with diversity and street network design of a station area (Park et al., 2018).

Due to the increasing availability of land-use data in recent years, many Chinese scholars have begun to pay attention to the relationship between land-use and travel behaviour of residents. For example, Pan, Shen, and Zhang (2009) used logit models to analyse land-use and travel characteristics in four different neighbourhoods in Shanghai. Their results showed that the traditional neighbourhood with mixed land use is conducive to short-distance and low-carbon travel by walking and cycling.

However, land-use diversity is increasingly expected to lead to station areas becoming '24/7' locations and generating transit trips during off-peak periods, such as nights or weekends (Cervero, Guerra, & Al, 2017); it supposed to help reduce travel demand and facilitate non-motorised uses in non-commuting trips, other than influencing commuting trips directly.

Reductions in car use could be achieved by addressing 'within-precinct' factors such as improving the quality of pedestrian infrastructure and reducing generous car parking standards and 'beyond-precinct' factors by improving metropolis-wide public transport accessibility (Griffiths & Curtis, 2017).

There are also some other studies indicating that mode choice for routine travel may be driven by habit. This consideration potentially makes car-to-transit mode shifts challenging (Langlois et al., 2015; Schneider, 2013). In the U.S., increasing investments in public transport, however, have not been proportionately translated into increased ridership or productivity.

In terms of the reduction of travel emissions, which are basically computed from travel mode and distance, not surprisingly, research results have not reached a consensus, since land use factors had mix results on travel mode and trip distance respectively according to various findings discussed above.

Some studies suggest that density is negatively related to transport emissions, whereas others believe that the influence is marginal. Comparing with China, the density of Western cities can be particularly low; an empirical research study in Melbourne, Australia by Sharpe (1982) found that transport emissions could only be reduced by 11% when increasing the density 3-fold.

Brownstone and Golob (2009) compared the travel behaviour of two households with similar socioeconomic characteristics but in different density areas, demonstrating that vehicle mileage and gasoline consumption in low-density households were indeed more than high-density areas.

Switching to the context of a high density city, the density factor needs to be treated cautiously and discussed after controlling other key factors.

1.4 Social economic (SE) profile and emissions

Social economic factors such as male gender, car ownership, job occupation and income levels were proved to have significant relations with individual travel and CO_2 emissions (Nicolas & David, 2009; Loo & Li, 2012; Naess, 2010; Xiao, Chai, & Liu, 2011; Xu et al., 2015).

Furthermore, research by Brand et al. (2013) in the UK showed that a small proportion of people were responsible for a disproportionately large share of travel emissions (i.e., 60% of the emissions were produced by only 20% of the population). Effective goal-oriented policy formulation requires a better understanding of local context. We need to reflect the necessity for profiling high-emission producers and making policies aimed at those people to increase the effectiveness of such policies. Investigating their personal characteristics and behaviour in the local environment becomes fundamental.

1.5 Mode and emissions

In China, how can commuters' CO_2 emissions be more effectively reduced with the construction of a large-scale metro network? More empirical research is still needed to support policy-making. In addition, in some cases, quite a large amount of the increase in metro passengers has come from previous bicycle riders or bus passengers in China following the improvement in metro services. As a result, the total travel emissions may not be reduced. Similarly, research by Poudenx (2008), based on a European case study, confirmed this point that travel emissions are not necessarily decreased with the promotion of a transit system. Mode shift should consider car use reduction while maintaining non-motorized mode share.

Research in Shanghai finds that metro has helped temporarily reduce the pace of motorisation for citizens living near suburban metro stations by delaying car purchases and lowering the probability of car use in commuting. However, car ownership has been observed to increase quite rapidly despite the positive effects of a much-expanded and improved metro system, and once a person owns a car, they are highly likely to drive to work (Pan, Shen, & Zhao, 2013). With urban expansion, there are around 12 million people staying out of the outer city rings, where increasing the density of metro will be difficult due to economic affordability. People staying outside of the outer ring will become potential drivers.

In high density cities, increasing car ownership and the moderation effect of massive expansion of transit networks are two of the main contextual aspects leading to contradicting effects on emissions. The number of cars owned and proximity of transit are to be considered as key factors regarding emissions.

For built environment variables, density, especially destination density including employment, have a positive effect on non-motorized modes, but not on distance travelled by car, leading to the role of uncertainty in emissions reduction. Additionally, not much examination of destination density has been conducted simultaneously with employment. This will be studied when dealing with built environment elements.

The factors impacting on commuting CO_2 emissions in the Shanghai context will be grouped into three categories: social economic attributes on the individual level, public transport service including the proximity to a metro station, and built environment characteristics.

The purpose of this research is as follows: Firstly, for SEs, to profile the higher emitters; secondly, to find the effect of metro services on commuting CO_2 emissions; and finally, to examine the relationship of built environment variables, especially at place of employment destinations, and commuting CO_2 emissions.

2. SURVEY AND RESEARCH METHODOLOGY

2.1 Survey sample

27 residential compounds were chosen as survey sites. The questionnaire was completed by face-to-face interviews with randomly selected households in the compounds. Finally, 1190 valid responses were obtained. The location of the compounds and workplace distribution are shown in Figure 1. All samples were divided into four areas according to their geographic location: inner ring (A), middle ring-inner ring (B), outer ring-middle ring (C) and outer ring (D).

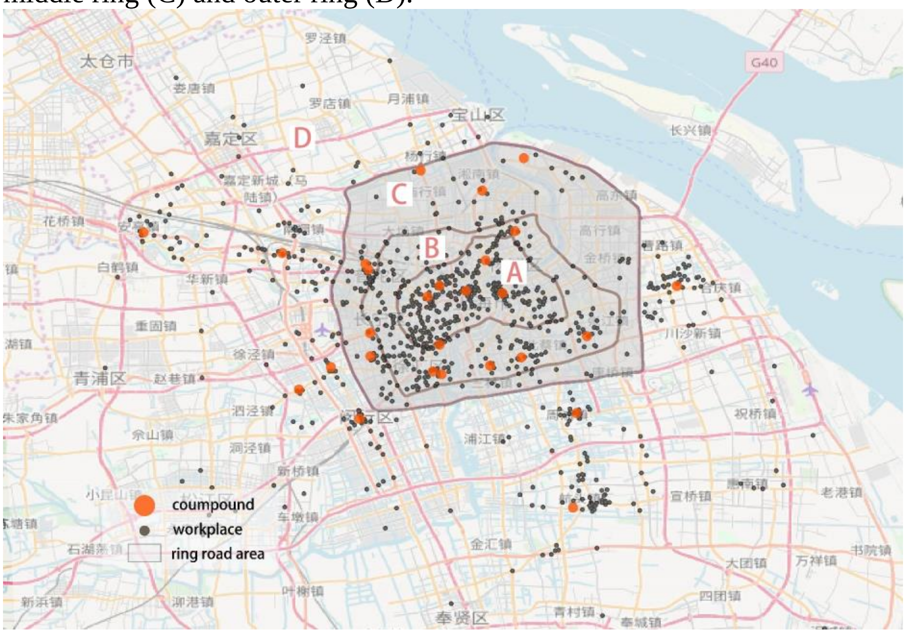

Figure 1. Location of residential compounds and workplaces

2.2 Methodology

This study analyses the relationship between commuting CO_2 emissions and social economic factors, the built environment, as well as public transport service. The research can be divided into three steps. The first is to conduct a household travel survey to obtain personal commuting characteristics and personal socioeconomic attributes. The built environment information of these communities is then collected, including the type and number of nearby points of interest (POI) and public transportation.

After that, it is necessary to get the CO_2 emissions information of each commuter, which is calculated by multiplying the CO_2 emission factor of a transportation mode by the network distance travelled. The calculation of the CO_2 emission factor will be introduced in Section 2.3, and the road network distance can be obtained directly using the Baidu map API. In the process of obtaining the distance of the road network, the CO_2 emissions of all parts of the traveller's commuting process is to be added. For example, a traveller may first use a bus to reach a metro station and then use the metro to reach their workplace; then, the total commuting CO_2 emissions are calculated as the sum of both bus and metro CO_2 emissions.

Finally, multiple linear regression models were applied to find socioeconomic attributes, public transport service variables and built environment factors with respect to CO_2 emissions.

2.3 Calculation of CO_2 emissions

The primary requirement is to calculate the CO_2 emission factors for each travel mode. Although many research studies (Brand et al., 2013; Grazi, van den Bergh, & van Ommeren, 2008; Loo & Li, 2012) have already calculated these factors, the emission factors are nevertheless computed based on the situation in Shanghai and compared to other research results (Table 2).

First, the emission factors are strongly associated with vehicle type, passenger loading, engine size, etc. (Stead, 1999), as well as the primary source of energy, all of which clearly vary in different cities. Second, vehicle passenger loadings of public transport are much higher at peak hours than at off-peak hours, which then makes emission factors of commuting significantly different from travel at other times. It is appropriate to calculate the emission factors of each travel mode in Shanghai by adopting local data (Table 1).

The detailed calculation process is as follows.

$$M_i = D_i \times E_i \tag{1}$$

$$E_i = C_i \times \rho_i \times q_i \times e_i / P_i \tag{2}$$

where M_i is travel CO_2 emissions by mode I (g),

D_i is travel distance (m),

E_i is the CO_2 emission factor (g/m) of the travel mode,

C_i is the energy consumption per km (L/km) of the travel mode,

ρ_i is energy density (kg/L),

q_i is the calorific energy value (Tj/Kg),

e_i is the CO_2 emissions factor of the energy consumed by mode used (Kg/Tj), and

P_i is the passenger-loaded travel mode.

Table 1. The local data of Shanghai adopted in formula (1) and formula (2)

Travel mode	Energy consumption per Km	Energy density	Energy calorific value (Tj/Kg)	Co_2 emission factors of energy (Kg/Tj)	Passenger loadings
Car	0.088 (L/Km) (Li & Qian, 2008)	0.725 (Kg/L) (93#gas)	44.3*10^{-6} (IPCC, 2006)	69,300 (IPCC, 2006)	1.2 (Stead, 1999; SCCTPI, 2011))
Bus	0.4 (L/Km) (Zhao, Zhang, & Yu, 2009)	0.835 (Kg/L) (0#diesel)	43*10-6 (IPCC, 2006)	74,100 (IPCC, 2006)	50
Metro	1.27 Kg/carriage*Km (raw coal) (Su, Lu, & Xu, 2012))		25.8*10^{-6} (IPCC, 2006)	94,600 (IPCC, 2006)	425 (carriage) (Metro carriage in Shanghai has two types: type A and C. The number of 425 passenger per carriage is calculated according to the passenger loadings of each type at commuting time and the share of metro lines with type A/C carriages across all lines)
Taxi	0.1 (L/Km) (Li & Qian, 2008)	0.725 (Kg/L) (93#gas)	44.3*10^{-6} (IPCC, 2006)	69,300 (IPCC, 2006)	1.0 (SCCTPI, 2011)
Motorcycle	0.03(L/Km)	0.725 (Kg/L) (93#gas)	44.3*10^{-6} (IPCC, 2006)	69,300 (IPCC, 2006)	1.0
E-bike	0.0063Kg/Km (raw coal)		25.8*10^{-6} (IPCC, 2006)	94,600 (IPCC, 2006)	1.0
Company bus	0.4 (L/Km)	0.835 (Kg/L) (0#diesel)	43*10-6 (IPCC, 2006)	74,100 (IPCC, 2006)	28
Shopping mall bus	0.4 (L/Km)	0.835 (Kg/L) (0#diesel)	43*10-6 (IPCC, 2006)	74,100 (IPCC, 2006)	40 (SCCTPI, 2011)
Non-motorized transport	0	0	0	0	1

Table 2. Commuting CO_2 emission factors in Shanghai compared with other research studies.

Travel mode	CO_2 emission factors (g/person*km)			Divided by emission factor of the car in this paper
	Lowest from other research	Highest from other research	Calculated in this paper	
Car	37	178.6	163.2	1
Bus	15	104	21.3	0.13
Metro	4.7	9.1	7.3	0.04
Taxi	104	388	222.6	1.36

Motorcycle	54	113.6	66.8	0.41
E-bike	—	—	15.4	0.09
Company bus	—	—	38.0	0.23
Shopping mall bus	—	—	26.6	0.16
Non-motorised transport (foot and bicycle)	0	0	0	0

Data source: (Grazi, van den Bergh, & van Ommeren, 2008; Loo & Li, 2012; Su, Lu, & Xu, 2012).

3. ANALYSIS OF COMMUTING CO_2 EMISSIONS

3.1 Location and CO_2 emissions

The mean and median of commuting CO_2 emissions were counted on the basis of the location of residence and workplace in four parts (Figure 2). As shown in the figure, the commuting CO_2 emissions have a gradually increasing trend as the location area moves gradually away from the inner ring. If we compare commuting CO_2 emissions based on residence and workplace location, it can be seen that residents who stay in the inner ring emit less than those who work in the same area. The residents' commuting CO_2 emissions within the inner ring are lower than employees who work in the same location area. In contrast, in other location areas, there was no substantial difference in CO_2 emissions for residents or workers in the same area. This result may indicate that there are more jobs in the inner ring (A) and people who live there may have a short commuting distance.

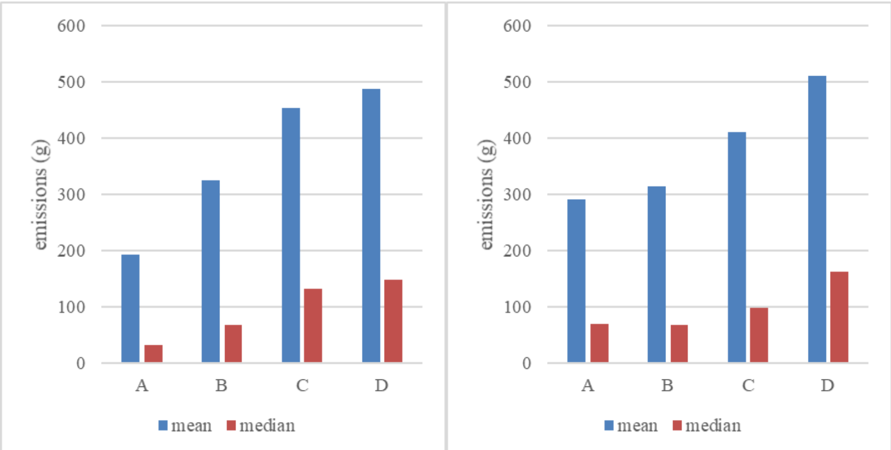

Figure 2. CO_2 emissions based on compounds (left) and workplaces (right) based on location (A to D is defined in *Figure 1*)

The factors directly affecting CO_2 emissions are commuting distance and travel mode. First, the commuting distance was analysed according to the location region (A to D) of workplace and residence locations (Figure 3). The distance was found to increase with distance away from the city centre within the outer ring. The distance is short for people staying outside of the ring; hence, many people staying there will work locally.

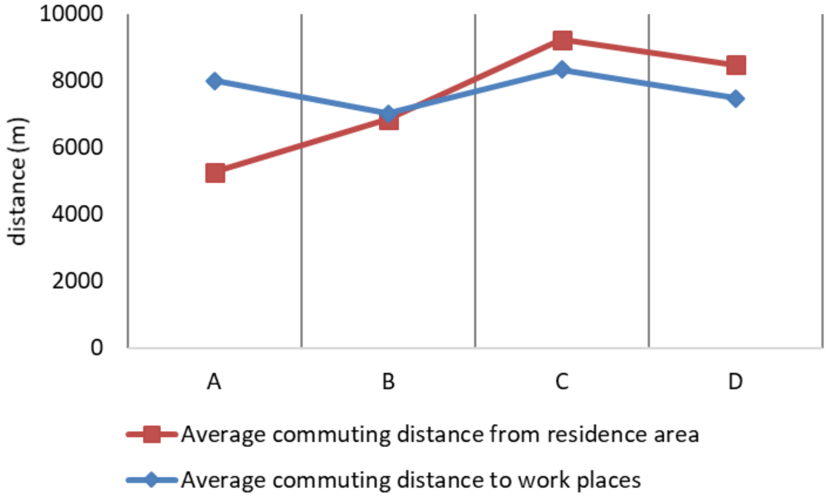

Figure 3. Location and average commuting distance

Travel mode is another important factor that affects commuting CO_2 emissions. The residents' location and travel modes were analysed jointly (Figure 4). Taking walking and cycling as a whole, the non-motorised mode gradually declined with residence location away from the downtown area, the observation may explain why CO_2 emissions increased with distance away from the city centre. In addition, due to the high density of the metro network in the city centre, the modal share by metro was found to decline with distance away from the city centre. The modal share by metro in the inner ring was more than twice that in the outer ring. However, when taking the bus and metro as a whole, it can be seen that the mode share variation by public transport is not so high.

Modal share by public transport in the inner ring was 41.9%, which was only 7.7% higher than that in the outer ring. Suburban commuters tend to use the bus more instead of the metro, in comparison with people staying in the central city area. Car use is an important contributing factor for high CO_2 emissions. From the inner to outer rings, the car use increases. The modal share by car in area C was higher than in area D. Through the comparison of travel mode, it can be found that commuting mode in the inner ring is more dominated by walking and public transportation, which is an important factor leading to low CO_2 emissions by residents in the area.

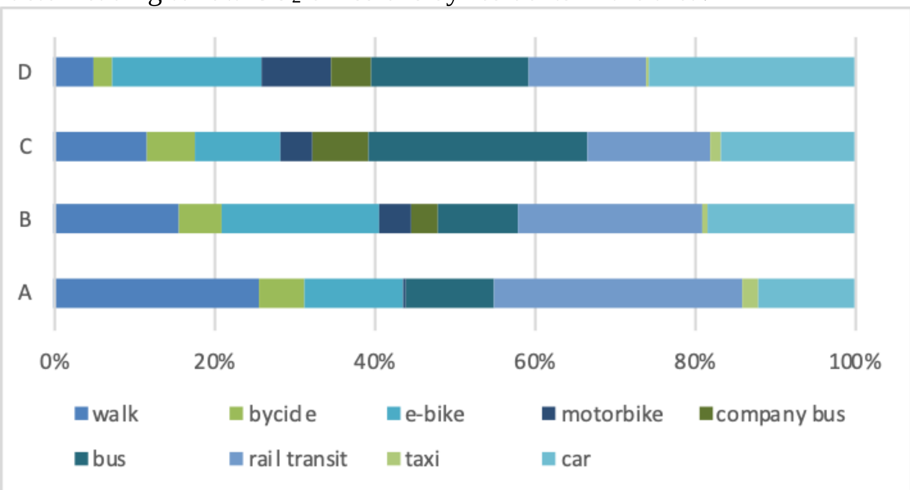

Figure 4. Location and travel mode

To explore the contribution of the different groups of people in terms of their CO_2 emissions, people were divided into five groups according to their CO_2 emissions, and the proportion of CO_2 emissions of each group with respect to total CO_2 emissions was calculated among the four geographic location areas (Figure 5). We found that the top 20% of emitters produced nearly 80% of the total CO_2 emissions, whereas residents in the bottom 20% generated less than 1% of the total emissions. Within the inner ring, 20% of top emitters produce about 90% of CO_2 emissions.

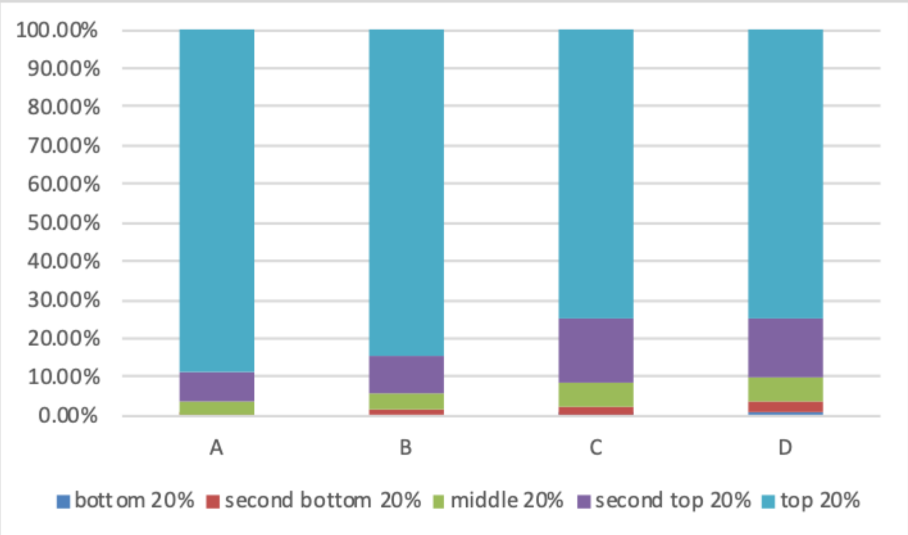

Figure 5. CO_2 emissions by emitter group and location area

3.2 Metro proximity and commuting CO_2 emissions

In this section, residents' CO_2 emissions are compared with good/poor metro services. We defined residential areas within a distance of 1 km to a metro station as areas with a good metro service (close to the metro), and those areas at a distance of more than 1 km as having poor metro service (far from the metro). There were 562 samples located within a 1km distance to the metro station and 628 samples located 1km away from the station.

Table 3 illustrates the relationship between average travel distance and commuter CO_2 emissions. As observed in the table, the travel distance of the two group types was found to be the same, but people with a poor metro service will emit significantly more CO_2.

Table 3. Average CO_2 emissions and commuting distance

	Average CO_2 emissions (g/p)	Average commuting distance (km)	Average CO_2 emissions intensity (g/(p*km))
Poor metro service	465.5	7.63	61
Good metro service	299.1	7.63	39.2

An analysis of location areas and metro service is shown in Figure 6. In general, the commuting CO_2 emissions for those people far away from a metro station was 465.5 g, whereas for those staying close to a metro station, the emissions were only 299.1 g. The commuting CO_2 emissions for the people from a community far from a metro station increased by nearly 50% compared to those staying close to a metro station.

Let us further analyse the difference in the emissions by location areas. Generally, the density of the metro networks tends to be low in suburban areas; hence, it is also necessary to explore the impact of the location factor on commuting CO_2 emissions. We divide the survey sites into two parts by the outer ring. The average distance between the compound to the metro station within the outer ring was 1176 m, whereas outside of the outer ring, the access distance to a metro station was 3366 m, which is nearly three times the access distance when comparing with people within the outer ring.

For people with a poor metro service (located more than 1 km away from a metro station) in the area outside of the outer ring, their average CO_2 emissions was 556.0 g, which is higher than the emissions by those people in the inner ring even with a poor metro service. The differences in CO_2 emissions between those who live close to and far away from metro stations becomes increasingly large with higher distances to the city centre. For people with a good metro service, whether that be inside or outside of the outer ring, the difference in CO_2 emissions was relatively low. This result indicates the importance of transit-oriented development for controlling CO_2 emissions with urban expansion to suburban areas, where commuting CO_2 emissions are higher. Therefore, even in the suburbs, when better public transport services are provided, the commuting CO_2 emissions can also be relatively well controlled.

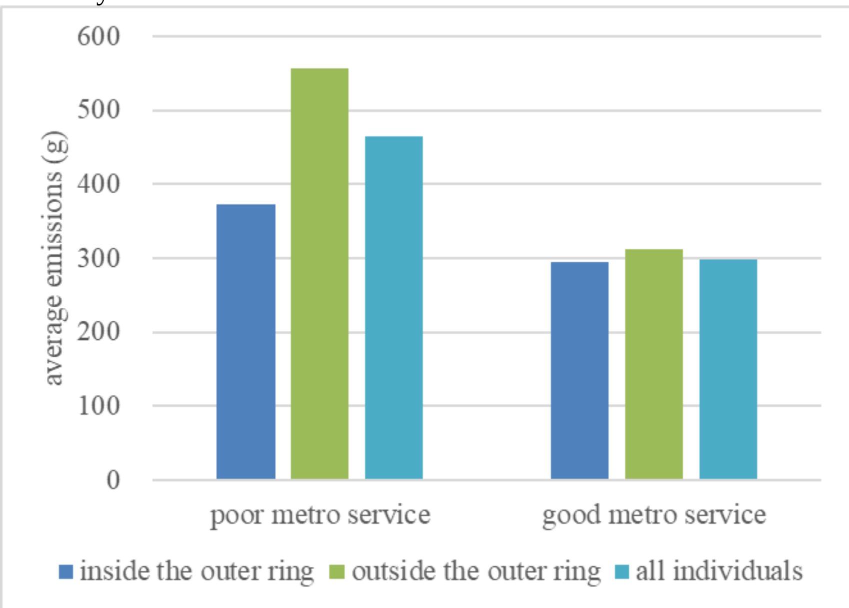

Figure 6. Effect of transit proximity and area on CO_2 emissions.

Comparing the commuting modal share of the two types of compounds, as shown in Figure 7, it can be seen that in the neighbourhoods near a metro station, the modal share by car decreased by nearly 10%, and the modal share by metro increased by almost 20%. The proportion of public transportation increased by 11.5%. The modal share by non-motorised mode increased by 5% in the compounds with a good metro service; this is an important reason for the reduction in commuting CO_2 emissions in compounds close to the metro.

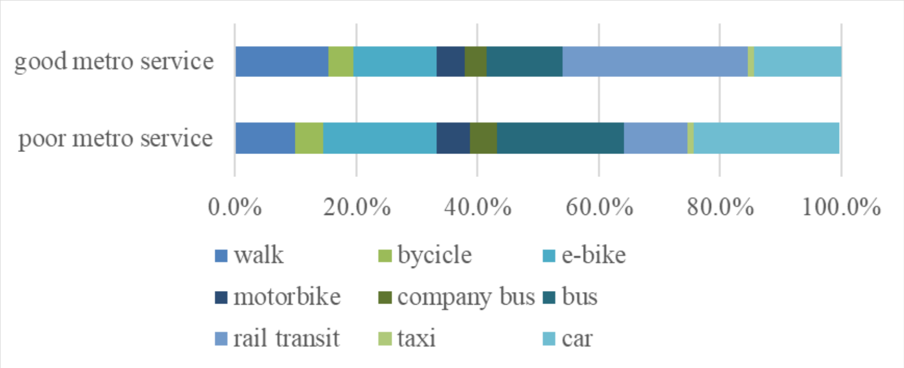

Figure 7. Modal split and metro proximity.

In terms of the contribution of CO_2 emissions from different social groups, it can be seen that 80% of the CO_2 emissions were generated by 20% of high-emitters regardless of whether or not metro services were provided (Figure 8). This result may indicate that 20% of the high-emitters dominated the total commuting CO_2 emissions, irrespective of whether or not the metro is provided, indicating that the impact of a metro service on high-emitters is quite limited currently - more effective measures should be applied to them.

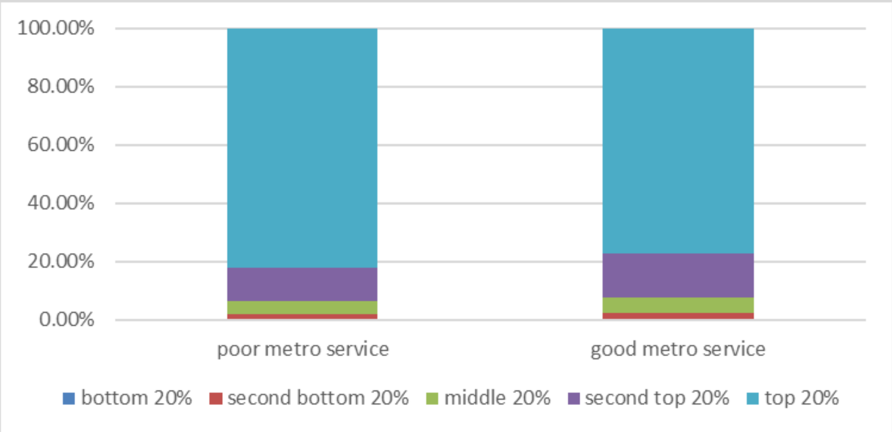

Figure 8. Distribution of CO2 emissions among the groups

3.3 Socioeconomic characteristics and CO_2 emissions

Considering the effects of socioeconomic characteristics and proximity to a metro station on CO_2 emissions of commuting simultaneously, it can be observed that with increased commuter age, the emissions increased. This is probably due to the fact that older commuters tend to adapt a motorised mode to commute. The number of cars in a household affected emissions in a clear manner, irrespective of their home location proximity to a metro station. Once residents own a car, CO_2 emissions will increase dramatically. However, the provision of a metro service could reduce this increasing rate to some extent (Figure 9).

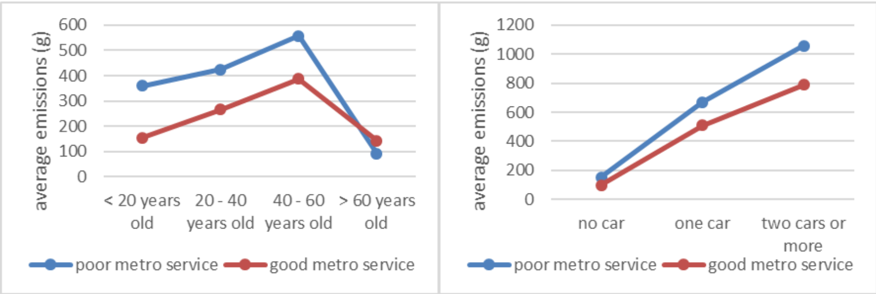

Figure 9. Effects of age (left) and number of cars in household (right) on commuting CO2 emissions.

We classified individual income into three categories: lower than 5,000 RMB per month, between 5,000 and 20,000 RMB and more than 20,000 RMB. We analysed the impact of income, car ownership and level of metro service on CO_2 emissions together, as Figure 10 shows; whereas car ownership increases people's CO_2 emissions substantially, low-income people will emit less than other groups. However, for the low-income group with cars, their CO_2 emissions were significantly higher than the medium-income group if they did not have cars. Occupation also influences CO_2 emissions. Managers emit on average 560.1 g of CO_2 for one commuting trip, whereas the average emissions in the survey was 378.5 g.

Regarding the effect of proximity of home location to a metro station, better proximity indeed led to less commuting CO_2 emissions (except for the low-income group who owned a car).

We found that the low-income group produced lower emissions, even though they owned cars. For medium- and high-income groups with more cars, their emissions significantly increase. Generally, in survey, people only report their salary income; however, they may have other income benefits from additional sources, such as occupation allowance and investment benefits. In the following section, the impact of occupation is analysed.

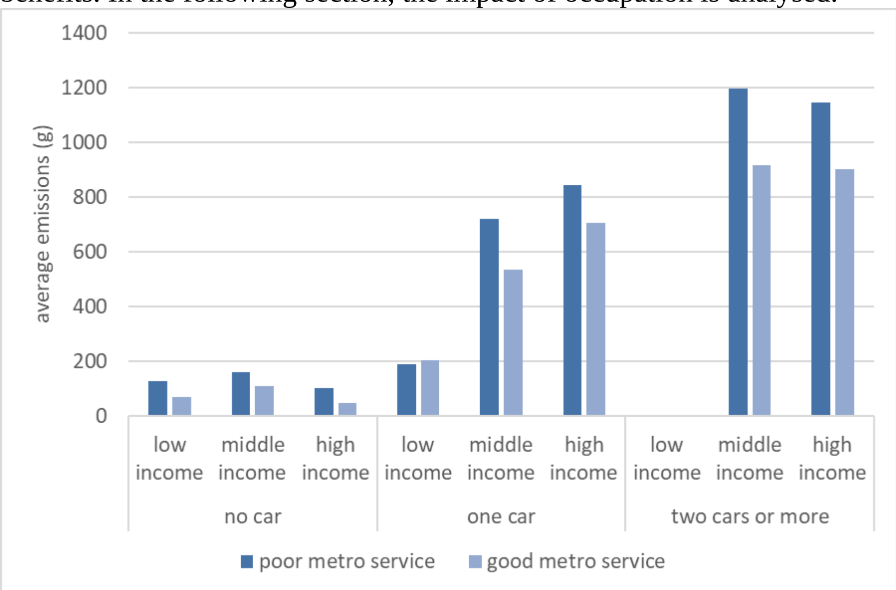

Figure 10. Effect of one income, car ownership and metro proximity on CO_2 emissions.

3.4 Multiple linear regression model on CO_2 emissions

Here, we employed a multiple linear regression model to explain the commuting CO_2 emissions with three main factors: socioeconomic characteristics, accessibility of public transit and built environment. Each variable is described in Table 4 below:

Table 4. Description of variables

	Variables	Description
Individual socioeconomic characteristics	Gender	1, Female, dummy
	Age_LS 24	1, less than 24, dummy
	Work_3	1, Managers, dummy
	Work_4	1, Professionals, dummy
	Area_less_120	Housing size less than 120 m^2
	NumberCarOwned	Number of cars owned, Ordered
	NumberBicycleOwned	Number of bicycles owned, Ordered
Public transportation service	h_close_metro	Distance to the nearest metro station from home location is less than 1 km, dummy
	w_close_metro	Distance to the nearest metro station from work location is less than 1 km, dummy
	h_NumberBusStation	Number of bus stations in 500 m from home location, Continuous
	w_NumberBusStation	Number of bus stations in 500 m from work location, Continuous
Built environment	w_road_den	Road density within 1 km buffer of work location, Continuous
	HHParkingSpace	Average car parking space by household in the community to which the home location belongs, Continuous
	1kmPark	Number of parks within 1 km buffer of work location, Continuous
	1kmKindergarten	Number of kindergartens within 1 km buffer of work location, Continuous
	1kmPrimarySchool	Number of primary schools within 1 km buffer of work location, Continuous
	1kmHighSchool	Number of high schools within 1 km buffer of work location, Continuous
	1kmSupermarket	Number of supermarkets within 1 km buffer of work location, Continuous
	1kmHospital	Number of hospitals within 1 km buffer of work location, Continuous
	w_employment_density	Employment density within 1000 m buffer of work location (per/km^2)

In the model, we only use three home location variables, which are community car parking space by household, good/poor metro service and number of bus stations within 500 m of the community. Because the survey was conducted in 27 compounds, and there may be a multicollinearity problem if more variables of home location are applied, in this study, we did not use the POI variables of home location.

After several round model tests, the results of the multiple linear regression model are shown in Table 5. The variables are divided into three groups: socioeconomic characteristics, public transport service and built environment features. Three models are estimated to explore the influence of various groups of attributes on the emissions. F-test values of the three models demonstrate the significance of the regressive function. Hence, there was at least one variable valid in this function.

Model 1: several socioeconomic factors had a significant effect on CO_2 emissions—gender, occupation, apartment area and the number of cars owned. Males produced more emissions than females, confirming the results of other studies (Brand et al., 2013; Huang, Liu, & Cao, 2015). Car ownership had some influence on car use, and people generally prefer to drive to work, producing more emissions. Apartment size was a significant factor—people with bigger apartments produced more commuting emissions also.

Model 2: the public transport service variables were added to Model 1. The result shows that the availability of a metro service close to a work location is positive to CO_2 emissions. People who live near a metro station but who work far away from a metro station still produce more CO_2 emissions. Inside the outer ring, 58% of people who live near a metro station have private cars, whereas car ownership was only 28% for people staying close to a metro station but outside the outer ring. Some people still drive to work even if they live near a metro station and produce more emissions. People may be attracted to take the metro to work where their workplace is close a station. As a result, they produce fewer emissions. Bus service also has some effect on emissions. If there are more bus stations near the home location, people may produce fewer emissions.

Model 3: the built environment variables were added to Model 2. Road density, and the number of primary schools and supermarkets in the workplace location were found to be significant in terms of CO_2 emissions. Higher road density may encourage people to walk, for example where people do not have to drive a long distance to buy something because there may be some supermarkets near their workplace, and so they will be less dependent on cars. Also in Model 3, the metro proximity to the workplace was also found to be significantly positive, this is because of the commuting distance being longer for people who work in a place close to a metro station. For people with a car whose workplace is close or far away from a metro station, their commuting distances are 9.0 km and 7.5km respectively, and the difference in modal share by car is small. Whereas the significance of home location is negative, though it was insignificant. The results show the complexity of an urban system. 'Metro only' is not an effective solution to lower commuting CO_2 emissions, and more refined policies should be explored.

Table 5. Results of multinomial linear regression model

Variables	**Model 1**		**Model 2**		**Model 3**	
	coefficient	*p* value	coefficient	*p* value	coefficient	*p* value
constant	297.3**	0	492.9**	0	651.1**	0
Gender	-216.2**	0	-220.0**	0	-223.3**	0
Age_LS 24	-39.6	0.564	-43.2	0.526	-39.4	0.561
Work_3	207.7**	0	201.5**	0	186.9**	0.001
Work_4	166.4**	0.001	139.0**	0.005	132.2**	0.007
Area_less_120	-127.5**	0.03	-156.4**	0.008	-170.4**	0.004
NumberCarOwned	385.2**	0	381.5**	0	381.8**	0
NumberBicycleOwned	-55.3	0.111	-54.8	0.115	-56.7	0.104
h_close_metro			-85.0*	0.069	-66.3	0.185
w_close_metro			92.7*	0.067	161.1**	0.003
h_NumberBusStation			-24.9**	0	-18.8**	0.007
w_NumberBusStation			0.2	0.975	12.7*	0.089
w_road_den					-30.8**	0.003
HHParkingSpace					-38.1	0.444
1kmPark					-14.1	0.298

1kmKindergarten			13.1	0.597
1kmPrimarySchool			50.0**	0.04
1kmHighSchool			8.3	0.416
1kmSupermarket			-25.6**	0.046
1kmHospital			-5.2	0.155
w_employment_density			0.0005	0.153
Adj. R-squared	0.158	0.171	0.186	
F-statistic	32.83	26.46	14.54	

*: p value is between 0.1 and 0.05.
**: p value is less than 0.05

4. CONCLUSION

Various measures have been introduced to lower CO_2 emissions, including new technologies for increasing the efficiency of energy consumption and cleaner energy. Travel mode and commuting distance are key factors for controlling CO_2 emissions. Encouraging public transport and carpooling to increase vehicle passenger load are also effective approaches for reducing emissions. In addition, shortening commuting distance is also a highly efficient method for emissions reduction. Therefore, avoiding so-called 'leapfrog' urban expansion, transit-oriented development should be encouraged.

The distribution of commuting CO_2 emissions among the population groups analysed in this study was found to be significantly uneven. It was observed that in Shanghai, the top 20% of commuters were responsible for 80% of the total CO_2 emissions. This highly uneven distribution indicates that effective policies should be particularly targeted at high-emitters. For such emitters who own a car and travel longer distances, developing strategies to shift their travel mode will be critical.

Metro is a relatively green and low-carbon travel mode. Car use control for those people staying close to a metro is still an important approach for ensuring that commuter CO_2 emissions are reduced. Improving metro accessibility is typically considered to be an effective method for lowering commuting CO_2 emissions, but where richer people locate themselves close to a metro station and do not commute by metro, the influence of metro on CO_2 emissions will be less important. Under the conditions of a large amount of non-motorised vehicles (NMV) or electric two-wheel vehicles, we should not neglect the contribution of NMV on reducing CO_2 emissions, and people should be encouraged to use NMV. Mode shifting from those modes to metro will also be less helpful with respect to lowering CO_2 emissions.

The empirical research described in this paper provides a relatively detailed and comprehensive analysis of the relationship between commuting CO_2 emissions with factors including socioeconomic characteristics, public transport service, and the urban built environment. This research identified which population groups are more responsible for higher emissions, and pointed out that policies directly targeting these groups should be worth further analysing in order to reduce commuter GHG emissions more effectively.

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