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ORIGINAL ARTICLE

Urban CO_2 emissions in Xi'an and Bangalore by commuters: implications for controlling urban transportation carbon dioxide emissions in developing countries

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Abstract China and India together have more than one third of the world population and are two emerging economic giants of the developing world now experiencing rapid economic growth, urbanization, and motorization. The urban transportation sector is a major source of carbon dioxide (CO_2) emissions in China and India. The goal of this study is to analyze the characteristics and factors of CO_2 emissions produced by commuters in Chinese and Indian cities and thus to identify strategies for reducing transportation CO_2 emissions and mitigating global climate change. Xi'an in China and Bangalore in India were chosen as two case study cities for their representativeness of major cities in China and India. The trends of CO_2 emissions produced by major traffic modes (electric motors, buses, and cars) in major cities of China and India were predicted and analyzed. The spatial distributions of CO_2 emissions

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produced by commuters in both cities were assessed using spatial analysis module in ArcGIS (Geographic Information System) software. Tobit models were then developed to investigate the impact factors of the emissions. The study has several findings. Firstly, in both cities, the increase of vehicle occupancy could reduce commuting CO_2 emissions by 20 to 50 % or conversely, if vehicle occupancy reduces, an increase by 33.33 to 66.67 %. It is estimated that, with the current increasing speed of CO_2 emissions in Xi'an, the total CO_2 emissions from electric motors, buses, and cars in major cities of China and India will be increased from 135×10^6 t in 2012 to 961×10^6 t in 2030, accounting for 0.37 to 2.67 % of the total global CO_2 emissions of 2013, which is significant for global climate change. Secondly, households and individuals in the outer areas of both cities produce higher emissions than those in the inner areas. Thirdly, the lower emissions in Xi'an are due to the higher density and more compact urban pattern, shorter commuting distances, higher transit shares, and more clean energy vehicles. The more dispersed and extensive urban sprawl and the prevalence of two-wheeler motorbikes (two-wheeler motorbike is abbreviated as "two-wheeler" in the following sections) fueled by gasoline cause higher emissions in Bangalore. Fourthly, car availability, higher household income, living outside the 2nd or Outer Ring Road, distance from the bus stop, and working in the foreign companies in Bangalore are significant and positive factors of commuting CO_2 emissions. Fifthly, "70-20" and "50-20" (this means that generally, 20 % of commuters and households produce 70 % of total emissions in Xi'an and 20 % of commuters and households produce 50 % of total emissions in Bangalore) emission patterns exist in Xi'an and Bangalore, respectively. Several strategies have been proposed to reduce urban CO_2 emissions produced by commuters and further to mitigate global climate change. Firstly, in the early stage of fast urbanization, enough monetary and land investment should be ensured to develop rail transit or rapid bus routes from outer areas to inner areas in the cities to avoid high dependency on cars, thus to implement the transit-oriented development (TOD), which is the key for Chinese and Indian cities to mitigate the impact on global climate change caused by CO_2 emissions. Secondly, in Bangalore, it is necessary to improve public transit service and increase the bus stop coverage combined with car demand controls along the ring roads, in the outer areas, and in the industry areas where Indian foreign companies and the governments are located. Thirdly, Indian should put more efforts to provide alternative cleaner transport modes while China should put more efforts to reduce CO_2 emissions from high emitters.

Keywords Global climate change · Urban transportation · CO_2 emissions by commuters · Spatial distribution · Impact factor · China and India

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report stated that recent global warming, sea level rising, and glacier melt were mainly caused by greenhouse gas (GHG) emissions generated by human activities (IPCC 2007). Among the GHG emissions, carbon dioxide (CO_2) is the single most important anthropogenic greenhouse gas which contributes about 65 % of total GHG emissions (WMO 2014). The transportation sector is a major source of CO_2 emissions and currently contributes 20–25 % of global CO_2 emissions. Its global share is projected to rise to 30–50 % by 2050 (Brand et al. 2013). It is estimated that the most targeted measure to reduce GHG emissions in an urban development context should be aimed at reducing transportation CO_2 emissions (Norman et al. 2006).

China and India together have more than one third of the world population and are two emerging economic giants of the developing world. There exist a group of cities in China (ranking between 5th and 65th; Beijing, Shanghai, Shenzhen, and Guangzhou not included) and in India, which are not the largest cities but are among the fastest growing cities in the world (Jones Lang LaSalle (JLL) 2015). The total population of these cities in China exceeds 300 million, larger than the total population of United States (US). The total economic output of these Chinese cities is ca. $8.6 trillion, accounting for 9 % of the global output, and is expected to reach $15 trillion (15 % of the global output) in 2025. Now, China and India are experiencing rapid urbanization and motorization (Pucher et al. 2007; Han 2010). CO_2 emissions from transportation sector account for a large percentage, about 8 % of total CO_2 emissions in China (Wang et al. 2011) and 32, 17, 13, 19, 43, 56, and 25 % of total CO_2 emissions in Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad, and Ahmadabad of India, respectively (Ramachandra et al. 2015). Commuting traffic is a major part of urban traffic and has been viewed as the most important traffic in the urban transportation (Meyer and Miller 2001). Commuting trips account for 51.6 and 67 % of the urban passenger transportation in Xi'an and Bangalore, respectively (Mamatha and Madhu 2007; Xi'an City Traffic Management Committee and Chang'an University (XCTMCCU) 2012). The increase of CO_2 emissions produced from commuting trips will be huge in these Chinese and India cities during the fast urbanization and motorization and thus may cause severe impacts on the global climate change.

Xi'an and Bangalore were chosen as the two case study cities for their representativeness of major Chinese and Indian cities. Also, China and India are both rich in history and culture. Xi'an and Bangalore are typical cities with many heritages, rich cultures, and protected historical center districts. The two cities need to accommodate old traditions and modern development during the rapid urbanization and motorization (Ramachandra and Shwetmala 2009; Ramachandra et al. 2012; Wang et al. 2013, 2015).

Previous studies have found that socio-economic characteristics of individuals and households are related to transportation CO_2 emissions, including age, education level, car availability, occupation, and income (Carlsson-Kanyama and Lindén 1999; Brand and Boardman 2008; Weber and Matthews 2008; Susilo and Stead 2009; Brand and Preston 2010; Ko et al. 2011; Brand et al. 2013; Büchs and Schnepf 2013). Households in rural, suburb, and urban districts have different levels of transportation CO_2 emissions (Moriarty 2002; Troy et al. 2003; Nicolas and David 2009; Ko et al. 2011; Xiao et al. 2011; Liu et al. 2012; Büchs and Schnepf 2013). Furthermore, straight line distances from the household location to the city center have been found to be correlated with vehicle kilometer traveled (VKT) and the transportation CO_2 emissions (Miller and Ibrahim 1998). Previous research is short of comparative analysis between similar cities experiencing rapid economic growth, urbanization, and motorization in China and India, which are crucial for the global climate change. Also, the impacts of the urban spatial characteristics on the transportation CO_2 emissions in the previous studies focused on the scattered household locations, not on the entire city.

Therefore, the goal of this study is to analyze the characteristics and the changing trends of the commuting CO_2 emissions in Chinese and Indian cities during the process of the rapid economic growth, urbanization, and motorization. The study analyzes the characteristics, spatial distributions of commuting CO_2 emissions, and their relationships with individual/households' socio-economics, travel activities, and urban spatial characteristics in the entire urban area of Xi'an and Bangalore. Based on the analysis and the findings, several strategies are proposed for the reduction of transportation CO_2 emissions. This study will be useful for the low-carbon transportation development in Chinese and Indian cities and will also be a good reference for other similar cities in the developing world. Therefore, it is important for the global climate change mitigations.

2 Related work

Based on the previous studies, this section sets out the methodologies for transportation CO_2 emission calculation, the relationship expected between socio-economic status, household spatial distribution, urban form, and transportation CO_2 emissions. These highlight the factors and characteristics which affect the CO_2 from commuters and inform the study approach for the two case study cities.

2.1 Transportation CO_2 emission calculations

Transportation CO_2 emissions are produced at various stages of the transportation development process, such as vehicle manufacturing, infrastructure construction and operations, traffic operations, and infrastructure maintenance. For road transportation, the fuel consumption during the traffic operation stage accounts for 95–98 % of the total fuel consumed in the infrastructure construction, operations, maintenance, and traffic operation stages (Araújo et al. 2014). For metro operating at design occupancy level, the CO_2 emissions of the metro operation account for 98 % of the total CO_2 emissions during the metro infrastructure and facility construction and metro operation (Zhang et al. 2014b). For buses operating at design occupancy level, the CO_2 emissions of the buses during the traffic account for 99 % of the total CO_2 emissions in the stage of the bus facility construction and operations and bus vehicle operations (Zhang et al. 2014b). Currently, very few studies have been conducted with regards to the CO_2 emissions at the vehicle or metro train manufacturing stage. CO_2 emissions during the traffic and metro operating stage account for most of the emissions in the transportation. Hence, this study mainly considers the emissions during the traffic and metro operation stages.

The common method for calculating transportation emissions was recommended in 1996 (IPCC 1997); the transportation CO_2 emissions are equal to the amount of the energy consumed or the distance travelled for a given mobile source activity multiplied by the emission factor for a given fuel type, vehicle type, and the emission control. Since vehicle fuel consumption depends on transport level, operating characteristics (vehicle occupancy, travel speed, and engine size), emission control, maintenance procedures, and vehicle age (Redsell et al. 1988; Gover et al. 1994; Potter 1997; Anable et al. 1997), researchers have conducted tests to investigate the range of fuel consumption and emissions for real-world operations (Liu and Hou 2009; Huo et al. 2011; Zhang et al. 2014a).

2.2 Socio-economic characteristics and transportation CO_2 emissions

A number of studies have been conducted to examine the relationship between socio-economic characteristics and transportation CO_2 emissions in different cities and countries. It was found that people with higher income produced more transportation CO_2 emissions (Carlsson-Kanyama and Lindén 1999; Brand and Boardman 2008; Weber and Matthews 2008; Susilo and Stead 2009; Brand and Preston 2010; Ko et al. 2011; Brand et al. 2013; Büchs and Schnepf 2013), people with full-time jobs produced more transportation CO_2 emissions than those with part-time jobs (Carlsson-Kanyama and Lindén 1999; Susilo and Stead 2009; Ko et al. 2011; Brand et al. 2013) and the unemployed (Brand and Boardman 2008), households with at least one car produced more transportation CO_2 emissions than those without any cars (Ko et al. 2011; Brand et al. 2013), households with two or more cars produced more than twice transportation CO_2 emissions of the households with only one car (Brand and Boardman 2008; Brand and Preston 2010), people with age of 36–65 produced more transportation CO_2 emissions than those in other ages (Brand and Boardman 2008; Brand and Preston 2010; Brand et al. 2013), and people with higher education levels produced more transportation CO_2 emissions than those with lower education levels (Büchs and Schnepf 2013).

2.3 Household locations and transportation CO_2 emissions

The relationship between transportation CO_2 emissions and household location has also been studied in the recent years. It was found that people located in the peri-urban areas produced the largest transportation CO_2 emissions with 1000 kg/year/individual for daily travel and 700–800 kg/year/individual for long-distance travel (Nicolas and David 2009). In Seoul metropolitan area, people located at the edge of the metropolis produce more transportation CO_2 emissions than those located in other parts of Seoul (Ko et al. 2011). It was also found that the transportation CO_2 emissions produced by the neighborhoods located in the central district were less than those in the suburbs (Xiao et al. 2011; Liu et al. 2012), and whether the district was classed as a suburb or not was a strong indicator of the transportation CO_2 emissions (Xiao et al. 2011). Büchs and Schnepf (2013) found that rural places were strongly associated with higher transportation CO_2 emissions than urban households in UK. The straight line distance from the zone to the central business district (CBD) has been found to be the most important factor in VKT per worker in the Greater Toronto Area. It can be interpreted as a measure of the effect of *sprawl* or *decentralization*. The VKT per worker increases by 0.25 km on average as a worker lives 1 km farther away from the CBD (Miller and Ibrahim 1998).

2.4 Urban form and transportation CO_2 emissions

Low-density suburban development is more energy and GHG intensive than high-density urban development on a per capita basis (Norman et al. 2006). Increasing residential density can lead to a significant reduction in transportation emissions (Hong and Shen 2013). VKT declines as the compactness of subdivisions increases, and vehicles tend to be driven at lower average speed in more compact subdivision. The lower speed is not significant enough to offset the reduced VKT; therefore, total gasoline consumption and the associated CO_2 emissions still tend to be lower in more compact developments (Emrath and Liu 2008). There exists a significant inverse relationship between the land use density, street connectivity (block density), and vehicle emissions while controlling for the effects of household size, vehicle ownership, and income (Frank et al. 2000). The type of the neighborhood is correlated with transportation CO_2 emissions (Guo et al. 2014). For four types of neighborhoods (traditional, grid, enclave, and superblock) in Jinan of China, the superblock neighborhoods produce the highest emissions, which are related to the higher household annual income, whereas traditional neighborhoods produce the lowest emissions. It is also found that mixed land use and convenient accessibility to public transportation can reduce transportation CO_2 emissions. In the study of Hong and Shen (2013), a Bayesian multilevel model with spatial random effects and instrumental variables was employed to control for spatial autocorrelation and self-selection. The results indicate that the effect of residential density on transportation emissions is influenced by spatial correlation and self-selection. Also, they found that increasing residential density led to a significant reduction in transportation emissions.

3 Methodology

This section will present the study methodology. First, the household sampling and characteristics of the samples in the two cities will be discussed. Then, the calculation method of the transportation CO_2 emission and its sensitivity analysis will be presented. Next, the Tobit models will be developed to investigate factors of the commuting CO_2 emissions. Also, we will present the method of using the spatial join module in ArcGIS to show the spatial distribution of the home-based commuting CO_2 emission by zone in the entire urban area of Xi'an and Bangalore.

3.1 Data collection

Household surveys were carried out in the urban area of Xi'an and Bangalore to collect data of commuting CO_2 emissions. The statistical method from Meyer and Miller (2001) was used to determine the sample size as shown in Eq. (1). At least 1476 and 756 commuting trip observations in Xi'an and Bangalore are needed, respectively, to achieve the precision within ±5 % ($r=0.05$) of the real value at 95 % of the time ($\alpha=0.05$).

$$n=\frac{\left[Z_{1-(1/2)\alpha}\right]^2(1-p)}{r^2 p} \tag{1}$$

where r is the margin of error or precision and is assumed to be 0.05 (assuming an estimate of the sample size within ±5 % of the real value at 95 % of the time), p is the observed value of the proportion of the commuting trips in the urban passenger transportation, and $Z_{1\text{-}(1/2)\alpha}$ is the standard normal statistic corresponding to the $(1\text{-}\alpha)$ confidence level.

In Xi'an, simple random sampling was implemented in each zone in 2012. On average, 9 to 10 households were surveyed in each zone and a total of 1501 households were surveyed. In Bangalore, the survey was carried out on the basis of a stratified (economic status) random selection procedure during 2011–2012. The validation of the sampled data was conducted during 2012–2013. The survey covered 1967 households representing heterogeneous population belonging to different income, education, and social aspects. The distributions of the sampled households and the areas, population, and densities between the ring roads in Xi'an and Bangalore are shown in Table 1.

Commuting mode, trip distance, commuting frequency, household location, and workplace were included in the questionnaire. Furthermore, socio-economic characteristics of the households and individuals, including household annual income, household tenure, car availability, age, work unit type, and education level of the household members, were also surveyed. Table 2 presents the levels of each characteristic in the survey. It is found that some common characteristics exist in both Xi'an and Bangalore: (1) most commuters have good education level (65.9 and 62.2 % commuters in Xi'an and Bangalore have college degrees or above, respectively); (2) there is a high percent of commuters working in private enterprises (41.7 %

Table 1 Area, population, density, and sample distributions by ring roads in Xi'an and Bangalore

Xi'an	1st Ring Road	1st–2nd Ring Road	2nd–3rd Ring Road	Outside 3rd Ring Road
Area (km^2)	10.78	64.51	271.57	
Population (million people)	0.396	1.324	1.791	
Population density (thousand people/km^2)	36	20	6.5	
Sample size (household/%)	93/6.2 %	469/31.2 %	848/56.5 %	91/6.1 %
Bangalore	CBD	CBD-Outer Ring Road	Outer Ring Road-Peripheral Ring Road	Outside Peripheral Ring Road
Area (km^2)	15.65	203.35	493.97	
Population (million people)	0.193	4.036	1.610	
Population density (thousand people/km^2)	12.3	19.8	3.2	
Sample size (household/%)	12/0.6 %	962/48.9 %	993/50.5 %	

in Xi'an and 25.4 % in Bangalore); and (3) a high percentage of commuters have their own houses/apartments (81.2 % in Xi'an and 58.2 % in Bangalore). However, (1) Xi'an has higher household annual incomes (72.1 % more than $10,000), a higher rate of car availability (54.4 %), and a higher percentage of commuting by car (28.56 %) than Bangalore has. (2) Bangalore has more household members (averagely 4.53 per person in one household) and a higher two-wheeler ownership rate (55.4 %).

3.2 Calculation of commuting CO_2 emissions and sensitivity analysis

The commuting CO_2 emissions were calculated as the emission factor (by mode, fuel type, and occupancy) multiplied by trip distance (IPCC 1997), as shown in Eq. (2).

$$C = \mathrm{EF} \times L \tag{2}$$

where C is the CO_2 emission (kg/passenger/km), EF is the emission factor (by mode, fuel type, and occupancy), and L is the trip distance (km).

Well-to-wheel (WTW) CO_2 emission intensity by fuel types suggested by Huo et al. (2012) was applied in this study. The fuel consumed (e.g., liter of gasoline consumed per 100 km) by vehicles is associated with uncertainty because it is affected by several factors such as driving speed. For instance, during commuting hours, driving may become less fuel efficient due to congestions (Huo et al. 2011). The actual vehicle occupancy is not a fixed value either. Hence, we collected local data on the range of these values in Xi'an and Bangalore through surveys and the related literatures to calculate the ranges of the CO_2 emission factors by mode, fuel type, and occupancy, as shown in Eq. (3).

$$\mathrm{EF}_{\max,\min} = \frac{\mathrm{CI} \times \mathrm{FC}_{\max,\min}}{\mathrm{VO}_{\min,\max}} \tag{3}$$

where CI is the WTW CO_2 emission intensity by fuel type, FC is the fuel consumption, and VO is the vehicle occupancy.

Table 2 Socio-economic characteristics and sample distributions by ring roads in Xi'an and Bangalore

	Levels	Xi'an		Bangalore	
		Number	Percent	Number	Percent
Age	<35 years old	1378	47.9 %	547	13.9 %
	35–55 years old	1364	47.4 %	3119	79.3 %
	>55 years old	137	4.8 %	268	6.8 %
Work unit type	Government	113	4.2 %	593	19.9 %
	Public institution	511	19.0 %	234	7.8 %
	Foreign company	32	1.2 %	152	5.1 %
	Private enterprise/local company	1120	41.7 %	758	25.4 %
	State-owned company	453	16.9 %	83	2.8 %
	Others	454	16.9 %	1166	39.0 %
Education level	Middle school graduate	307	10.7 %	322	8.5 %
	Graduated from the high school or technical secondary school	671	23.4 %	1106	29.3 %
	Graduated from college	664	23.1 %	413	10.9 %
	Bachelor's degree	1029	35.9 %	1391	36.8 %
	Master's degree	167	5.8 %	426	11.3 %
	Ph.D. degree	31	1.1 %	119	3.2 %
Household members	Average number of household members	3.22		4.53	
Household traffic vehicles	Household car availability	817[a]	54.4%[a]	1415[b]	71.9%[b]
Household annual income	<US$2,000	9	0.6 %	197	10.0 %
	US$2,000–6,000	77	5.2 %	839	42.7 %
	US$6,000–10,000	326	22.1 %	381	19.4 %
	US$10,000–16,000	580	39.3 %	306	15.6 %
	US$16,000–20,000	311	21.1 %	64	3.3 %
	US$20,000–40,000	139	9.4 %	125	6.4 %
	>US$40,000	34	2.3 %	55	2.8 %
Housing tenure	House owner occupied	1158	81.2 %	1136	58.2 %
	House is rented	268	18.8 %	817	41.8 %
Household location	Inside the 1st Ring Road/CBD	93	6.20 %	12	0.6 %
	1st–2nd Ring Road/CBD-Outer Ring Road	469	31.25 %	962	48.9 %
	2nd–3rd Ring Road/Outer-Peripheral Ring Road	848	56.50 %	993	50.5 %
	Outside the 3rd Ring Road/Peripheral Ring Road	91	6.1 %		

[a] In Xi'an, household car availability refers to people owning car or willing to buy car

[b] The car availability of the household in Bangalore's questionnaires includes both cars and two-wheelers; two-wheelers account for 77.1 % of these two types of vehicles (BT 2015)

The calculation results of CO_2 emission factors are presented in Table 3. The average value of each CO_2 emission factor was used in the calculation of commuting CO_2 emissions for Xi'an and Bangalore.

Considering the rapid growth of motorization in Chinese and Indian cities, it is necessary to investigate the impact of the reduction in vehicle occupancy and the increase in traffic congestions on commuting CO_2 emissions. Thus, the sensitivity of CO_2 emission factor

Table 3 Well-to-wheel CO_2 emission factors by fuel type, travel mode, and occupancy in Xi’an and Bangalore

Travel mode	Fuel type	WTW CO_2 intensity (t CO_2 eq./unit of fuel)[a]	Fuel consumptions per 100 km[b]	Occupancy (passengers/vehicle)[h]	WTW CO_2 emission factor (kg/passenger/km)	Average WTW CO_2 emission factor (kg/passenger/km)
Xi’an						
Car	Gasoline	3.87/t	7.80~10.45 (L)	1~3	0.073~0.295	0.184
Normal coach	Diesel	3.94/t	39.12~42.38 (L)	20~50	0.027~0.072	0.050
Taxi	Compressed natural gas (CNG)	2.76/1000 m^3	8~10 (m^3)	2~5	0.044~0.138	0.091
Bus	CNG	2.76/1000 m^3	52~58 (m^3)	60~100	0.014~0.027	0.021
Metro	Electricity	0.83/1000 kWh	3340~3350 (kWh)[c]	1100~1600/train	0.017~0.025	0.021
Electric bicycle[d]	Electricity	0.83/1000 kWh	1.1~1.25 (kWh)[e]	1~2	0.005~0.010	0.008
Electric motor[f]	Electricity	0.83/1000 kWh	1.6~1.7 (kWh)[g]	1~2	0.007~0.014	0.011
Bangalore						
Car or two-wheeler[i]	Gasoline	3.87/t	1.23~10.45 (L)	1~3	0.032~0.184	0.067
Taxi	Gasoline	3.87/t	7.80~10.45 (L)	2~5	0.044~0.148	0.096
Bus	Diesel	3.94/t	36~39 (L)	30~50	0.024~0.044	0.034

m^3 cubic meter, *kWh* kilowatt hour, *L* liter

[a] Data was from Huo et al. (2012)

[b] Data was from Liu and Hou (2009), Huo et al. (2011), Zhang et al. (2014a), and Ramachandra et al. (2015); the fuel consumptions considered the factor of vehicle speed in the peak hours

[c] Data was collected from the survey of Xi’an Metro Co., Ltd

[d] The highest speed of the electric bicycle is 20 km/h

[e] Data was from National Standard of the People’s Republic of China, GB17761-1999, Electric bicycles—general technical requirements, issued by China State Bureau of Quality and Technical Supervision

[f] The highest speed of the electric motor is more than 20 km/h

[g] Data was collected from the questionnaire surveys of the electric motor users in Xi’an

[h] Data came from Xi’an Transport Development Annual Report in 2012 and field surveys in Bangalore in 2012

[i] In the Bangalore’s questionnaires of the travel mode, car and two-wheeler were combined in one choice option; thus, the CO_2 emission factor of car or two-wheeler is weighted by proportions of car and two-wheeler, which are 22.9 % for cars and 77.1 % for two-wheelers (BT 2015). The average value of CO_2 emission factor for car and two-wheeler is 0.067 kg/passenger/km

to vehicle occupancy and fuel consumption was analyzed. That is, the change of CO_2 emission factor due to the changes of vehicle occupancy and fuel consumption was calculated using Eq. (4).

$$\Delta_{EF} = \frac{CI \times FC_{average} \times (1 + \Delta_{FC})}{VO_{average} \times (1 + \Delta_{VO})} \tag{4}$$

where Δ_{EF} is the change of CO_2 emission factor due to the changes of vehicle occupancy and fuel consumption, Δ_{FC} is the change of fuel consumption, and Δ_{VO} is the change of vehicle occupancy.

In the future, in both China and India, if the total number of vehicles increases, the vehicle occupancy decreases, and the traffic congestions increase, the CO_2 emissions will increase significantly. Therefore, to estimate this tendency, the CO_2 emissions in the future from major transportation modes (electric motors, buses, and cars) in Chinese and Indian cities were also calculated based on the past increasing trend on CO_2 emissions.

3.3 Spatial distribution of CO_2 emissions by commuters

The spatial join module in the ArcGIS software was used to explore the characteristics of spatial distributions of the household and individual commuting CO_2 emissions by zone in the urban area of Xi'an and Bangalore and to find where the high commuting CO_2 emissions are from.

3.4 Tobit modeling

To explore the impact factors of the emissions and the characteristics of the high and low emitters in the urban areas of the two cities, the relationships were modeled between the household/individual commuting CO_2 emissions and the urban spatial and household/individual socio-economic characteristics. The distributions of the household and individual commuting CO_2 emissions were analyzed. The significance levels for the normality test are all smaller than 0.05 as shown in Table 4, which means that it is hard to say these distributions follow normal distributions. Also, it is observed that the household and individual commuting CO_2 emissions are left censored at zero. Therefore, the Tobit model was established to analyze the relationships between the CO_2 emissions by commuters and their factors.

Table 4 Normality test for CO_2 emissions by commuters in Xi'an and Bangalore

	Kolmogorov-Smirnov		Shapiro-Wilk	
	Statistic	Significance	Statistic	Significance
Individual emissions (Bangalore)	0.181	0.000	0.827	0.000
Household emissions (Bangalore)	0.165	0.000	0.843	0.000
Individual emissions (Xi'an)	0.272	0.000	0.665	0.000
Household emissions (Xi'an)	0.245	0.000	0.709	0.000

The Tobit model presented in Eq. (5) was used.

$$y_i = \begin{cases} x_i^{'}\beta + \varepsilon_i & \text{if} \quad y_i^* = x_i^{'}\beta + \varepsilon_i > 0, \\ 0 & \text{if} \quad y_i^* = x_i^{'}\beta + \varepsilon_i \leq 0. \quad i = 1, 2, \cdots, N \end{cases} \tag{5}$$

where y_i is the dependent variable, y_i^* is the latent variable, $x_i^{'}$ is a vector of independent variables, β is a vector of estimable parameters, N is the number of observations, and ε_i is a random term. In the Tobit model for household CO_2 emission by commuters, the dependent variable is the household commuting CO_2 emissions; the potential independent variables are household car availability, household annual income, housing tenure, household location separated by the ring roads, straight-line distance from the household to the city center, and distance to the nearest bus stop/metro station. Similarly, in the Tobit model for individual CO_2 emissions by commuters, the dependent variable is the individual commuting CO_2 emissions; the potential independent variables are household car availability, age, work unit type, education level, household locations separated by the ring roads, straight-line distance from the household to the city center, and distance to the nearest bus stop/metro station.

In the process of Tobit modeling, all the potential independent variables were considered. Then, based on the interim modeling results, less significant independent variables were removed. The best Tobit models of household and individual commuting CO_2 emissions were established with all significant variables.

4 Trends of commuting CO_2 emissions in Chinese and Indian cities and their global impacts

4.1 Overview of Xi'an and Bangalore

The basic information of Xi'an and Bangalore is shown in Table 5.

4.1.1 Rapid growth in the economic, urbanization, and motorization

In Xi'an, the GDP increased from US$ 10.55 billion in 2000 to US$ 71.29 billion in 2012. Now, Xi'an ranks the 13th among Chinese cities (JLL 2015). In Bangalore, from 2000 to 2013, the GDP continued increasing except in 2009 (Glastris 2013). In 2011, the GDP of Bangalore was US$ 83 billion, and now, Bangalore ranks the sixth among Indian cities (Indiancn 2013). Xi'an's leading industries are cultural activities, high technology, and equipment manufacturing. Bangalore's economy is prospering on the information technology (IT) industry, which contributes ca. 74 % to the city's revenues in the year 2000 to 2001 (Parthasarathy 2004). Bangalore has been economically and socially fragmented due to the gap in income between the workers of IT sectors and local industries (Sabapathy et al. 2012).

In 2010, the built-up area in Xi'an reached 522.28 km^2, 37 times of the area in 1949 (Xu 2012). The city area of Bangalore is now 741 km^2, grown about 10 times since 1949 (Ramachandra et al. 2012). In Xi'an urban central area, the population was 3.09 million in 2003 and increased to 4.48 million in 2014. Similarly, the population of Bangalore increased from 4.13 million in 1991, 5.68 million in 2001, to about 9.58 million in 2014 (Ramachandra et al. 2012).

Table 5 Basic information of Xi'an and Bangalore

	Urban area (km^2)	Population (million)	GDP (US$ billion)	Per capita income (US$)
Xi'an[a]	522	4.48	71	10,905
Bangalore[b]	741	9.58	83	10,247
	City ranking[c]	Commuters by bus (million person times/day)	Metro passengers (million person times/day)	Number of buses
Xi'an	13th	2.47	0.16	7695
Bangalore	6th	3.50		4203
	Average vehicle speed in CBD (km/h)	Average volume/capacity (V/C) in CBD	Cars/LMV[b] (million)	Two-wheelers (million)
Xi'an	5–15	0.9	1.044 (car)	0.440[d]
Bangalore	4–13	3.5[h]	1.102 (LMV)[b]	3.725
	Urban form			
Xi'an	Three ring roads and radial roads, leading industries mostly located outside the 2nd Ring Road, historical and cultural protection inside 1st Ring Road			
Bangalore	Two ring roads and radial roads, leading industries mostly located outside the Outer Ring Road, building and market maintain traditional in CBD			

Sources: (Mamatha and Madhu 2007; Sudhira et al. 2007; Ramachandra et al. 2012; XCTMCCU 2012; Indiancn 2013; Sudhakara and Balachandra 2013; XBS and NBSXIT 2013; BT 2015)

[a] In Xi'an, the data of urban central area is for the year of 2010 and the data of resident population in the urban central area is for the year of 2014; other data of Xi'an in the table is for the year of 2012

[b] In Bangalore, the data of the urban area is for the year of 2009; the data of the population is for the year of 2014; the data of the GDP and per capita income is for the year of 2011; the data of average V/C in CBD and number of light motor vehicle (LMV) and two-wheeler is for the year of 2014 and comes from the Department of Transportation in Bangalore (BT 2015); and the data of the commuters by bus and number of buses is for the year of 2007

[c] City ranking data of Xi'an comes from the study of JLL (2015), and city ranking data of Bangalore comes from the reports of the ten richest cities rankings in India (Indiancn 2013)

[d] In Xi'an, there is prohibition of two-wheelers inside the 2nd Ring Road

In Xi'an, the number of the motor vehicles increased from 0.46 million in 2005 to 1.47 million in 2012, with an average annual growth rate of 18 %. Among these vehicles, the number of cars increased from 0.18 million in 2005 to 1.04 million in 2012, with an average annual growth rate of 28.1 %, and the car ownership was 159 cars per 1000 people in 2012 (XCTMCCU 2012). In Bangalore, the average annual growth rate of the vehicles was 20.22 % per year from 1980 to 2005, and the car ownership rate is 47 per 1000 population (Sudhakara and Balachandra 2013). Additionally, there is a sharp increase of two-wheeler ownership (3.72 million, 69.1 % of all traffic vehicles in 2014).

Both cities are facing severely increasing motorized traffic, especially for the car trips (28.56 % of the mode share in Xi'an in 2012) and two-wheeler trips (42 % of the mode shares in Bangalore in 2007) during the commuting, and walking and cycling trips decreased. In Xi'an, the bus ridership (37.94 % of the mode share) was 4.8 million per day on 243 routes with a fleet of 7695 buses in 2012. The passenger volume of Xi'an Metro Line 2 that began operations in September 2011 has reached 0.16 million people per day (XCTMCCU 2012). In Bangalore, the buses (20 % of the mode share in 2007) served about 3.5 million commuters per day with a fleet of 4203 buses (Mamatha and Madhu 2007). The metro in Bangalore is still under construction. Quick motorization, inconvenient bus services, and increasing commuting distances have led to a large amount of travels by cars or two-wheelers in both cities.

4.1.2 Similar industry distribution and quick urban sprawl

Xi'an and Bangalore have similar urban forms regarding ring roads, radial roads, and industry distributions. Within the 1st Ring Road in Xi'an, it is the city center with large malls, entertainment venues, government offices, and famous historic scenic spots. In the late 1990s, a government-led initiative created several economic zones that focused on new high-technology industry, ecological and cultural tourism industries between the 2nd Ring Road and the 3rd Ring Road. The economic zones in the south, southwest, and southeast outside the 2nd Ring Road developed more quickly than those in the northern part. Similarly, in Bangalore, there exist the government offices, commercial sites of retail and wholesale, cultural institutions, and transport hubs in the CBD area. Bangalore's IT industry and the concentration of small and medium enterprises clustered mostly along or outside the Outer Ring Road (Sudhira et al. 2007).

Also, both cities sprawl by ring roads and radial roads quickly. In Xi'an, the newly developed suburbs in 1990s have now become part of the city sprawl as the urban area gradually spread out. Similarly, in Bangalore, as the city gradually sprawled, industrial estates at the periphery of the city along or beyond the Outer Ring Road have become part of the sprawl.

Compared with Xi'an, Bangalore has a less dense and more extensive urban sprawl in the outer areas, outskirts, and peri-urban regions of the city. At the urban fringe of Bangalore, the sprawl is haphazard and unplanned (Pucher et al. 2005; Mamatha and Madhu 2007; Ramachandra et al. 2012). In Xi'an, there is denser and more compact urban sprawl. Bangalore's haphazard and unplanned urban sprawl pattern is due to the land privatization, highly market-oriented economic development, and government's lack of urban and transportation planning control and land use control, while Chinese governments have the ability to control the urban and transportation planning and land use.

4.1.3 Congested CBD

In the CBD of Xi'an, there are severe congestions during peak hours. The reasons include many large malls, entertainment venues, and government offices have attracted a huge amount of traffic; there exist some through traffic between the northern and the southern districts; and the famous historic scenic spots and old streets in the CBD attract tourists to this area. These all lead to more traffic volumes and congestions in the CBD area. The average volume/capacity (V/C) is as high as 0.9 in the CBD area; on other roads, it ranges from 0.4 to 0.8 (XCTMCCU 2012).

Bangalore's transportation is even worse in its CBD (Mamatha and Madhu 2007). The Outer Ring Road is 8 km away from the CBD. If people want to use this ring road for travelling, the detour is a burden in terms of time and cost. Therefore, people tend to use the CBD as a thoroughfare, which is one of the reasons for the congestions in the CBD area. Besides, the government offices, commercial sites, cultural institutions, and transport hubs are all located in the CBD area. These attracted lots of traffic in the CBD. In peak hours, the average travel speed in the CBD is 13 km/h. In the core area of the CBD, the average travel speed in the peak hours is as low as 4 to 7 km/h. And, the V/C is as high as 3.5 in CBD area; on other roads, it ranges from 2.34 to 2.96 (Mamatha and Madhu 2007). (Due to a large number of two-wheelers in India, India uses a special method to calculate traffic capacity, which is different from normal method.)

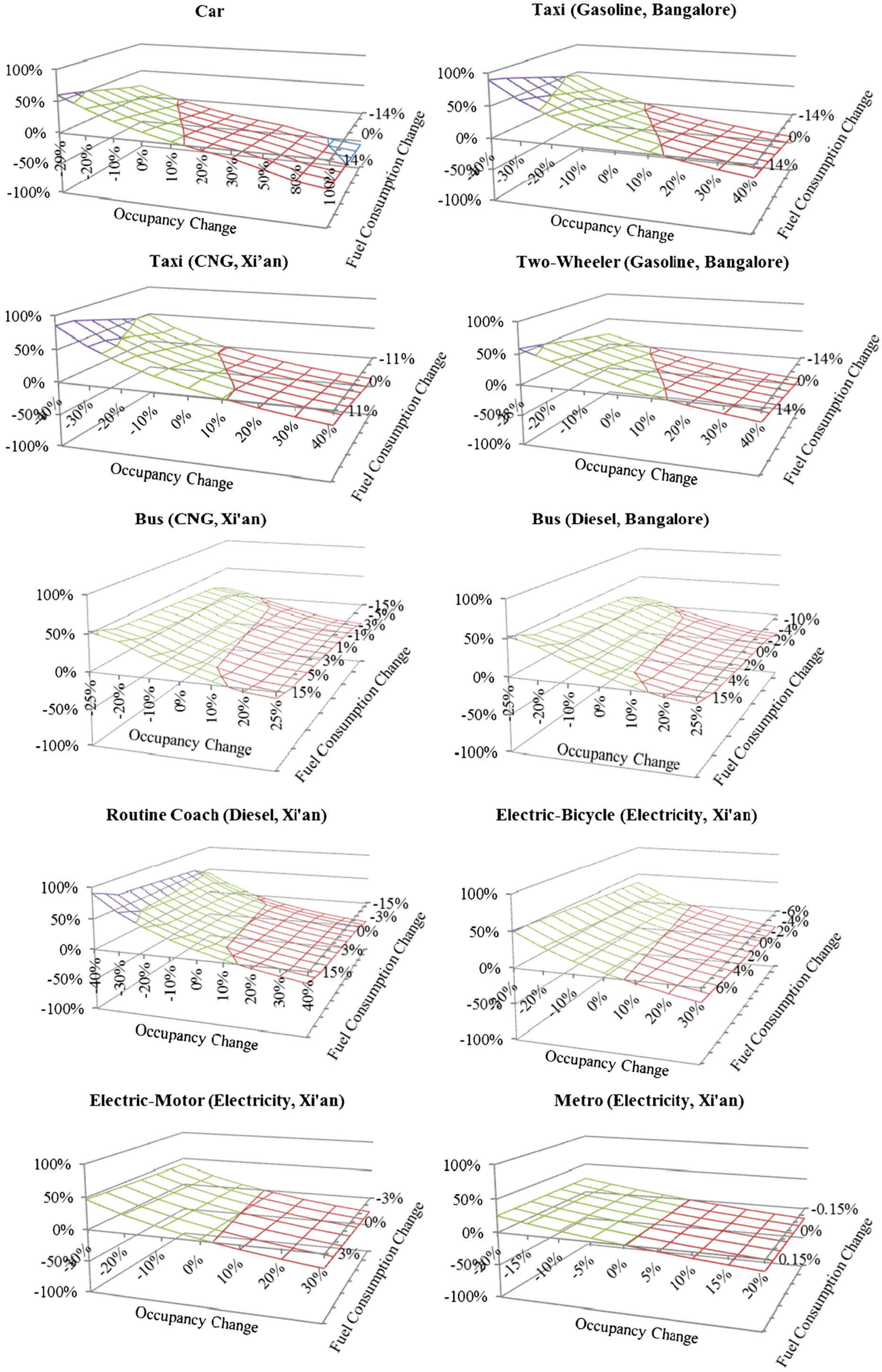
4.2 The ranges and trends of urban commuting CO_2 emissions in Chinese and Indian cities

The average commuting CO_2 emission per person per kilometer varies with fuel consumption and vehicle occupancy. The sensitivity analysis of CO_2 emission factor by mode and fuel type is shown in Fig. 1, and the maximum changes of CO_2 emission factors are shown in Table 6. It is found that the occupancy has a significant impact on the CO_2 emission factor (kg/passenger/km). The variation of the occupancy can cause −50 to +66.67 % variations on the CO_2 emission factors of car, normal coach, and taxi. If vehicles travel smoothly and do not have frequent idling, the CO_2 emission factors of cars and two-wheelers can be reduced by 14 %. If the road is congested with poor road conditions, the CO_2 emissions of cars and two-wheelers can be increased by 14 %. From the perspective of the global CO_2 emission reductions, increasing vehicle occupancy in China and India has the largest impact on controlling the increase of commuting CO_2 emission and the global climate change mitigations. In addition, traffic congestion reduction, pavement condition improvement, and reduction of frequent driving speed changes are also important for CO_2 emission reduction.

4.3 Trends of CO_2 emissions for major travel modes in Chinese and Indian cities

In 2008, the trips by electric motors, buses, and cars in Xi'an were 0.89, 5.34, and 2.42 million, respectively, and the average trip distance was 5.4 km. In 2012, the trips by electric motors, buses, and cars in Xi'an increased to 1.48 million (with an annual increase rate of 13.64 %), 5.89 million (with an annual increase rate of 2.47 %), and 3.39 million (with an annual increase rate of 8.82 %), respectively, and the average trip distance reached 5.81 km (with an annual increase rate of 1.85 %). In 2012, the CO_2 emission factors for electric motors, buses, and cars are 0.011, 0.021, and 0.184 kg/passenger/km. Using the same annual increase rates of the trips of electric motors, buses, and cars and the average trip distance from 2008 to 2012, it is estimated that, by 2030, the trips by electric motors, buses, and cars in Xi'an will reach 14.88, 9.13, and 15.55 million, respectively, and the average trip distance will increase to 8.08 km. Based on the calculation in Sect. 4.2, under the worst situation where the vehicle occupancy decreases and the traffic congestions increase, the CO_2 emission factors for electric motors, buses, and cars will be increased to 0.015, 0.031, and 0.295 kg/passenger/km. Then, by 2030, the total CO_2 emissions from the above three travel modes in Xi'an will reach 15×10^6 t, about 7.8 times of current CO_2 emissions; the annual average CO_2 emissions per person will reach 1.6 t, about 7.1 times of current level.

Based on the estimated CO_2 emissions in 2030 of Xi'an and the population of Xi'an and other major Chinese cities, by 2030, it is estimated that the total CO_2 emissions from electric motors, buses, and cars in major Chinese cites (Beijing, Shanghai, Shenzhen, and Guangzhou excluded) will reach 480×10^6 t. If India has the similar increasing tendency in CO_2 emissions as China has, the annual average CO_2 emissions per person in both China and India will reach 1.6 t in 2030, increased from 0.22 t in 2012; the total CO_2 emissions from the above three travel mode in China and India will be increased from 135×10^6 t in 2012 to 961×10^6 t in 2030 (accounting for 0.37 to 2.67 % of the total global CO_2 emissions of 2013), which will affect the global climate change significantly. Hence, to mitigate global change, it is important to explore the characteristics of the commuting trips and to find strategies to reduce commuting CO_2 emissions in China and India.



Car

Taxi (Gasoline, Bangalore)

Taxi (CNG, Xi’an)

Two-Wheeler (Gasoline, Bangalore)

Bus (CNG, Xi'an)

Bus (Diesel, Bangalore)

Routine Coach (Diesel, Xi'an)

Electric-Bicycle (Electricity, Xi'an)

Electric-Motor (Electricity, Xi'an)

Metro (Electricity, Xi'an)

Fig. 1 Sensitivity analysis of the well-to-wheel CO_2 emission factor to fuel consumption and vehicle occupancy in Xi’an and Bangalore by mode

Table 6 Maximum changing extents of well-to-wheel CO_2 emission factors with the changes of fuel consumption and the occupancy in Xi'an and Bangalore

		Only fuel consumption change percent		Only occupancy change percent		Both fuel consumption and occupancy change percent	
Travel mode	Fuel type	Decrease	Increase	Decrease	Increase	Decrease	Increase
Car/two-wheeler[a]	Gasoline	−14.00/−14.00 %	14.00/14.00 %	−50.00/−28.57 %	40.85/38.39 %	−57.00/−38.57 %	60.56/58.33 %
Taxi	CNG/gasoline[a]	−11.00/−14.00 %	11.00/14.00 %	−28.57/−28.57 %	66.67/66.67 %	−36.43/−38.57 %	85.00/90.00 %
Bus	CNG/diesel[a]	−15.00/−15.00 %	15.00/15.00 %	−20.00/−20.00 %	33.33/33.33 %	−32.00/−32.00 %	53.33/53.33 %
Normal coach[b]	Diesel	−15.00 %	15.00 %	−28.57 %	66.67 %	−39.29 %	91.67 %
Metro[b]	Electricity	−0.15 %	0.15 %	−16.67 %	25.00 %	−16.79 %	25.19 %
Electric bicycle[b]	Electricity	−6.00 %	6.00 %	−23.08 %	42.86 %	−27.69 %	51.43 %
Electric motor[b]	Electricity	−3.00 %	3.00 %	−23.08 %	42.86 %	−25.38 %	47.14 %

[a] Two-wheelers and taxis use gasoline and buses use diesel according to the data of Bangalore

[b] Only Xi'an has this travel mode information

5 Commuting CO_2 emission distribution, model results, and countermeasure analysis

5.1 Key challenges revealed from distribution of commuting CO_2 emissions

The percentiles of the individuals and households commuting CO_2 emissions in Xi'an and Bangalore are shown in Fig. 2. It is seen that the emissions in Xi'an are lower than those in Bangalore except the highest 10 % households. The average and median values of the individual and household emissions in Table 7 also show that the emissions in Bangalore are higher than those in Xi'an. The average individual CO_2 emissions by modes in Table 7 and emission factor by modes in Table 3 indicate that longer commuting distance is a major factor for higher CO_2 emissions in Bangalore. The average commuting distance in Bangalore (7.09 km) is twice of that in Xi'an (3.8 km). The longer distance in Bangalore is due to its haphazard and dispersed urban growth, and the shorter distances in Xi'an can be attributed to its compact and high-density pattern. Thus, one key challenge for Indian cities is to develop the compact and high-density urban pattern so as to reduce their commuting distances and improve their public transit operation efficiency.

It is found that, in Xi'an, 20 % of the commuters produced 78 % the total emissions; in Bangalore, 20 % of the commuters produced 56 % the total emissions. Also, 20 % of the households produced 73 % the total emissions in Xi'an; 20 % of the households produced 53 % the total emissions in Bangalore. Therefore, generally, "70-20" and "50-20" emission patterns exist in Xi'an and Bangalore, respectively. This result is different from the "60-20" emission rule in UK (Brand and Preston 2010; Susilo and Stead 2009), the "50-10" emission rule in Dutch (Susilo and Stead 2009), and the "60-10" emission rule in Seoul (Ko et al. 2011), which indicates that the high emitters produce a disproportionate fraction of the total emissions. It also indicates that the high emitters produced higher proportion of CO_2 emissions in Chinese cities. Thus, another key challenge for Chinese and Indian cities, especially for Chinese cities, lies in that they should focus on reducing CO_2 emissions from the high emitters. Other global cities' experiences of reducing the transportation CO_2 emissions may also be applied to Indian cities.

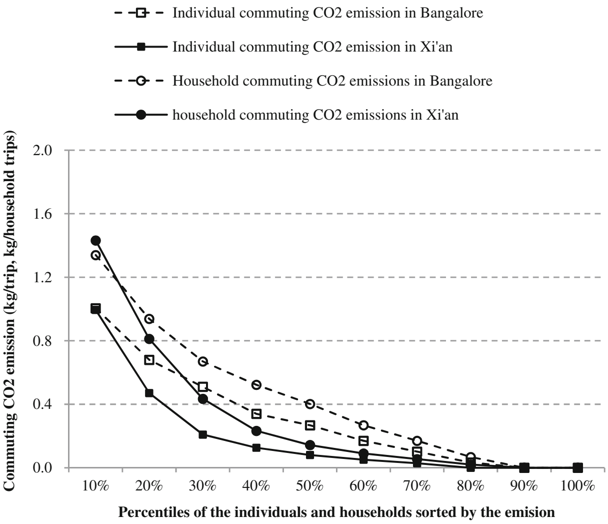


Fig. 2 Percentiles of CO_2 emissions by commuters

Table 7 Summary of commuting CO_2 emissions, population, and vehicles in Xi'an and Bangalore

	Household and individual commuting CO_2 emissions			
	Household CO_2 emissions		Individual CO_2 emissions	
	(kg/household)		(kg/trip)	
City	Xi'an	Bangalore	Xi'an	Bangalore
Minimum	0.00	0.00	0.00	0.00
Maximum	3.96	3.6	2.33	2.4
Average	0.45	0.55	0.28	0.41
Median	0.14	0.39	0.08	0.27
	Average commuting CO_2 emissions by modes (kg/trip)			
City	Xi'an		Bangalore	
Bus	0.087		0.347	
Metro	0.134			
Normal coach	0.293			
Taxi	0.382		0.986	
Car	0.838		0.569[a]	
Motor/electric motor/electric bicycle	0.055			
	Population and vehicles			
City	Xi'an		Bangalore	
Population (million)	4.48[b]		9.58	
Car/LMV (million)	1.044 (car)		1.102 (LMV)[c]	
Bus	7695		4203	
Two-wheeler (million)	0.440[d]		3.725	

[a] In Bangalore, the average commuting CO_2 emissions by car include both car and two-wheelers

[b] The data refers to the population in the Xi'an urban central area

[c] In Bangalore, LMV refers to the light motor vehicle

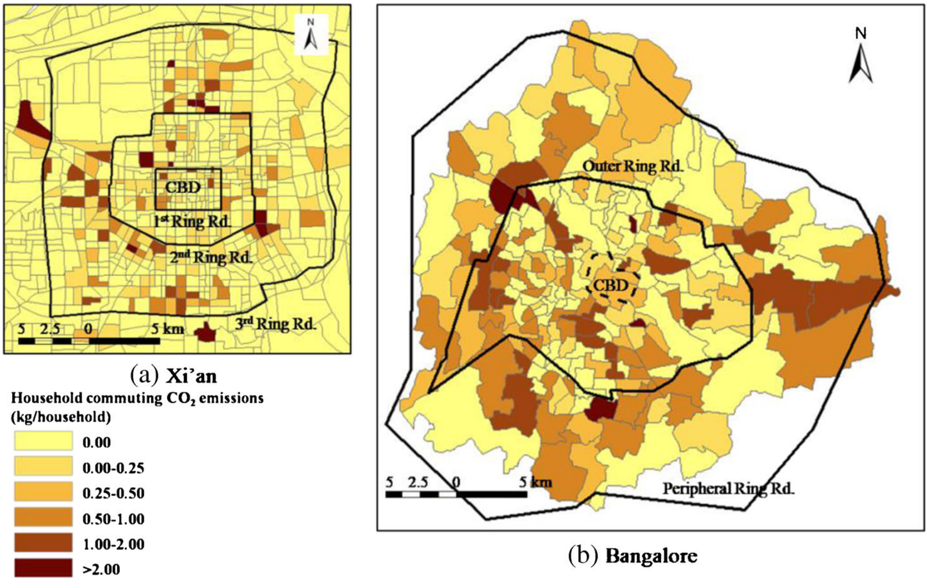
[d] In Xi'an, there is prohibition of two-wheelers inside the 2nd Ring Road

Figures 3 and 4 present the spatial distributions of household and individual commuting CO_2 emissions in Xi'an and Bangalore, respectively. It is seen that Bangalore has higher emissions than Xi'an in general, and households and individuals located in the outer areas produce much more emissions than those in the inner areas and CBDs. The highest emissions scattered along/outside the 2nd Ring Road in Xi'an and the Outer Ring Road in Bangalore, respectively. These indicate that, from the urban spatial perspective, the key challenge of low-carbon development is to reduce higher emissions along the ring roads and in the outer areas.

5.2 Tobit models for CO_2 emissions by commuters and corresponding countermeasures

5.2.1 Tobit model results

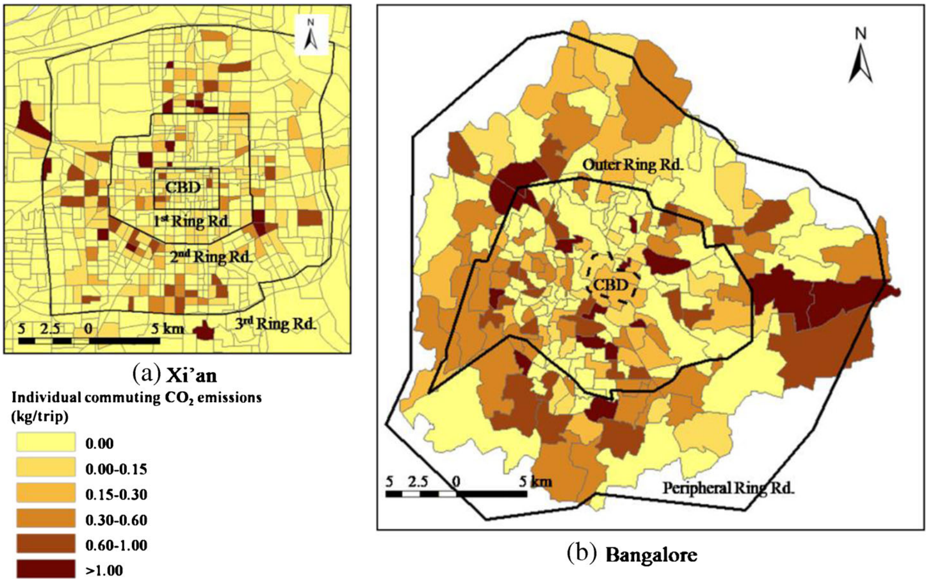
The Tobit models for commuting CO_2 emissions are shown in Table 8 below. The results show that the car availability is the key factor of both household and individual commuting CO_2 emissions in the two cities. The coefficients of the car availability in Xi'an models are bigger


(a) Xi'an

(b) Bangalore

Fig. 3 Distributions of average household commuting CO_2 emissions by zone (kg/household, sum of commuting CO_2 emissions of each commuter in the household)

than those in the corresponding Bangalore models. This is because there are more cars in Xi'an than in Bangalore and because the two wheelers account for 77.1 % of the car and two-wheeler in Bangalore. It is the first time that our method found that household locations separated by the ring roads have a great impact on both household and individual commuting CO_2 emissions in all the four models. Households and individuals located outside the 2nd or


(a) Xi'an

(b) Bangalore

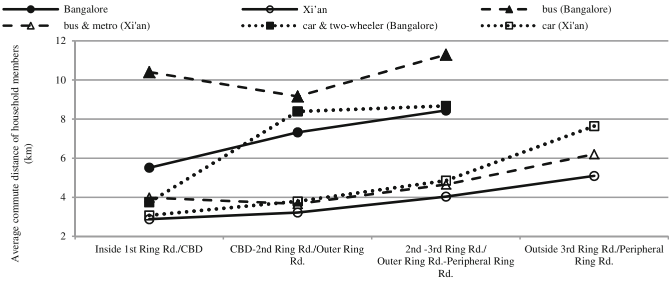
Fig. 4 Distributions of average individual commuting CO_2 emission by zone (kg/trip)

Table 8 Tobit models for commuting CO_2 emissions

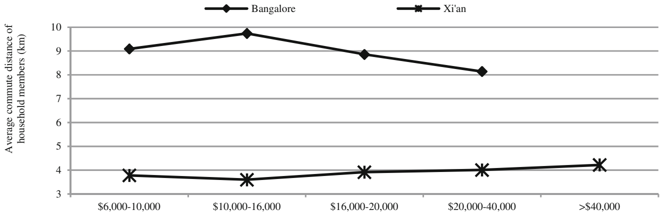
	Household		Individual	
Independent variables	Xi'an	Bangalore	Xi'an	Bangalore
Car availability	0.572 (0.000)	0.256 (0.000)	0.407 (0.000)	0.303 (0.000)
Household location by ring roads				
Inside the 1st Ring Road/CBD	−0.248 (0.000)		−0.135 (0.001)	
1st–2nd Ring Road/CBD-Outer Ring Road	−0.178 (0.000)	0.195 (0.000)	−0.075 (0.000)	
2nd–3rd Ring Road/Outer-Peripheral Ring Road		0.298 (0.000)	0.020 (0.150)	0.072 (0.000)
Household annual income				
US$6,000–10,000		0.186 (0.000)		
US$10,000–16,000	0.135 (0.000)	0.419 (0.000)		
US$16,000–20,000	0.159 (0.001)	0.357 (0.001)		
US$20,000–40,000	0.233 (0.006)	0.236 (0.021)		
>US$40,000	0.556 (0.001)			
Work unit type				
Work in the government				0.207 (0.000)
Work in the foreign enterprise				0.333 (0.000)
Work in the local company				0.173 (0.000)
Work in the state-owned company				0.150 (0.006)
Distance to the nearest bus stop (km)				0.107 (0.046)
F value	77.74	219.96	135.14	221.19
Probability > *F*	0.000	0.000	0.000	0.000
Log pseudolikelihood	−1181.364	−1659.755	−1397.139	−1834.1607
Observations	1240	1835	1952	2433

The numbers in the brackets refer to significance levels. In Bangalore, car availability includes both cars and two-wheelers. In Xi'an, car availability refers to people owning car or willing to buy car

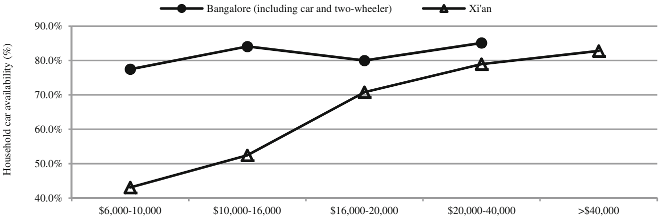
Outer Ring Road produced larger CO_2 emissions than those located in the inner areas. This indicates that geographic location separated by the ring roads is a good indicator of the commuting CO_2 emissions. It is related to mode supply, mixed level of land use, and the commuting distances in the areas separated by the ring roads, and it has great values in the urban planning and management practice. The average commuting distance is 5.51 km inside the CBD of Bangalore and increases sharply to 7.32 km outside the CBD and to 8.44 km outside the Outer Ring Road. The average commuting distance is 2.88 km inside the 1st Ring Road of Xi'an and increases to 3.22, 4.03, and 5.09 km between the 1st and 2nd Ring Roads, between the 2nd and 3rd Ring Roads, and outside the 3rd Ring Road, respectively, as shown in Fig. 5a. By analyzing Figs. 3, 4, and 5a, we can find that there are longer average commuting distance, higher average and total commuting CO_2 emissions, and more average emission distributions among the individuals and households in Bangalore than in Xi'an. Considering the future rapid economic growth, urbanization, and motorization in Bangalore, there is a need to reduce the possible sharp increase of the commuting CO_2 emissions in Indian cities. In addition, the percentages of the car availability in different household locations separated by the ring roads are also different. There is a higher percentage of car availability in the outer area



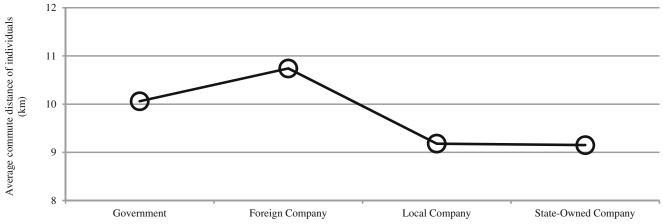
(a) Average commute distance of household members by household locationand by travel mode



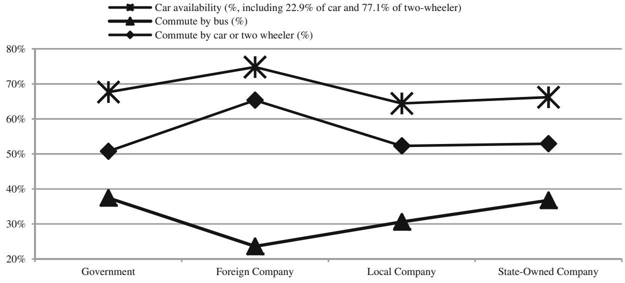
(b) Average commute distance of household members by household annual income



(c) Percentage of household car availability by household annual income



(d) Average commute distances of individuals by work unit type in Bangalore



(e) Car availability and car/bus shares by work unit type in Bangalore

Fig. 5 Average commuting distances, car availability, and car/bus shares than that in the inner area. According to the statistical results, in Xi'an, the percentages of car availability are 36.8, 52.4, and 61.6 %, respectively, for the sampled households inside the 1st Ring Road, between the 1st and 2nd Ring Roads, and between the 2nd and 3rd Ring Roads. In Bangalore, the percentages of sampled households with car availability between the CBD and Outer Ring Roads and between the Outer and Peripheral Ring Roads are 71.5 and 73.2 %, respectively.

Apart from the household location separated by the ring roads and car availability, household annual incomes have been proven to be another key factor of the household commuting CO_2 emissions in Xi'an and Bangalore. The result of Xi'an model shows that household commuting CO_2 emissions increase with the household annual income's increase. It could be because the households with higher income tend to have longer commuting distance and higher percentage of car availability. Details are shown in Fig. 4b, c. The impact of household annual income on the household CO_2 emission in Bangalore model is different from that in Xi'an model. It is found that, in Bangalore model, household commuting CO_2 emissions are not linearly increasing with the household annual income's increase as in Xi'an model. Also, the households with middle-level income of US$ 10,000–16,000 tend to produce the highest commuting CO_2 emissions; correspondingly, these households have the longest commuting distances and the highest percentage of the car and two-wheeler's availability, as shown in Fig. 4b, c.

Previous studies found that full-time workers produced more transportation CO_2 emissions than part-time workers (Carlsson-Kanyama and Lindén 1999; Susilo and Stead 2009; Ko et al. 2011; Brand et al. 2013) and unemployed (Brand and Boardman 2008). While in this study, for the first time, we found that the type of work unit for the full-time worker is a key factor for the commuting CO_2 emissions in Bangalore's model, even though this factor is not significant in the Xi'an model. In Bangalore, foreign company workers produce higher CO_2 emissions than the government staff and the workers in local and state-owned companies. This is mainly due to the long commuting distance, high percentages of the car and two-wheeler's availability, and the high percentage of car uses among the foreign company workers, as shown in Fig. 4d, e. In addition, this is also because the household annual income of foreign company workers in Bangalore is 22 % higher than the overall average level.

Distance to the nearest bus stop is another factor of the individual commuting CO_2 emissions in Bangalore. The model results show that 0.107 kg more individual CO_2 emissions can be produced if the commuters live 1 km farther away from the nearest bus stop. However, in Xi'an models, this factor is not significant.

In summary, there are two common factors which affected the commuting CO_2 emissions in the all models of Xi'an and Bangalore, car availability and household location separated by the ring roads. For household CO_2 emission models of Xi'an and Bangalore, household annual income is a significant factor. The difference between the models lies in that work unit type and distance to the nearest bus stop are only significant in Bangalore's individual emission model.

5.2.2 Countermeasures based on the model results

The results of the Tobit models show that the positive factors for the commuting CO_2 emissions in Bangalore include car availability, high household income, working in foreign company, living in the outer areas of city, and distance to the nearest bus stop. The positive factors for the commuting CO_2 emissions in Xi'an include car availability, high household income, and living in the outer areas of city. Among these factors, car availability has the largest impact on the commuting CO_2 emissions, followed by household income, working in foreign company, living in the outer areas, and distance to the nearest bus stop. Consequently, the key countermeasure to reduce the high CO_2 emissions is to encourage the emitters to take public transit instead of driving cars. As there is a high requirement on the comfort and convenience for trips by high emitters, the high emitters will not use public transit if the bus service is poor or the bus is inconvenient. Therefore, only by providing good public transit service and high bus stop coverage rate, mixed with the car demand management policy at the same time, the high emitters with car availability can take public transit.

In Xi'an and Bangalore, the closer to the city center, the higher the population density is and the severer the traffic congestions are. In contrary, the farther to the city center, the better the road conditions are and the higher the car availability is. Since the public transit typically costs passengers more travel time than self-driving, the residents with car availability, far away from the bus stop, and living in the outer areas or along the ring roads are more likely to commute by driving. As the city sprawls, the commuting distance of the residents living in the outer area of the city will be longer and longer. Consequently, the traffic congestion will be easily formed in a large scale with commuting CO_2 emissions increasing sharply in the central urban area. Therefore, there is a need to develop rapid transit system from the outer area to the inner area in the cities of China and India, such as rail transit and bus rapid transit (BRT). Due to the reason that there is no link between the land development revenue and the transportation investment in the early stage of urban development in both Xi'an and Bangalore, metro- or BRT-oriented development is hard to be implemented now. In other words, fund shortage for the transit-oriented development (TOD) in new developing areas in the early stage of urban development can further cause the shortage of the land for public transit terminal, transfer, and facilities and finally leads to the high commuting CO_2 emissions. In addition, it is necessary to implement parking demand control in the industrial development area, especially in the area with foreign companies and government in Indian cities; at the same time, the good transit service should be developed.

6 Discussion

From the analyses in this study, it is seen that the resident samples in the two case cities have good education level and thus are more open to strategies for global climate change mitigation. Most commuters working in the private companies are sensitive to the cost of commuting. It is also found that a high percentage of commuters own houses/apartments; therefore, the probability of changing their house locations is low, especially in the short term. The increase in CO_2 emissions by commuters during the fast development period of a city is mainly due to travel mode changes and commuting from newly developed areas. Avoiding the sharp increase of car use, implementing TOD pattern at the early stage of the land development, and providing outstanding public transport service are important to reduce the commuting CO_2 emissions.

It is also seen that the vehicle occupancy is an important factor of commuting CO_2 emission in both China and India. Maximizing the vehicle occupancy of cars, normal coach, and taxis could reduce commuting CO_2 emissions by as much as 50 %; decreasing the vehicle occupancy could increase commuting CO_2 emission by as much as 66.67 %. Therefore, avoiding smaller vehicle occupancy is critical to control the increase of commuting CO_2 emissions.

The analyses show that the characteristics of the high emitters are car availability, high income, working in the foreign company, and living in the outer areas/along the ring roads or far away from the bus stop. Reducing their emissions is important in both China and India. The outer areas of a city usually have better road conditions, lower service level of public transport, limited rail transit, or bus rapid transit to the central area of the city; it is hard for commuters to use travel modes other than self-driving, which leads to high commuting CO_2 emissions. Therefore, the adjustment in urban planning, construction of rail transit, or rapid bus routes in the outer-inner area directions, as well as cycling and walking system, public transport service level improvement, and avoiding fast increase of car uses are the keys to low-carbon urban transportation development. In Chinese and Indian cities, the implementation of transportation pricing, transportation management, and public transit priority policies can guide commuters with high income to use public transportation and make them less car-dependent.

Traffic congestions already exist in the central areas of the cities in both China and India. How to increase the mode share of public transport and to reduce travels by car is a challenge for city leaders. There is a need to balance the overall efficient development of the city and the ability to drive in the central area of the city.

The larger emissions and longer commuting distances in Bangalore indicate that Indian cities should focus on high density and compact development, which can reduce average commuting distance, and can also improve public transport operations and service levels since the lower density, sprawled, and decentralized urban form has caused inefficiencies for the public transport. The use of clean energy vehicles in Xi'an is another reason for the lower commuting CO_2 emissions. In Xi'an, buses and taxis are driven by compressed natural gas (CNG); metros and two-wheelers are powered by electricity. These can help reducing the commuting CO_2 emissions to some extent, which can be learned by Indian cities.

In addition, even though Xi'an is a good example of compact urban development pattern compared with Bangalore at present, if Xi'an continues to develop under this pattern in the future, the central area will suffer from increasing traffic pressures and increasing transportation CO_2 emissions. An alternative strategy is to control the development intensity in the central urban area and try to apply a multicenter strategy for the urban development.

7 Conclusions

The increase of transportation CO_2 emissions in Chinese and Indian cities in the future will significantly impact the global climate change. By 2030, the total CO_2 emissions from major travel modes (electric motors, buses, and cars) in major Chinese cites (Beijing, Shanghai, Shenzhen, and Guangzhou excluded) will reach 480×10^6 t. The annual average CO_2 emissions per person will be increased to 1.6 t in 2030 from 0.22 t in 2012. It is estimated that the total CO_2 emissions from the above three travel modes in major China and India cities will be increased from 135×10^6 t in 2012 (0.37 % of the total global CO_2 emissions) to 961×10^6 t in 2030 (2.67 % of the total global CO_2 emissions), which will affect the global climate change significantly. Hence, to mitigate global change, it is important to explore the characters of the commuting trips and to find strategies to reduce commuting CO_2 emissions in China and India.

From the analysis in this paper, several common characteristics in both Xi'an and Bangalore can be found, including (1) both cities are under fast urbanization and quick motorization; (2) the residents have good education level; (3) a high percentage of commuters work in private companies; (4) a high percentage of commuters own houses/apartments; (5)

both cities sprawl by radial and ring roads and leading industries are located outside or along the 2nd Ring Road in Xi'an and Outer Ring Road in Bangalore; (6) traffic congestions exist in central areas of the city; (7) commuters with car availability, high income, or living in the outer areas/along the ring roads are high CO_2 emitters and a small percent of commuters produce the majority of the CO_2 emissions; and (8) the vehicle occupancy and traffic congestion have large impacts on reducing CO_2 emissions. It is found that the changes on vehicle occupancy of car, normal coach, taxi, and bus could reduce CO_2 emissions by as much as 20 to 50 % or increase CO_2 emissions by as much as 33.33 to 66.67 %, and the changes on traffic congestions could reduce or increase CO_2 emissions by as much as 11 to 15 %. The differences between the two cities include (1) Xi'an has higher population density and compact urban form; (2) the sprawl in the outer areas of Bangalore is large, haphazard, and unplanned; (3) the household income, car ownership rate, commuting by car, and commuting share of public transport in Xi'an are higher than those in Bangalore; (4) the average commuting distance in Xi'an is shorter than that in Bangalore; (5) the average individual or household CO_2 emissions in Xi'an are lower than those in Bangalore; and (6) Bangalore has more household members (averagely 4.53 per person in one household) and a higher two-wheeler ownership rate (55.4 %).

The reasons of these findings are (1) better road conditions, longer commuting distance in the outer areas, and weak public transport service have caused more car uses and high CO_2 emissions in both cities; (2) Bangalore's lower density and more dispersed urban growth has caused even longer commuting distances, poor transit service, prevalence of the two-wheelers fueled by gasoline, and thus higher emissions than those in Xi'an; and (3) the buses and taxis driven by CNG and metro and electric motors driven by electricity also helped in reducing the transportation CO_2 emissions in Xi'an.

A number of countermeasures can be proposed from this study for the global low-carbon transportation development and climate change mitigation. Firstly, it is important for Chinese and Indian cities, especially for Chinese cities, to focus on reducing the commuting CO_2 emissions and controlling the potential increase of commuting CO_2 emissions produced by the high emitters and individuals located in the outer areas, with car availability, or high income during the rapid economic growth, urbanization, and motorization, and to provide the substitute travel modes for self-driving. Secondly, the keys to reduce the commuting CO_2 emissions in Chinese and Indian cities are increasing vehicle occupancy, ensuring the priority of public transit and its outstanding service, controlling the car uses, and implementing parking demand management in the area of the industry zone. Furthermore important, in the early stage of the land development in Chinese and Indian cities, investment in public transit must be guaranteed to support TOD. Thirdly, radial rail transit and rapid bus routes in the inner-outer directions should be developed with outstanding service levels so that high emitters with car availability, high income, and living in the outer areas will use public transit instead of car for commuting. Fourthly, Indian cities need more compact and high-density urban development patterns to reduce the travel distance. Fifthly, the use of clean energy vehicles can also help in reducing the transportation CO_2 emissions in Chinese and Indian cities. These strategies are significant for reducing CO_2 emissions in Chinese and Indian cities and other similar cities in the developing countries. Thus, they are important for the global climate change mitigations.

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