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Modeling vehicle emissions in different types of Chinese cities: Importance of vehicle fleet and local features

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ABSTRACT

We propose a method to simulate vehicle emissions in Chinese cities of different sizes and development stages. Twenty two cities are examined in this study. The target year is 2007. Among the cities, the vehicle emission factors were remarkably different (the highest is 50–90% higher than the lowest) owing to their distinct local features and vehicle technology levels, and the major contributors to total vehicle emissions were also different. A substantial increase in vehicle emissions is foreseeable unless stronger measures are implemented because the benefit of current policies can be quickly offset by the vehicle growth. Major efforts should be focused on all cities, especially developing cities where the requirements are lenient. This work aims a better understanding of vehicle emissions in all types of Chinese cities. The proposed method could benefit national emission inventory studies in improving accuracy and help in designing national and local policies for vehicle emission control.

1. Introduction

China's vehicle population has increased explosively during the past two decades, with an accelerated growth rate. In particular, China exceeded the U.S. in vehicle sales in 2009, becoming the largest vehicle market in the world. As a result, vehicle emissions have become a growing environmental concern of mega-cities since the 1990s in China (He et al., 2002; Chan and Yao, 2008). In the meantime, as the number of vehicles has also increased dramatically in medium and small cities, the concern over vehicle pollution is not confined to mega-cities any more. Vehicle emissions are becoming a major environmental issue in cities of all sizes in China.

For a long time, mega-cities (such as Beijing, Shanghai, and Guangzhou) have been the focus of vehicle emission studies and control strategies (Fu et al., 2001; Hao et al., 2000; Wang et al., 2008a, 2005, 2010; Huo et al., 2009). Although there have been several studies that provided estimates of vehicle emissions for those mega-cities, few studies focused on other cities. Because of lack of necessary data at city level, vehicle emissions were usually estimated as provincial totals in national or regional emission inventories, then downscaled to cities or grids by socioeconomic or population data (Cai and Xie, 2007; Zhang et al., 2009). A comprehensive picture of vehicle emissions covering all sizes of cities in China is absent.

Information on vehicle emissions at city level is not only of great importance for improving the accuracy of national vehicle emission inventories, but also important for vehicle emission control policies. In a rapidly developing and urbanizing country like China, city numbers, urban areas, and vehicle population will continuously increase in the future. Given the fact that the vehicle fleet turnover is a slow process (e.g., 15 years for cars), policymakers have to accelerate the progress of emission control policies to offset this large potential increase in vehicle emissions. A better understanding of vehicle emissions at city level would help policymakers to make efficient and effective policies at both national and local levels.

This work first develops a common methodology of estimating vehicle emissions of all types of Chinese cities. The characteristics

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of the vehicle fleets in Chinese cities differ significantly, for instance, passenger cars occupy a larger proportion of the fleet in mega-cities than in medium and small cities, southern cities usually have more motorcycles than northern cities, and northern industrialized cities have more heavy-duty trucks for transporting coal, materials, and other industrial items. Therefore, it is important to select cities that can cover the different characteristics of the vehicle fleets as much as possible. We selected 22 Chinese cities as cases for this work. Fig. 1 illustrates the locations and socioeconomic information of the 22 cities in 2007 (State Statistical Bureau of China, 2008). As shown, the selected cities are located all over China and cover all city sizes, including all four municipalities (Beijing, Shanghai, Tianjin, and Chongqing), seven provincial capitals, nine mid-size cities, and two small-size cities (or perhaps more precisely, towns). Vehicle emissions from those cities are then estimated and analyzed, to explore the vehicle emission patterns of cities of various sizes and development stages in China. The 22 cities are selected from both rapidly developing regions (Beijing and Tianjian in the Jing-Jin-Tang region, Shanghai and Ningbo in the Yangtze River Delta region, and Zhuhai, Shenzhen, Foshan and Dongguan in the Pearl River Delta region) and western regions where economic development is relatively slow. In this study, we estimated vehicle emissions of carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxide (NO_x), particulate matter with diameters of 10 μm or less (PM_{10}), and carbon dioxide (CO_2) in each city in 2007, based on city-specific analysis of vehicle types, driving patterns, technology distribution etc.

2. Methodology and data

For each city, the total amount of pollutant *j* emitted from vehicles is calculated using the following equation:

$$E_j = \sum_i (VP_i \times EF_{i,j} \times VKT_i) \quad (1)$$

where *j* represents pollutant type (CO, VOCs, NO_x, PM_{10}, and CO_2); E_j is the amount of emissions of pollutant *j*; *i* represents vehicle type (in this study, vehicles are classified into five categories, light-duty passenger vehicles [LDVs], light-duty trucks [LDTs], heavy-duty passenger vehicles [HDVs], heavy-duty trucks [HDTs], and motorcycles [MCs]); VP_i represents the vehicle population of vehicle *i*; $EF_{i,j}$ is the emission factor of pollutant *j* for vehicle *i*; and VKT_i is vehicle kilometers traveled (VKT) of vehicle *i* in 2007.

2.1. Vehicle population by type

China's transportation statistics contain vehicle population data for most cities, which are directly adopted in this study. As for the cities whose vehicle populations are not reported by China's statistics – there are three of them: Zitong, Jiutai, and Urumqi – we estimated their vehicle population by using the Gompertz curve, which relates vehicle ownership growth to per capita gross domestic production (GDP) growth (Wang et al., 2006). For each of the three cities, a Gompertz curve is established based on the socioeconomic information of its province (State Statistical Bureau of China, 2002–2009), and then it is used to calculate the city's vehicle population using urban socioeconomic information. For the cities that don't have data on vehicle population by type in statistics, the shares of each vehicle type of total vehicle

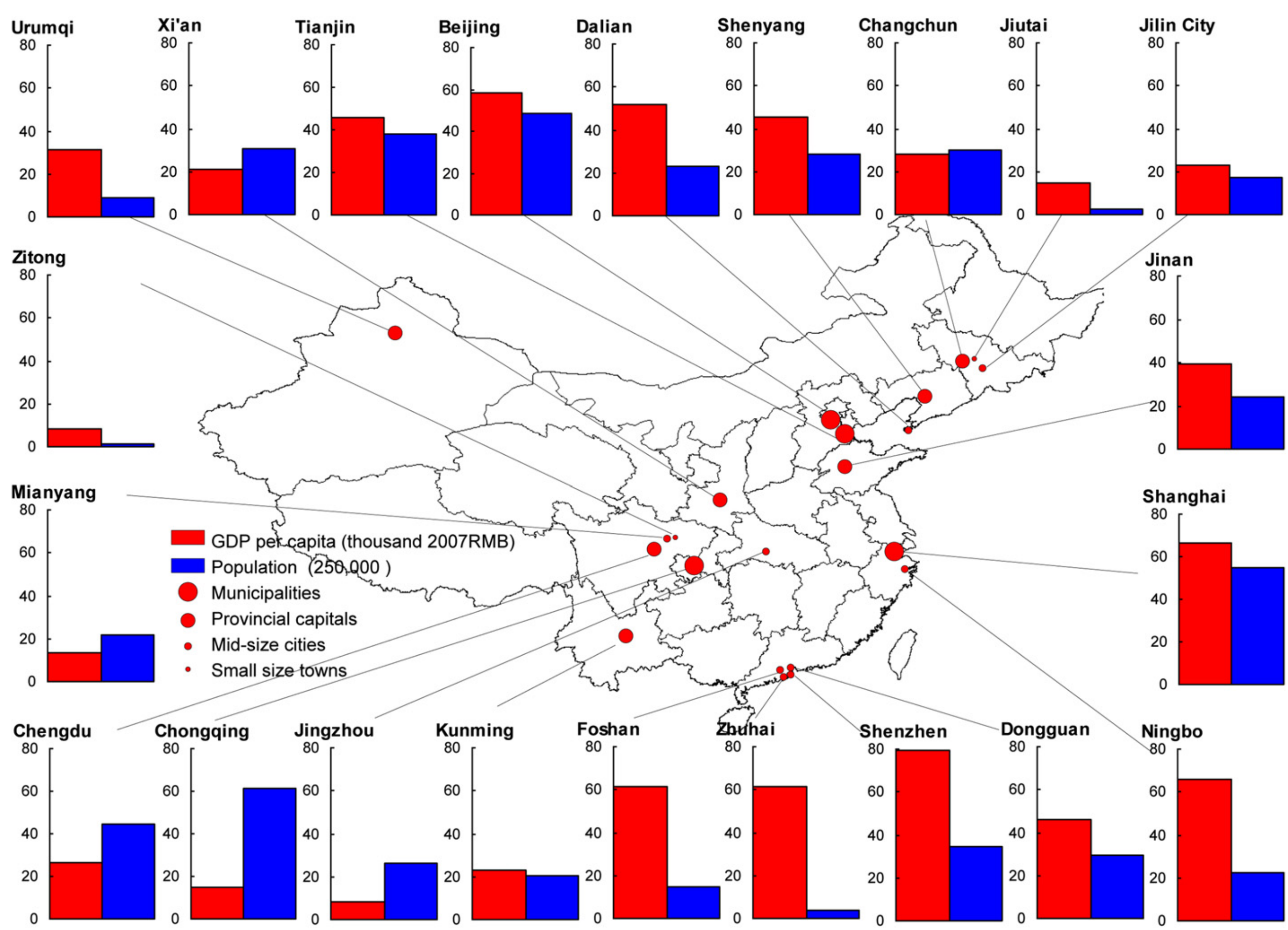

Fig. 1. Location and socioeconomic information of the 22 selected Chinese cities in 2007.

Table 1
Vehicle population by type of the 22 cities.

	Total VP		Vehicle population (thousand)				
	(Thousand)	Share of LDVs	LDV	LDT	HDV	HDT	MC
Beijing	2938	81%	2368	118	148	58	246
Tianjin	1172	62%	731	103	43	37	258
Shanghai	2457	36%	878	84	112	124	1260
Chongqing	1384	25%	346	120	38	119	762
Chengdu	1740	34%	597	112	38	93	900
Changchun	678	44%	302	47	17	31	281
Jilin	325	37%	120	24	8	18	155
Mianyang	401	18%	72	14	5	11	299
Ningbo	648	58%	376	85	20	23	144
Jiutai	37	21%	8	2	1	1	26
Zitong	26	6%	2	0	0	0	24
Foshan	1796	20%	362	154	28	32	1220
Shenzhen	1127	71%	797	188	77	45	20
Zhuhai	190	49%	93	32	12	6	47
Xi'an	661	51%	338	49	29	57	188
Dongguan	1109	37%	408	135	35	31	500
Shenyang	672	53%	359	86	44	51	131
Dalian	614	49%	301	72	37	43	160
Jinan	983	34%	336	73	20	32	522
Jingzhou	548	9%	49	13	6	11	470
Kunming	1131	60%	682	100	30	68	251
Urumqi	260	55%	143	45	16	36	20

population were assumed to be the same as those of their provincial vehicle fleets. Table 1 presents the detailed information on the vehicle population of the 22 cities.

2.2. Technology distribution

China implemented three stages of vehicle emission standards (equivalent to the Euro I, Euro II, and Euro III standards, respectively) within the past eight years (see Table 2), therefore technology levels vary significantly across the current vehicle fleet in one city. Because vehicles that newly come to market are required to be compliant with the emission standards in effect, so the share of each vehicle model year out of the entire fleet (defined as "model year distribution" in this study) is a critical factor in determining the technology distribution. We calculated the vehicle population of a certain model year by multiplying the number of new vehicles of that year by their survival rates in 2007 (Huo et al., 2007). China's statistics started to report the number of newly registered vehicles from 2002 (State Statistical Bureau of China, 2008), and the data before 2002 were estimated and adjusted on the basis of some sample surveys that had been conducted in Beijing, Shanghai, and Tianjin (Huo et al., 2009; Huang et al., 2005). For other cities, we assumed that the model year distribution of their fleet is the same as that of the national fleet (China Automotive Technology and Research Center, 1991–2007). We also determined other parameters associated with technology distribution (e.g., vehicle fuels, sizes, and accrued mileage) on the basis of our previous work and the available literature (Huo et al., 2009; Wang et al., 2006; Huang et al., 2005). Table 3 presents the detailed technology distribution of vehicles.

2.3. Vehicle emission model

We examine vehicle emissions generated from hot-stabilized activities (including running evaporative emissions), and cold and hot start activities. The International Vehicle Emission (IVE) model, which is developed by the International Sustainable Systems Research Center (Davis and Lents, 2002), was employed in this study to simulate the vehicle emission factors of the 22 cities. The data requirements of IVE include general information (e.g., altitude, temperature, I/M level, etc.), vehicle technology distribution, driving patterns, and soak time distribution of the target city. We collected the driving data of LDVs in all 22 cities, LDTs in two cities, HDVs in seven cities, and HDTs in five cities. The details of the technique of driving data collection are presented in our previous studies (Liu et al., 2007; Yao et al., 2007). On the basis of the data collected, we developed driving cycles for each type of vehicle and each city using the method reported in (Wang et al., 2008b). The soak time distribution was determined on the basis of the investigation on vehicle start-up in Beijing and Shanghai (Liu et al., 2007). The emission rate database of IVE was adjusted with the vehicle emission measurement work conducted in China (Wang et al., 2005; Yao et al., 2007, 2011; Liu et al., 2009) to reflect the vehicle emission levels of China. With the driving cycles, vehicle technology distribution, and other information as inputs, the IVE model produced the emission factors by vehicle type for each city.

Table 2
Vehicle emission standards of LDVs implemented in Chinese cities.

	Beijing	Shanghai	The remainder of China
Euro I	1999	1999	2000
Euro II	2003	2004	2004
Euro III	2005	2007	2007
Euro IV	2008	2010	2011–2012

Table 3
Technology distribution by vehicle type (share of each technology level out of total fleet) in Chinese cities.

		LDVs	LDTs	HDVs	HDTs
Beijing	pre-Euro I	0.097	0.341	0.248	0.354
	Euro I	0.139	0.353	0.332	0.347
	Euro II	0.320	0.150	0.245	0.148
	Euro III	0.444	0.155	0.176	0.151
Shanghai	pre-Euro I	0.071	0.291	0.239	0.468
	Euro I	0.244	0.377	0.441	0.330
	Euro II	0.488	0.232	0.231	0.133
	Euro III	0.198	0.100	0.089	0.068
Tianjin	pre-Euro I	0.155	0.383	0.411	0.553
	Euro I	0.203	0.287	0.346	0.321
	Euro II	0.441	0.188	0.145	0.077
	Euro III	0.201	0.142	0.098	0.049
Nationwide (Other cities)	pre-Euro I	0.115	0.323	0.333	0.404
	Euro I	0.265	0.367	0.423	0.399
	Euro II	0.437	0.211	0.171	0.132
	Euro III	0.183	0.099	0.073	0.066

2.4. Vehicle kilometer traveled

China doesn't officially publish VKT. The VKT data adopted in this study were acquired from a wide range of available literature, as well as the surveys that we conducted in Chinese cities. In this study, the VKT level of LDVs was estimated to be 22,000 km for Beijing (Huo et al., 2009), 20,000 km for Tianjin according to the survey we conducted in Tianjin, 28,000 km for Shanghai according to the survey data presented in (Huang et al., 2005), and 24,000 km for other cities (Wang et al., 2006); the VKT values of LDTs, HDVs, HDTs, and MCs were assumed to be 21,000 km, 55,000 km, 40,000 km, and 5800 km, respectively, for all cities, based on the surveys we conducted in Beijing, Tianjian, Foshan and other available literature (Wang et al., 2010; Huo et al., 2007; He et al., 2005).

3. Vehicle emission factors

Fig. 2 presents the emission factors of LDVs simulated by the IVE model. Fig. 2 reveals that vehicle emission factors vary significantly across the cities in China. The VOC emission factors range from 1.0 to 1.9 g/km, NO_x from 0.46 to 0.84 g/km, CO from 8.2 to 14.9 g/km, PM_{10} from 0.008 to 0.012 g/km, and CO_2 from 179.6 to 295.4 g/km. The highest emission factors are 50–90% higher than the lowest ones.

Technology distribution is one important factor influencing vehicle emission factors. Beijing and Shanghai implement vehicle emission standards ahead of other cities (see Table 2), which, however, does not make Beijing and Shanghai the cities with the lowest vehicle emission factors as might be expected. As highlighted in Fig. 2, Beijing and Shanghai have higher vehicle emission factors than half of the cities examined in this study (except for VOCs and CO in Shanghai); one reason for this might be the congested traffic and inefficient driving patterns in these two mega-cities.

As stated above, all the cities except for Beijing, Shanghai, and Tianjin adopt the same technology distribution of the national fleet, due to shortage of local data. Local factors (e.g., driving patterns) account for the significant difference in vehicle emission factors of these cities. As shown in Fig. 2, cities with higher average speeds tend to have lower emission factors. Geographic features affect

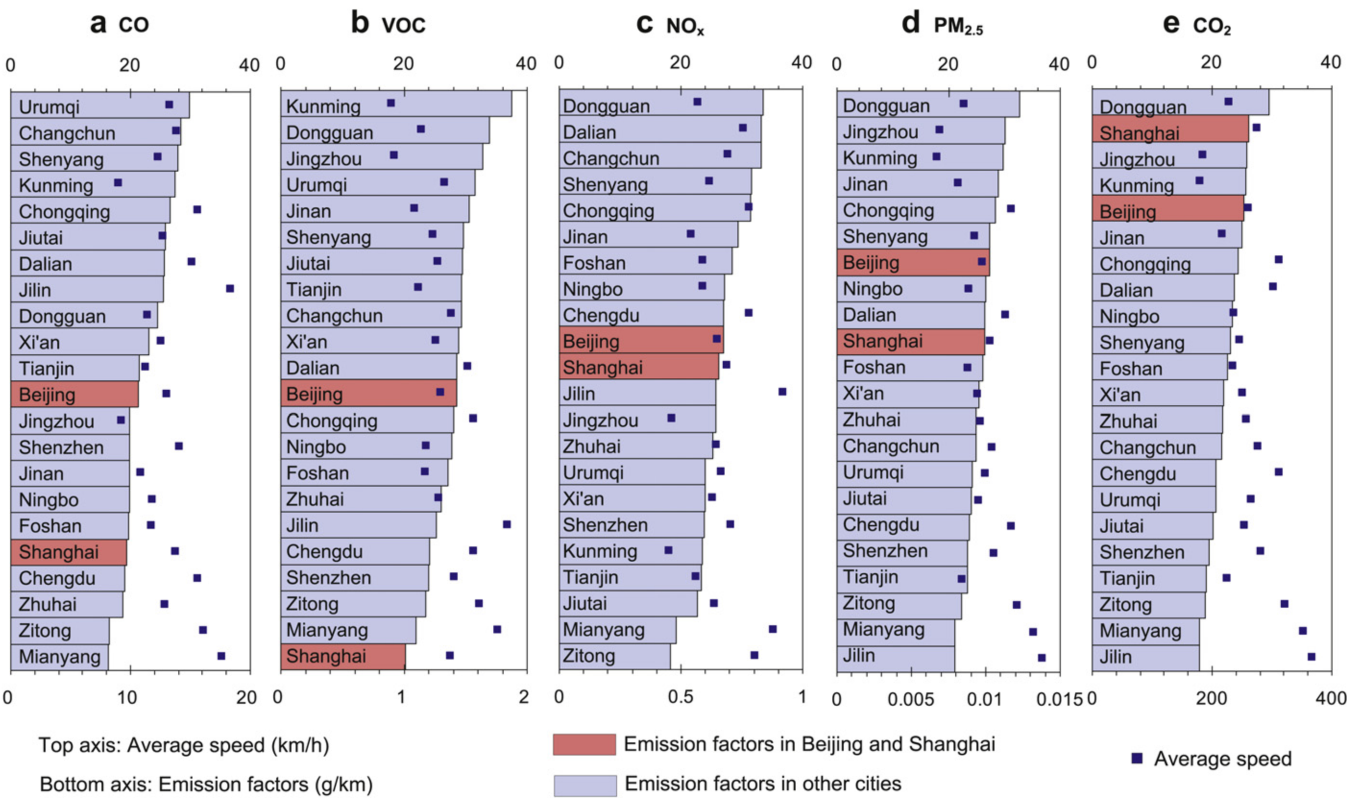

Fig. 2. Vehicle emission factors (g/km) of LDVs in Chinese cities in 2007 (the cities are ranked by the magnitudes of emission factors).

emission factors, too. For instance, the hilly terrain of Chongqing causes vehicles to climb frequently, which leads to relatively higher emission factors, even though the average speed is not low in Chongqing. Altitude is another important factor, especially for heavy-duty diesel vehicles (Bishop et al., 2001; Yanowitz et al., 2000). With a high altitude of 1900 m, Kunming has higher vehicle emission factors than most other cities. The cold weather is a major reason of the high emission factors of the cities located in the north of China (e.g., Changchun and Urumqi).

Local features can result in significant differences in emission factors and are critical for the accuracy of a vehicle emission inventory. However, they have been always neglected in previous vehicle emission inventory studies due to lack of data. A common method used in previous inventory studies is to choose one or two cities where data are readily available, such as Beijing, to represent the whole nation. Though Beijing might be reasonably representative of average national vehicle emission levels (as shown in Fig. 2), this simplification will create spatial uncertainties of the inventories, affect the accuracy of regional air quality studies that use such inventories, and lead to misleading emission estimates for important cities.

4. Vehicle emissions inventory

The vehicle emissions of the 22 cities were calculated using Equation (1), as shown in Fig. 3. The cities in Fig. 3 are listed in the order of city vehicle population, excluding motorcycles. Typically, the more vehicles a city has, the greater the vehicle emissions. But there are some exceptions to this: for instance, vehicle emissions of Kunming and Chongqing rank ahead of the order of their vehicle population, because of their unusually high emission factors.

For most cities, LDVs contribute 30–60% of VOC and CO emissions. In particular, the contributions of LDVs to total VOC and CO emissions in Beijing are much higher than in other cities, because of the higher population share of LDVs in Beijing (the population share of LDVs is 81% in Beijing, and lower than 60% in most other cities, see Table 1). MCs account for more than 15% of VOC and CO emissions in southern cities where MCs are popular (e.g., Shanghai and Foshan). In small cities, MCs are the largest contributor of vehicle emissions with a contribution of more than 50%. Since the major contributors to total vehicle emissions are different in each city, it will be, to some extent, more effective to tailor vehicle emission control strategies according to the local characteristics of vehicle emissions, for instance, to strengthen LDVs emission control in Beijing and to make extra requirements on MCs in cities such as Shanghai and Foshan.

Heavy-duty vehicles (HDVs and HDTs) are dominant contributors of vehicle NO_x (>75%) and PM_{10} (>95%) emissions for all cities, which indicates that heavy-duty vehicles are the keys to reducing urban NO_x and PM_{10} emissions. It should be noted that road transport is the second largest contributor to national NO_x emissions, with a contribution of 24% (Zhang et al., 2007). Recently, China set a new target to reduce the total amount of NO_x emissions of key sectors by 10% from 2010 to 2015, and controlling NO_x emissions from heavy-duty vehicles is of significant importance to achieve the target for China.

According to our estimates, heavy-duty vehicles contribute more than 40–60% of CO_2 emissions, though with less than 20% of the total vehicle fleet, suggesting that they should become a target fleet for CO_2 emissions control. While China has implemented fuel economy standards since 2005 for LDVs to save oil and CO_2 emissions, more actions should be taken for heavy-duty vehicles.

5. Discussion

The major challenge for China lies in the fact that China is in a period of rapid vehicle growth, especially as the majority of the new vehicle growth is taking place in regions with relative lenient control requirements compared to developed cities such as Beijing

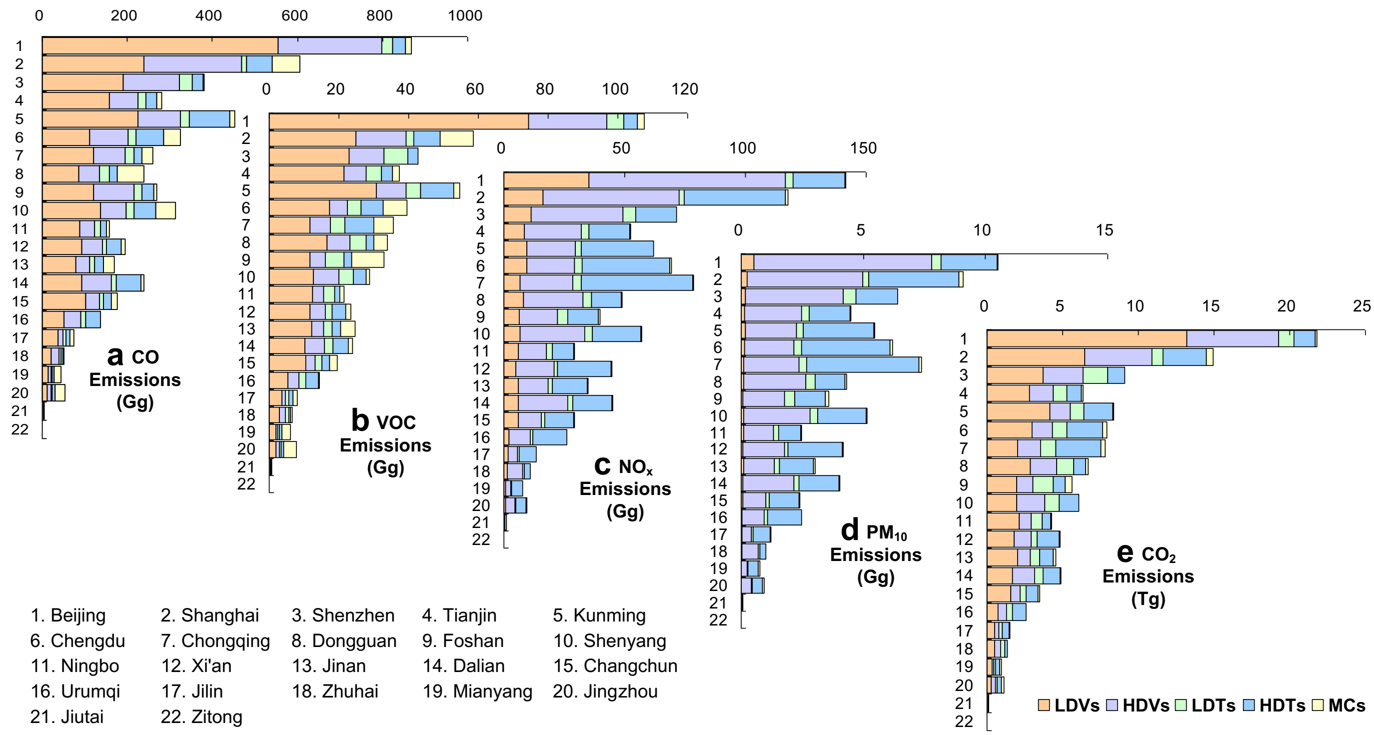

Fig. 3. Vehicle emissions by type in 2007 (the cities are listed in the order of city vehicle population excluding MCs).

and Shanghai. Beijing, Shanghai, and Guangzhou accounted for 9.1% of the national new vehicle growth from 2006 to 2007 and 8.3% from 2007 to 2008 (State Statistical Bureau of China, 2002–2009); this share is expected to continue to decrease as developing cities successively enter the vehicle boom period. Some previous studies (Wang et al., 2010; Wu et al., 2011) have concluded that the vehicle emissions in Beijing started to decrease as a result of the emission control measures taken in Beijing; however, the vehicle emission control measures in Beijing are far more stringent than in the rest of China (Wu et al., 2011), so a similar decline in vehicle emissions may not be expected yet in other Chinese cities unless similar measures are to be implemented. For example, the total vehicle emissions (except NO_x) were reported to keep increasing even in Shanghai and Guangzhou that ranked second after Beijing in controlling urban vehicle emissions (see Table 2) (Wang et al., 2010). Therefore, under the existing vehicle emission control scheme, the total vehicle emissions will increase substantially until the rate of increase in vehicle ownership begins to slow down, which is not expected in the near term in China. By a rough estimate, each phase of Euro emission standards could reduce emissions by 30–50%, while the vehicle population in Chinese cities is increasing by 15–20% annually, which means that the reduction in total emissions achieved by a new Euro emission standard could be offset by the growth in vehicle population in 2 or 3 years. However, a more accurate calculation is needed to simulate the variation in vehicle use and driving pattern as the vehicle population increases in the future. How to control this large potential increase in vehicle emissions is a critical issue for China, addressing which will rely on a comprehensive understanding of vehicle emissions of all types in all kinds of cities over time.

Fig. 4 illustrates the relationship of per-capita vehicle emissions to per capita GDP of the 22 cities. The vehicle emissions are observed to have a strong linear relationship with GDP in Chinese cities (some cities like Kunming and Urumqi deviate away from the line because their average vehicle emission factors are relatively higher). As per capita GDP grows fast in developing cities, per-capita vehicle emissions can be expected to increase, following the lines in Fig. 4. Considering that the sizes of these cities in China is still increasing, total vehicle emissions will inevitably increase if no special control measures are introduced. Transit usage could help to reduce per-capita vehicle emissions in cities significantly. However, the railway transit system was not well developed in most Chinese cities. Therefore, it is important for Chinese cities, especially where have high population-density and rapid vehicle population increase, to quicken the process of urban railway construction.

Fig. 5 compares per-capita vehicle emissions in Beijing, the U.S., and some western European countries (Centre on Emission Inventories and Projections, 2010; U.S. Environmental Protection Agency, 2010; U.S. Census Bureau, 2010). The U.S. and the European countries show a declining trend in per-capita vehicle emissions as per capita GDP increases, because vehicle ownership per capita has increased very slowly or remained unchanged while vehicle technologies have achieved significant improvements. Improvement in vehicle technology is an effective solution for China to offset the large potential increase in vehicle emissions.

Nevertheless, in spite of the great improvement in vehicle technology, the per-capita vehicle emissions in Beijing are still relative high compared to developed countries. As shown in Fig. 5, with fewer vehicles ownership per 1000 people (220 in Beijing vs. 800 in the U.S and 500–600 in European countries), Beijing has the same level of per-capita vehicle emissions as the U.S. and European countries. The primary reason is that Beijing started the Euro I emission standard in 1999, and until now there are still pre-Euro I vehicles (called "yellow-labeled" vehicles) in operation (about 10–11% in 2007, see Table 3 and Zhou et al., 2010), as the average lifetime of vehicles is 15 years. Beijing has to make tremendous efforts to scrap "yellow-labeled" vehicles, which could have been avoided if Beijing had implemented the Euro I standards several years earlier. Although the vehicle pollution issues in medium and small cities are not yet as important as those in mega-cities, given the fact that the vehicle fleet turnover is a slow process, it is important to take vehicle emission control measures as soon as

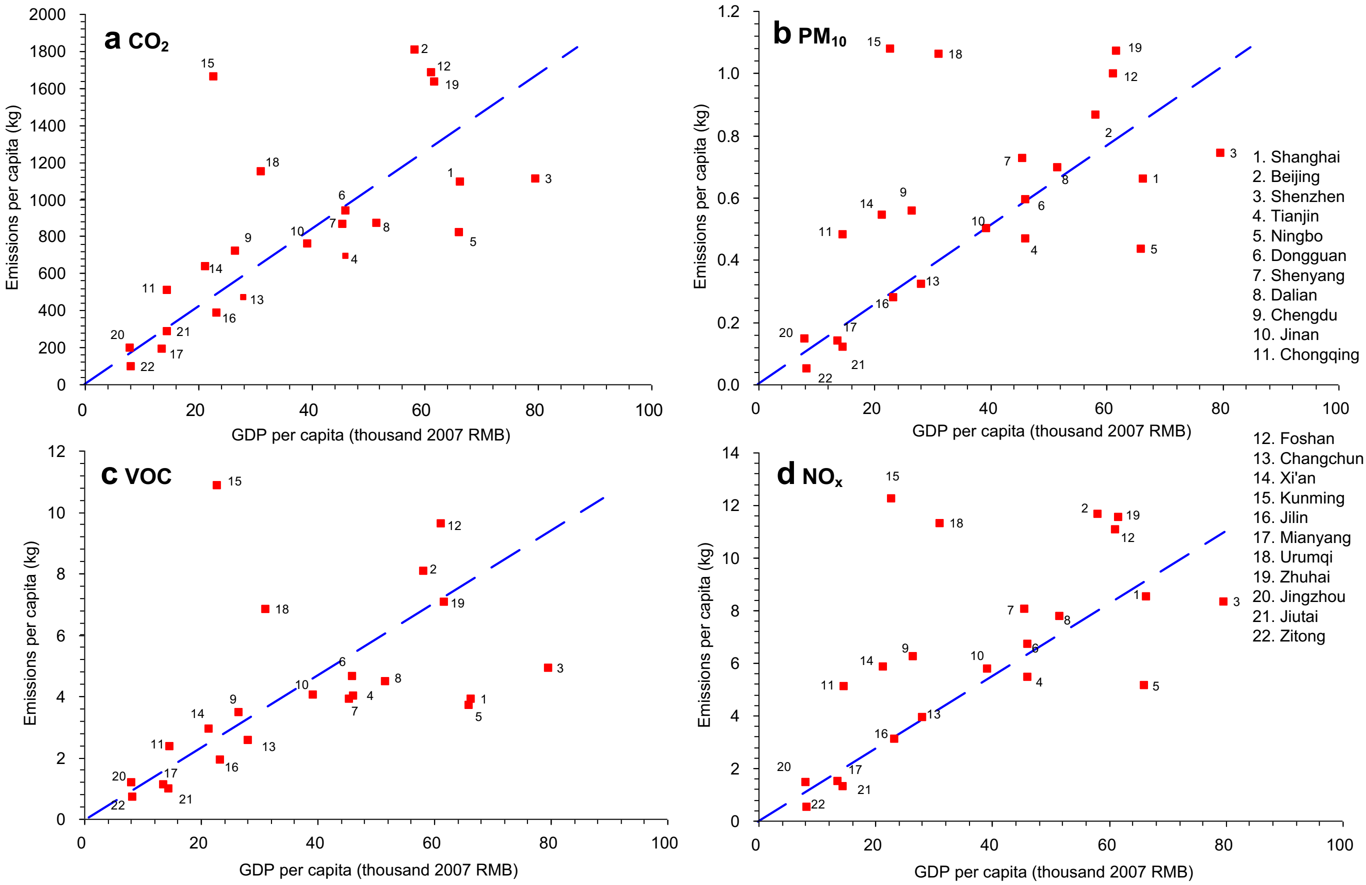

Fig. 4. Vehicle emissions per capita (kg) as a function of city per capita GDP in 2007.

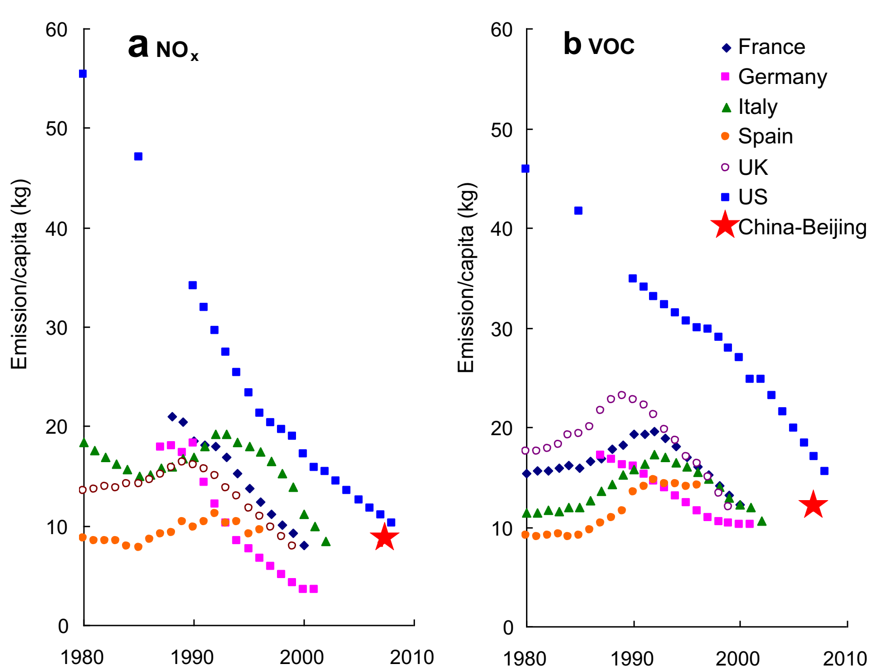

Fig. 5. Comparison of vehicle emissions per capita in Beijing and some developed countries.

possible. The process of vehicle technology improvement needs to be accelerated in China by requiring stronger emission standards (e.g., Euro V/VI) as quick as possible, which is the fundamental key to addressing the vehicle pollution issue in cities.

From the view of methodology, the implication of this work lies in providing a new method to improve the spatial resolution of China's vehicle emission inventory by estimating and forecasting vehicle emissions at city level. In China, transportation-related activity data are not well reported through the national or provincial statistical systems. Vehicle population data are usually available at provincial level only with simple classifications. This work presents a method to estimate vehicle emissions in various cities ranging from large mega-cities to large towns using available data, which could be adopted for all Chinese cities. The next step of our work will extend this method to all cities in China to develop a high-resolution vehicle inventory. It should be noted that further work is need to explore vehicle activity characteristics, including VKT level by city, split ratio for urban and highways, and more accurate vehicle driving patterns.

Acknowledgments

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