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ORIGINAL ARTICLE

Vehicular air pollutant emissions in China: evaluation of past control policies and future perspectives

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Abstract Transportation constitutes one of the largest sources of air pollution emissions in China. A series of measures have been taken to control vehicle emissions. In this study, we simulate the effects of the major vehicle control policies implemented in China and those to be implemented in the future by performing scenario analyses. As a result of the three stages of vehicle emission standards (states I, II, and III), the average emission factors (g/km) of light-duty gasoline vehicles in China for carbon monoxide (CO), volatile organic compounds, nitrogen oxides, and particulate matter measuring less than 2.5 μm in diameter were reduced by 78, 88, 90, and 85 %, respectively, between 2000 and 2012. Those of heavy-duty diesel vehicles were reduced by 66, 65, 30, and 67 %. If no emission standards had been implemented in that period, the levels of vehicle emissions in China would have been increased by two to six times the levels measured in 2000, as of 2012; the standards therefore helped to reduce emissions by 50–83 % between 2000 and 2012 compared to the uncontrolled scenario. In Beijing and Shanghai, where the standards were implemented earlier than in the rest of the country, the standards achieved greater reductions. In the future, if no new measures are taken, vehicle emissions (except CO) will continue to increase until 2020. Implementing the more stringent standards of states IV and V is very important to lowering future vehicle emissions, and the earlier the standards are in place, the greater the benefits they will provide. Phasing out old vehicles could accelerate emission reductions.

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1 Introduction

China has been experiencing dramatic growth in vehicle numbers, which have increased from 5.5 million in 1990 to 120 million in 2012 (excluding motorcycles and low-speed rural vehicles), 22-fold in 22 years (National Bureau of Statistics 2013). Vehicles have become a major source of air pollutant emissions in China. According to the multi-resolution emission inventory for China (MEIC), developed by Tsinghua University, vehicles contributed 11, 9, and 17 % of the national carbon monoxide (CO), volatile organic compound (VOCs), and nitrogen oxide (NO_x) emissions in China in 2010, respectively (MEIC 2013). The contributions are greater in mega-cities because of the high levels of vehicle ownership. For instance, in Beijing, vehicles contributed 42 and 66 % of VOC and NO_x emissions, respectively, in 2008 (Wang et al. 2010).

To control pollution emissions from vehicles, China has implemented a series of policy measures since 1998, including initiating and continuing to strengthen vehicle emission standards for new vehicles and phasing out old, high-emission vehicles. Figure 1 presents the trend in vehicle numbers versus vehicle emissions estimated by MEIC (2013), Zhao et al. (2013), the Ministry of Environmental Protection of China (MEP) (2010–2013), Wei et al. (2008), and Cai and Xie (2013). Although these studies indicate somewhat different trends in emissions, most of them show that vehicle emissions have not increased as rapidly as vehicle numbers have grown, and the emissions of some pollutants (e.g., CO and VOCs) have begun

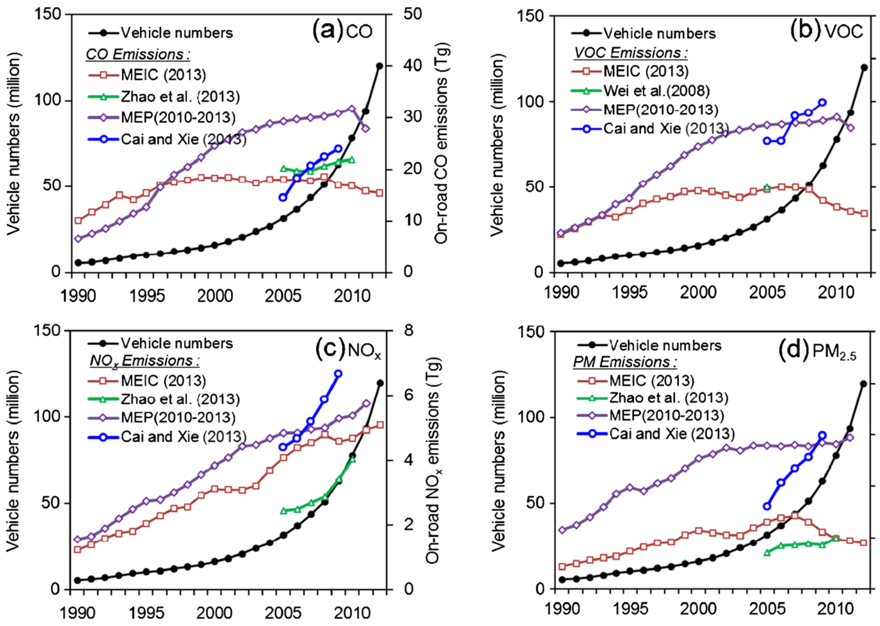

Fig. 1 Changes in vehicle emissions track with the growth in vehicle numbers in China between 1990 and 2012

to decline. The MEP reported that the recent decline in the growth rates of vehicle emissions was related to the policies implemented in the past (MEP 2010).

Vehicle ownership per 1,000 people is still very low in China (i.e., at 88 vehicles/1,000 people in 2012) compared to that in developed countries (e.g., at 500–800 vehicles/1,000 people in Japan, Europe, and the United States), and many studies have shown that the number of vehicles in China will continue to increase up to 2030 (Wang et al. 2006; Wang et al. 2011; Ou et al. 2010; Huo and Wang 2012); therefore, the development of appropriate vehicle emission controls will need to keep pace. In particular, China is currently facing a significant challenge: addressing regional air pollution characterized by high concentrations of $PM_{2.5}$ (particulate matter measuring less than 2.5 μm in diameter), with vehicles regarded as a key source that needs to be controlled (China's State Council 2013). Therefore, it is of great importance to understand the effects of past control policies and the potential effects of policies to be implemented in the near future to control vehicle emissions in a more effective manner.

In this study, based on the MEIC methodology, we evaluate past vehicle control policies in China between 2000 and 2012 by estimating the emission reduction afforded by each major policy. We then project vehicle emissions in China through 2020 under several policy scenarios to shed light on the potential effects of future vehicle emission control policies. This study mainly focuses on cars, buses, and trucks. It should be noted that, although not included in this study, motorcycles and low-speed vehicles are two important vehicle types in China, with 104 million and 11 million vehicles, respectively, in 2012, and together accounted for 17, 21, 9, and 5 % of the total CO, VOC, NO_x, and PM emissions from cars, buses, trucks, motorcycles, and low-speed vehicles in 2012 (MEP 2013).

The purpose of this study is to improve the understanding of the effects of vehicle emission control policies in China and thereby help decision makers develop effective control strategies.

2 Vehicle emission control policies

Many types of measures have been taken to control vehicle emissions in China on both a national and local basis, with compliance with some being mandatory and with others being voluntary and subsidies offered or extra fees charged; additionally, some measures are enacted on a permanent basis, and others only temporarily. The measures can be classified into four major categories: (1) policies to lower the emission levels of new vehicles via stringent vehicle emission standards and fuel quality requirements; (2) policies to reduce the emissions from old vehicles via phasing out old, high-emission vehicles; (3) policies to reduce vehicle use by restricting vehicle sales and use and encouraging public transportation systems; and (4) policies to provide alternative vehicles, such as zero-emission vehicles (e.g., pure-battery electric vehicles), in urban areas.

2.1 Strengthening vehicle emission standards and fuel quality requirements

China is following the vehicle emission standard system (including testing procedures and vehicle emission limits) developed by the European Commission. In 2000, China implemented the state I emission standards (equivalent to the Euro 1 emission standards) for light-duty vehicles on a nationwide basis. Subsequently, China implemented the state II and state III emission standards in 2004 and in 2007, respectively (which are equivalent to the Euro 2 and Euro 3 emission standards, respectively). It was planned that the state IV standard (equivalent to Euro 4) would be implemented at the end of 2010; however, implementation was delayed because of the inability of China’s oil companies to supply the entire country with gasoline and diesel that would be compatible with state IV vehicles. Some cities with severe vehicle emission pollution, such as Beijing and Shanghai, are ahead of the rest of China in terms of the adoption of vehicle emission standards. For example, Beijing implemented the state IV standard (also called Jing IV) in 2008 and state V (equivalent to Euro 5, also called Jing V) in 2013.

Figure 2 presents the progress of emission standards for light-duty vehicles and heavy-duty diesel vehicles both on a nationwide basis and in some major cities in China. Although the gap between China and Europe in terms of vehicle emission standards has been narrowing since China implemented the first phase of standards in 2000, China is still two phases (~6 to 9 years) behind Europe. In contrast, cities such as Beijing, Shanghai, and Guangzhou are close to catching up with the European levels.

Fuel quality can significantly affect the performance of vehicle emission control units; therefore, fuel quality must be regulated in concert with vehicle emission standards. In China, the regulations for vehicular fuels have always lagged behind those for vehicle emission standards. For example, China required the quality of gasoline to match the state III vehicle emission standards (state III gasoline hereafter for short) nationwide in 2009, 2 years after the

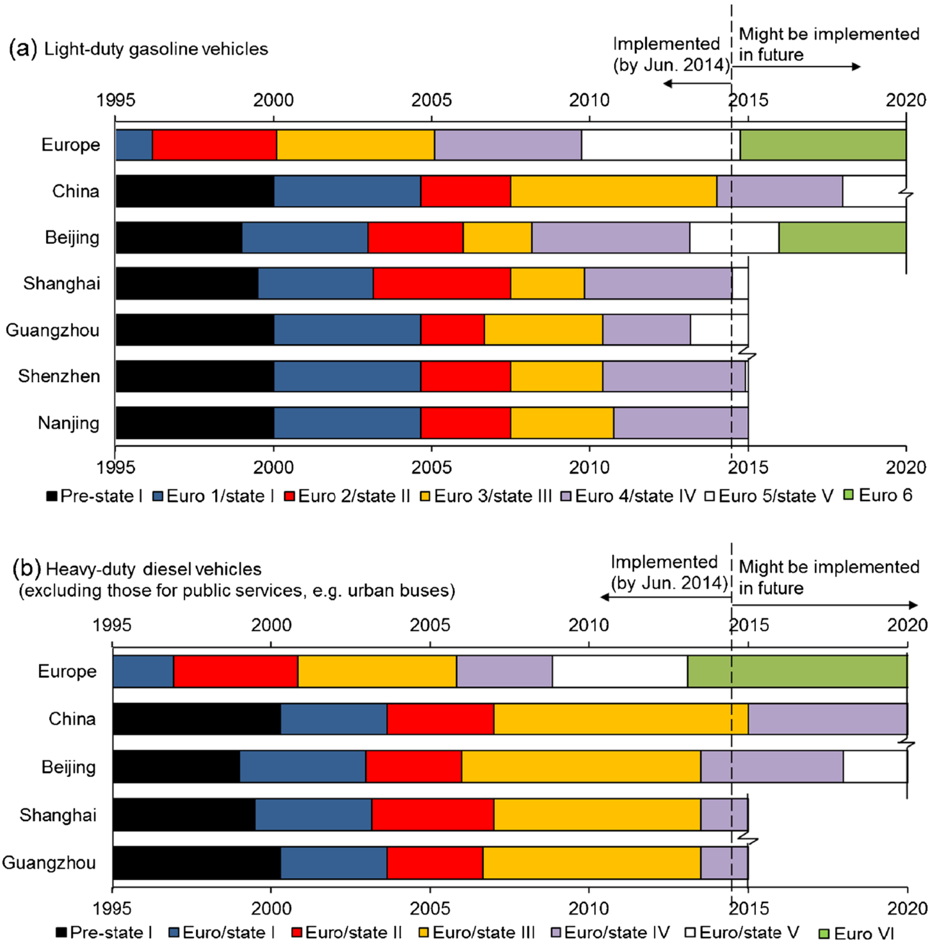

Fig. 2 Progress in implementing emission standards for vehicles in China in two phases (approximately 6 to 9 years) behind that in Europe

state III vehicle emission standard was implemented. For many years, the deficiency in fuel quality was the major bottleneck that prevented vehicle emission standards from being further tightened in China. Nevertheless, China required the use of state IV gasoline (with a sulfur content at ≤50 ppm) throughout the country in January 2014. Some cities have implemented stricter fuel quality requirements. For example, Beijing has supplied state V fuels since July 2012. Figure 3 compares the sulfur content levels of vehicular gasoline and diesel between China and some developed countries. China is approximately 10 years behind the United States (U.S.), Europe, and Japan in terms of vehicular fuel quality.

2.2 Phasing out old vehicles

Older vehicles have much higher emission levels than do new vehicles for two reasons: (1) old vehicles have less-advanced emission control technologies, and (2) the emission performance of vehicles deteriorates with age. For example, pre-state I (nearly no emission control) vehicles could emit 10 or even 100 times more pollutants than do new state IV vehicles (Huo et al. 2012a, b). Some pre-state I vehicles are still in operation, especially in the so-called Tier 2 and Tier 3 cities, because Chinese vehicles can operate for more than 15 years, and vehicles produced before 2000 were generally pre-state I. These older vehicles, although accounting for a small share of the vehicle fleet, were estimated to contribute approximately 50 % of the vehicle emissions in China in 2009 (MEP 2010).

To eliminate these old, high-emission vehicles, China has implemented a series of measures to target two groups of old vehicles: (1) pre-state I gasoline vehicles and pre-state I, state I, and state II diesel vehicles, which are referred to as yellow-labeled vehicles; and (2) those vehicles that could not meet the state IV standard and have been used for more than 6 years, which are referred to as aged vehicles.

In 2009, China implemented a nationwide vehicle scrappage program, which offered rebates of 450–900 USD to consumers for trading in yellow-labeled vehicles, and the rebates were doubled (tripled for some vehicle types) in 2010. In 2013, to address the pollution caused by $PM_{2.5}$ haze, China's State Council released the Atmospheric Pollution Prevention Action

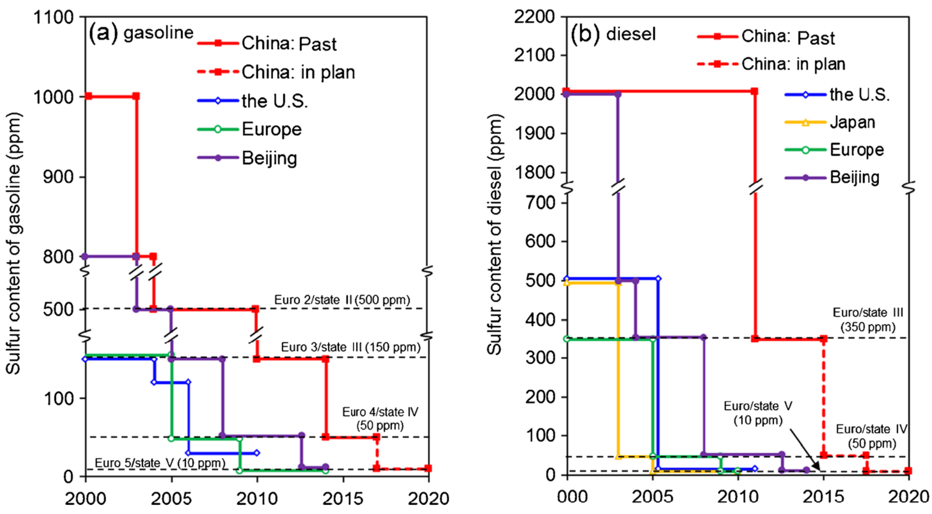

Fig. 3 Sulfur content of vehicular fuels are shown for **a** gasoline (*left*) and **b** diesel (*right*) in China, the U.S., Europe, and Japan

Plan (China's State Council 2013), which aims to speed up the scrappage of yellow-labeled vehicles and aged vehicles. The plan specifically involves phasing out all yellow-labeled, for-revenue vehicles registered before 2005 by 2015; 5 million yellow-labeled vehicles in the regions of Beijing–Tianjin–Hebei, the Yangtze River Delta (i.e., Shanghai and surrounding cities), and Pearl River Delta (Guangzhou and surrounding cities) by 2015; and all yellow-labeled vehicles nationwide by 2017. Some cities have even more ambitious plans. For example, Beijing scrapped nearly 1 million old vehicles between 2011 and 2013, which is equivalent to approximately 20 % of the current vehicle numbers in Beijing.

2.3 Restricting vehicle sales and use and improving public transportation systems

Vehicle sale and use restriction policies have been introduced in a few cities to solve severe traffic congestion and urban air pollution problems. Shanghai was the first city to restrict vehicle sales in China. In 1994, Shanghai started a license plate auction policy with a limited number of new license plates available each year (e.g., 110,000 plates in 2013), which made new license plates very expensive. In 2013, a license plate cost 80,000 Chinese Yuan (equivalent to 12,500 USD) on average. At the beginning of 2011, Beijing began to restrict monthly vehicle sales to 20,000 (note that the usual number of vehicle sales per month was more than 50,000 in Beijing at that time), and the sales quota is allocated to potential buyers through a lottery process. Beginning in 2014, the restriction of monthly sales was tightened to 12,000 vehicles. In 2012, Guangzhou initiated a similar policy to restrict vehicle sales to 120,000 a year, with 10 % allocated to new energy vehicles (e.g., electric vehicles), 40 % to be determined by a lottery system, and 50 % to be determined by auction. Other cities, such as Guiyang and Tianjin, have adopted similar vehicle sale restriction policies.

Various policies have been implemented at the city level to restrict private cars, yellow-labeled vehicles, trucks, and vehicles registered in other provinces to enter certain areas on certain days. In October 2008, Beijing introduced a policy to restrict 20 % of private cars from driving in urban areas during the daytime on workdays. The 20 % restricted are determined according to the last digit of the number plate; thus, for instance, cars with number plates ending in 1 and 6 are not allowed to drive in urban areas of Beijing on Mondays and those with number plates ending in 2 and 7 are not allowed on Tuesdays, with the weekday restrictions rotating every 3 months. This policy has helped alleviate traffic congestion and reduce vehicle emissions. Economic measures to restrict vehicle use are under discussion, such as raising parking fees and charging congestion fees in urban centers.

Improving urban public transit systems can provide citizens with a cleaner and more efficient option for travel. Larger cities in China are making great efforts to develop convenient, comfortable, and effective public transit systems, which will nonetheless require significant investment and long-term commitment.

2.4 Alternative vehicles

Although electric vehicles (EVs, including plug-in EVs and pure-battery EVs) and fuel cell vehicles produce emissions during electricity and hydrogen generation, they can achieve zero tailpipe emissions during vehicle operation and thus reduce emissions where vehicle activities occur; therefore, EVs are considered part of the solution for improving urban air quality. In 2012, China sold approximately 10,000 EVs, and China has made plans to achieve accumulated sales of half a million EVs by 2015 and 5 million by 2020 (China's State Council 2012). However, it should be mentioned that whether alternative vehicles can reduce on-road emissions should be carefully examined from a life-cycle perspective. Some studies show that

EVs might increase CO_2, SO_2, NO_x, and PM emissions in areas where coal accounts for a large percentage of the local generation mix, such as Beijing and Tianjin (Ji et al. 2012; Huo et al. 2013).

3 Simulation methodology and scenarios

3.1 Calculation of vehicle emissions from 2000 to 2012

In this study, the MEIC model is applied to calculate vehicle emissions in China from 2000 to 2012. The MEIC model was developed by Tsinghua University and aims to provide model-ready emission data for all anthropogenic sources in China to support both the air pollutant transport model and climate model at different spatial resolutions and time scales (MEIC 2013).

Based on China's statistics, the MEIC classified vehicles into eight categories: heavy-duty buses (HDBs), medium-duty buses (MDBs), light-duty buses (LDBs), mini buses (MBs), heavy-duty trucks (HDTs), medium-duty trucks (MDTs), light-duty trucks (LDTs), and mini trucks (MTs), with each category further subdivided into gasoline-fueled and diesel-fueled vehicles. Note that passenger cars are categorized as LDBs and MBs. In the analysis, we use light-duty vehicles (LDVs) to represent LDBs, MBs, LDTs, and MTs and use heavy-duty vehicles (HDVs) to represent HDBs, MDBs, HDTs, and MDTs. For each vehicle type, the MEIC estimates the emissions from each province by multiplying the provincial-level vehicle emission factors and vehicle activities. Vehicle emission factors, in grams per kilometer, were determined using vehicle emission measurement studies conducted in China (Wang et al. 2005; Yao et al. 2007, 2011; Liu et al. 2009; Huo et al. 2012a, b; Shen et al. 2014) and using meteorological correction factors (Zheng et al. 2014). Vehicle activities, the total vehicle kilometers traveled (VKTs), were estimated using the vehicle numbers obtained from Chinese statistics (National Bureau of Statistics 1995–2013) and from the annual VKTs of individual vehicles (Huo et al. 2012c) and subsequently adjusted by the provincial gasoline and diesel consumption figures indicated by China's statistics (National Bureau of Statistics 2000–2012) (the MEIC adjusted the activity data of all sectors by making the sum of the energy consumption of all sectors consistent with the statistics). For the fuel consumption rates of vehicles, please refer to our previous publications (Huo et al. 2011, 2012d). The methodology used to determine the emission deterioration rates of LDGVs were documented in Huo et al. (2012a), and the deterioration rates of HDDVs were assumed to be zero.

3.2 Projection of vehicle emissions through 2020

We use the Gompertz function to project the number of vehicles in each province in the future, as indicated by Eq. (1). The Gompertz function is an S-shaped curve and has been widely used in previous studies to simulate the growth in vehicle ownership per 1,000 people as per-capita gross domestic product (GDP) increases (Dargay and Gately 1999; Dargay et al. 2007; Huo and Wang 2012).

$$\text{Gompertz } \mathit{Function}: \quad V = V^* \times e^{\alpha e^{\beta E}} \tag{1}$$

where V represents vehicle ownership (vehicles/1,000 people), V^* represents the saturation level of vehicle ownership (vehicles/1,000 people), E represents an economic factor (here, per-capita GDP), and α and β are two parameters (with negative values) that determine the shape of the curve.

The saturation levels of vehicle ownership differ between urban and rural areas and are assumed to be 400 vehicles/1,000 people (the level of cities in Japan) and 500 vehicles/1,000 people (the level of rural areas in Japan), respectively, in this study. The vehicle ownership levels in Beijing and Shanghai are assumed to be 250 vehicles/1,000 people (the level in Tokyo). The future population and GDP levels in China are determined based on the World Energy Outlook 2012, which was produced by the International Energy Agency (2012), and are subsequently allocated to each province.

We project future VKTs based on a previous study (Huo et al. 2012c). We assume that the VKTs of private LDVs will decrease by 11 % from 2010 to 2020 and that the VKTs of other for-revenue vehicles will increase by 5 % from 2010 to 2020 because of the growth in transportation demand.

3.3 Scenario design

This study designs two sets of scenarios, to evaluate past policies and potential future policies, as shown in Table 1. For past scenarios, this study focuses on vehicle emission standards because they have been proven to be the most effective measures for reducing vehicle emissions (Wu et al. 2011). Three hypothetical scenarios (Scenarios P-II, P-III, and P-IV) are designed to explore the emission reductions of each stage of the past standards. Because Beijing and Shanghai implemented vehicle standards ahead of the rest of the country, their vehicle emissions under the scenarios are also simulated in this study.

For the future scenarios, two major measures, strengthening vehicle emission standards and phasing out old vehicles, are considered. By assuming different implementation schedules for the state IV and state V standards, this set of scenarios helps to quantitatively demonstrate the effects of implementing the standards earlier or later on vehicle emissions. Note that two

Table 1 Two sets of scenarios are designed to evaluate past policies and potential future policies

	Description
Past policies	
Scenario P-I	Emissions standards for states I, II, and III were implemented on the actual schedule.
Scenario P-II	State I and state II standards were implemented on the actual schedule, but state III standards were not implemented.
Scenario P-III	Only state I standards were implemented on the actual schedule.
Scenario P-IV	No vehicle emission standards were implemented since 2000.
Future scenarios	
Scenario F-I	No new measures have been implemented since 2012.
Scenario F-II	State IV is implemented in 2015.
Scenario F-III	States IV and V are implemented in 2014 and 2018, respectively.
Scenario F-IV	States IV and V are implemented in 2012 and 2017, respectively.
Scenario F-V	States IV and V are implemented in 2012 and 2017, respectively; 50 % of yellow-labeled vehicles are scrapped by 2014; 100 % of yellow-labeled vehicles are scrapped by 2015.

These scenarios focus on vehicle emission standards and yellow-labeled vehicle scrappage, two important measures that China has implemented and will continue to implement in the near future. To explore the emission reductions in each stage of the past standards, hypothetical scenarios are also designed hypothetical scenarios (Scenarios F-IV and F-V) are included to examine how much emissions could have been reduced in the future if China had implemented the state IV standards in 2012.

4 Results and implications

4.1 Evaluation of past policies

Figure 4 presents the trends in the average emission factors of gasoline LDVs (LDGVs) and diesel HDVs (HDDVs) in China, Beijing, and Shanghai under Scenario P-I. Vehicle emission factors are related to two key influencing factors: the zero-mileage emission level and the deterioration rates of emission factors. Owing to the implemented emission standards, the average CO, VOC, NO_x, and $PM_{2.5}$ emission factors for LDGVs decreased by 78, 88, 90, and 85 %, respectively, from 2000 to 2012, and those of HDDVs decreased by 66, 65, 30, and 67 %, respectively. As shown in Fig. 4, the NO_x emission factor for HDDVs decreased less dramatically than did those of other pollutants. Recent measurement studies (Huo et al. 2012b; Wu et al. 2012) showed that state III diesel trucks had equivalent or even higher on-road NO_x emission factors than those of state II diesel trucks; this discrepancy may have arisen because truck manufacturers used electronic controls, instead of effective after-treatment technologies, to reach a low-emission mode during certification tests.

Because Beijing and Shanghai implemented vehicle emission standards ahead of the rest of the country and are implementing stricter standards even now, each city had lower vehicle emission factors. In 2012, the average CO emission factor for the LDGV fleet was 12.2 g/km in China, 6.9 g/km in Beijing, and 9.3 g/km in Shanghai. Generally, the emission factors of

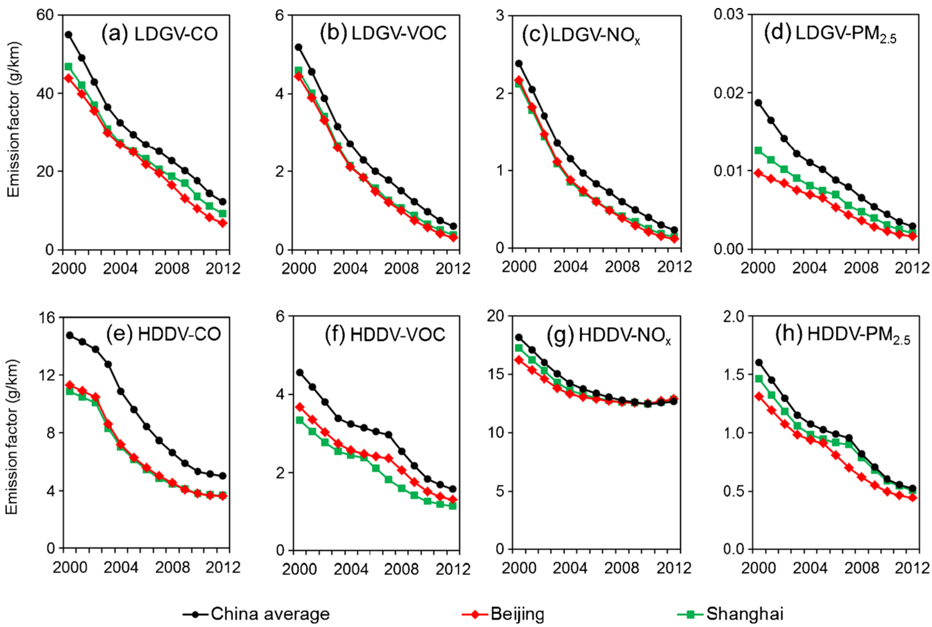

Fig. 4 Average emission factors of light-duty gasoline vehicles and heavy-duty diesel vehicles under Scenario P-I all show declines from 2000 to 2012, although NO_x declines were less dramatic

China's LDGV fleet were twice as high as those in Beijing and 31–68 % higher than those in Shanghai.

Figure 5 presents the vehicle emissions in China, Beijing, and Shanghai from 2000 to 2012 under the four scenarios for the past policies. Under Scenario P-I, vehicles in China emitted 15 Tg CO, 1.3 Tg VOCs, 4.9 Tg NO_x, and 0.17 Tg $PM_{2.5}$ in 2012. If no emission standards had been implemented since 2000 (Scenario P-IV), with the effects of the increasing vehicle activities and emission-related vehicle deterioration, the vehicle emissions in China would have been 64 Tg CO, 7.8 Tg VOCs, 9.9 Tg NO_x, and 0.63 Tg $PM_{2.5}$ in 2012, or two to six times the actual amount of emissions.

Table 2 presents the vehicle emission reductions in China under Scenarios P-I, P-II, and P-III compared to those under Scenario P-IV. The state I emission standard helped to reduce the CO, VOC, NO_x, and $PM_{2.5}$ emissions by 50, 62, 42, and 44 %, respectively, from 2000 to 2012 compared to those in the uncontrolled scenario. Under Scenario P-II, state I and II emission standards together reduced the CO, VOC, NO_x, and $PM_{2.5}$ emissions by 64, 72, 48,

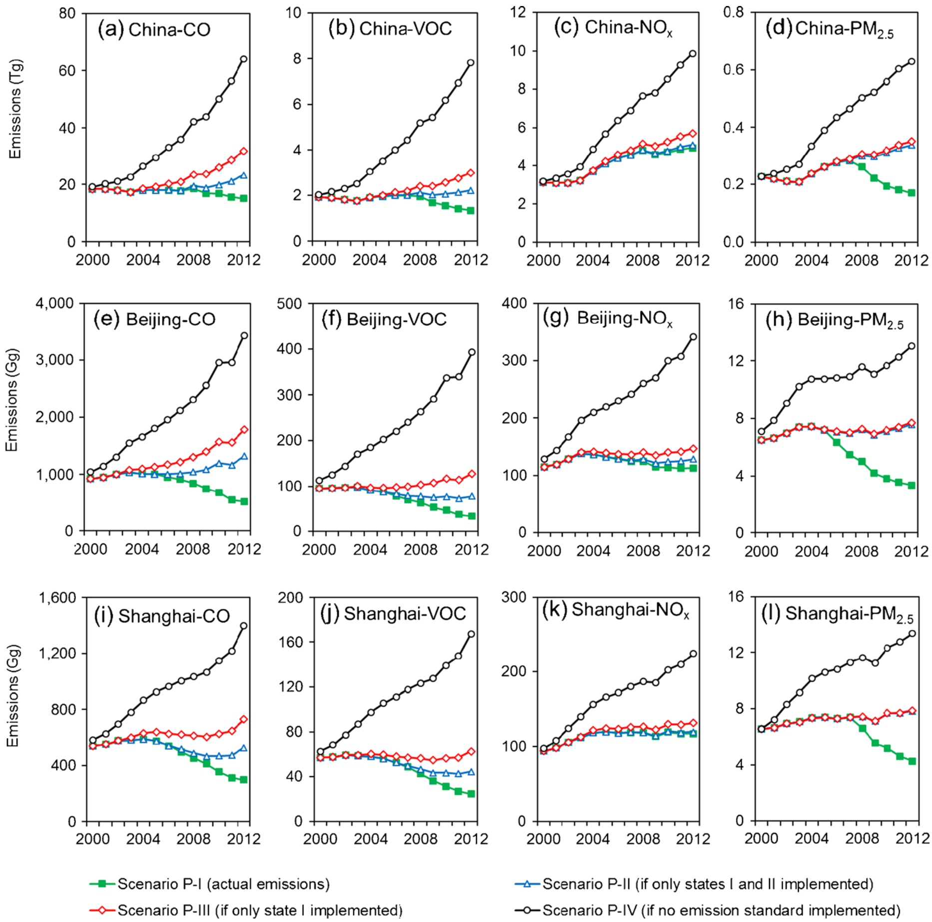

Fig. 5 Vehicle emissions from 2000 to 2012 in China under the four scenarios for the past policies show dramatic increases if no emission standards (Scenario P-IV) had been implemented

Table 2 Vehicle emission reductions under Scenarios P-I, P-II, and P-III compared to those under Scenario P-IV

	Scenario P-I			Scenario P-II			Scenario P-III		
	2004	2008	2012	2004	2008	2012	2004	2008	2012
CO	32 %	56 %	77 %	32 %	54 %	64 %	30 %	44 %	50 %
VOCs	38 %	62 %	83 %	38 %	59 %	72 %	37 %	54 %	62 %
NO_x	24 %	37 %	50 %	24 %	37 %	48 %	23 %	33 %	42 %
$PM_{2.5}$	29 %	48 %	73 %	29 %	40 %	46 %	29 %	39 %	44 %

Scenario P-IV is a hypothetical scenario in which no vehicle emission measures were taken in China in the past. Scenario P-I, Scenario P-II, and Scenario P-III are scenarios for the past policies and represent the real case with states I, II, and III implemented, a hypothetical scenario with only states I and II implemented, and another hypothetical scenario with only state I implemented

and 46 %, respectively, from 2000 to 2012 compared to those in the uncontrolled scenario. However, the emissions would still increase with the implementation of only state I and II emission standards because of the increasing vehicle stock and increasing vehicle use as well as vehicle emission deterioration.

Under Scenario P-I, the CO, VOC, NO_x, and $PM_{2.5}$ emissions could be reduced by 77, 83, 50, and 73 %, respectively, from 2000 to 2012 compared to those under Scenario P-IV. The CO, VOC, and $PM_{2.5}$ emissions in China started to decrease from 2008, when the state III emission standard was implemented. The three emission standard stages lowered the CO, VOC, and $PM_{2.5}$ emissions in 2012 compared to those in 2000 even though vehicle numbers increased 6.5-fold between 2000 and 2012. However, NO_x emissions in China continued increasing. Diesel trucks in China are a major contributor to on-road NO_x emissions, contributing more than 90 % of the total emissions (Zheng et al. 2014), and as stated above, measurement studies have found that there was little decrease in the NO_x emission factors between state II and state III diesel trucks. Therefore, the implementation of the state III standard brought little benefit by means of NO_x reductions. Nevertheless, as Fig. 5 shows, the state III standard was able to produce a significant reduction in $PM_{2.5}$ emissions because recent measurement studies show that state III trucks can produce $PM_{2.5}$ emissions at an approximately 50 % lower rate compared to state II trucks per kilometer driven (Huo et al. 2012b; Wu et al. 2012).

Because the standards were implemented earlier in Beijing and Shanghai, these two cities achieved greater emission reductions. In Beijing, the three stages of the standards reduced CO, VOC, NO_x, and $PM_{2.5}$ emissions by 85, 91, 67, and 74 %, respectively, by 2012 compared to those in the uncontrolled scenario (Scenario P-IV). Because the standards were implemented 1 to 3 years earlier than in the rest of the county, the peak vehicle emissions appeared 4 years earlier in Beijing (year 2004) than in the rest of China (year 2008). Therefore, the earlier the vehicle emission standards were implemented, the larger the reduction that could be achieved, which was especially true for regions with significant vehicle growth.

4.2 Evaluation of future policies

Figure 6 presents the vehicle emissions from 2010 to 2020 in China under the five scenarios. In the future, if no new measures are implemented, NO_x emissions will increase by 61 % from

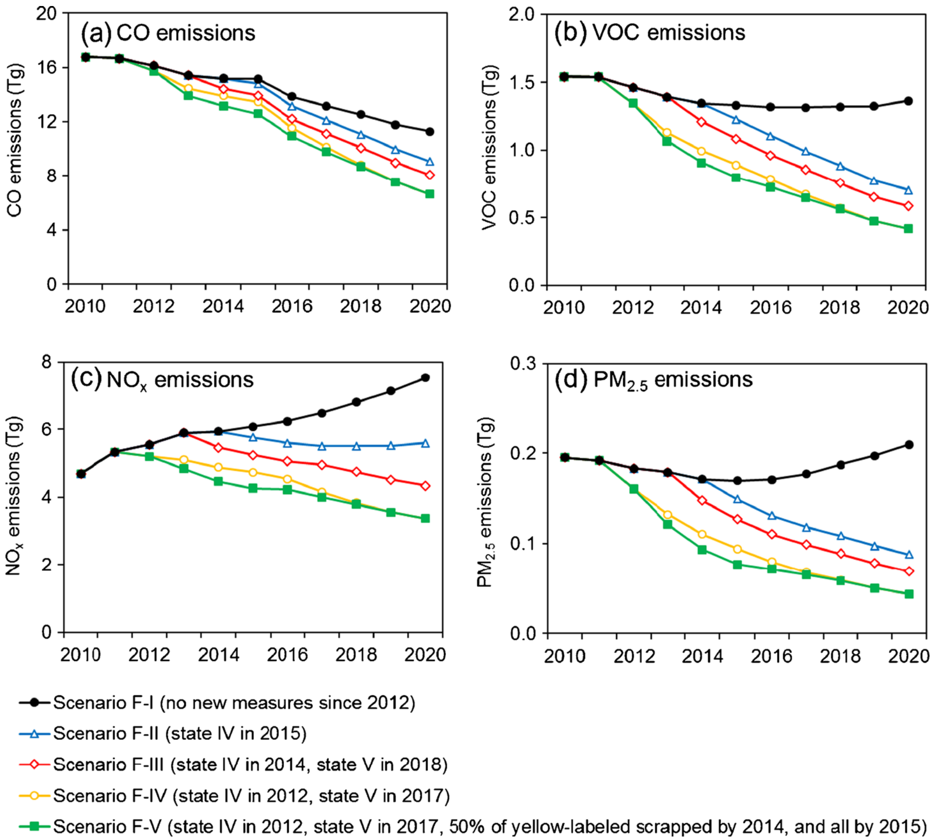

Fig. 6 Vehicle emissions from 2010 to 2020 in China are shown under the five scenarios for future policies

2010 to 2020 because of increasing vehicle activities and vehicle emission deterioration. VOC and $PM_{2.5}$ emissions, although currently decreasing, will increase in the near future because of increasing vehicle activities. CO emissions will continue decreasing through 2020 for two reasons: (1) the number of gasoline HDBs (HDGBs) and gasoline MDBs (MDGBs), two large contributors to CO emissions, is decreasing as a result of vehicle dieselization in China; and (2) new, clean vehicles are replacing old, high-pollution vehicles. However, when these processes are completed, if no new policies are implemented, CO emissions will eventually increase under the effects of the growth in vehicle activities and the deterioration of vehicle emission control equipment.

If China implements the state IV standard by 2015 (Scenario F-II), the VOC and $PM_{2.5}$ emissions from vehicles will be reduced by approximately 50 % from 2012 to 2020; however, NO_x emissions will increase slightly from 2012 to 2020. If China implements the state IV standard in 2014 and the state V standard in 2018 (Scenario F-III), which is most likely to be the case, a reduction of 10–24 % in vehicle emissions by 2020 could be achieved relative to emissions under Scenario F-II. It should be noted that neither of the two scenarios (F-II and F-III) would meet the target of reducing NO_x emissions by motor vehicles by 10 % between 2010 and 2015 as stated in the 12th Five Year Plan. This finding indicates that additional measures need to be taken to further reduce NO_x emissions from the transportation sector or that other sectors will need to further reduce NO_x emissions to offset the shortfall in the transportation sector to meet the 10 % overall reduction goal.

If China had implemented the state IV standard in 2012 and implements the state V standard in 2017, 18–37 % of emissions could be avoided by 2020 compared to those under Scenario F-III; however, NO_x emissions in 2015 would still be higher than the levels measured in 2010. With all yellow-labeled vehicles scrapped by 2015, NO_x emissions in 2015 could be 9.8 % lower than those measured in 2010; however, the effect of phasing out yellow-labeled vehicles will disappear in 2020 because these vehicles would normally be retired by then. According to the simulation results, implementing the state IV emission standards 1 year earlier could result in an increase in emission reductions by another 10–20 % by 2020.

5 Discussion

The results of this study show that vehicle emission standards have been effective in controlling vehicle emissions in China. Worldwide, vehicle emission standards are playing an irreplaceable role in vehicle emission control strategies in many countries. In some developed countries (e.g., the United States, European countries, and Japan) where vehicle activities are increasing very slowly or are even decreasing, national vehicle emissions have been decreasing significantly because of vehicle emission standards (Centre on Emission Inventories and Projections 2013; U.S. Environmental Protection Agency 2013). In the (U.S.), the CO, VOC, NO_x, and $PM_{2.5}$ emissions from highway vehicles in 2013 were 15, 13, 39, and 57 %, respectively, of those measured in 1970 (U.S. Environmental Protection Agency 2013). In China, vehicle activities (number of vehicles times the VKTs of each vehicle) will continue to increase rapidly in the future. Under current circumstances, implementing vehicle emission standards will be the most effective way to curb the growth in vehicle emissions, and the earlier the stricter standards are in place, the better the benefits that could be obtained will become. In addition, phasing out old vehicles can help accelerate emission reductions in the short term, which is especially important for China because there are still a large number of older, high-emission vehicles in operation. Meanwhile, identifying and eliminating malfunctioning super-emitters needs to be included in the vehicle control strategies at both the national and local levels, given the high contributions of these vehicles to total emissions.

Other measures, which are not simulated in this study, can affect vehicle emissions in different ways. Restrictions on vehicle sales and use can benefit the cities where these measures are in effect, but the benefit is relatively small within a national context. Measures such as utilizing new energy vehicles on a large scale and developing effective mass public transit systems require longer timelines for developing the required infrastructure but would be expected to deliver great benefits in the far future. Various economic measures should be considered to encourage the use of new energy vehicles and public transit tools, such as offering subsidies for purchasing new energy vehicles and providing discounts for monthly and annual public transit passes. In particular, improving logistics efficiency and reducing truck idling could help reduce vehicle emissions in China because diesel trucks contribute significantly to on-road NO_x and $PM_{2.5}$ emissions in China; therefore, such policies should be considered. In the future, the ultimate solution to controlling emissions from vehicles will rely not only on the diversity of fuel and vehicle technologies but also on better transportation management.

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