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RESEARCH ARTICLE

PM2.5 emissions from different types of heavy-duty truck: a case study and meta-analysis of the Beijing-Tianjin-Hebei region

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Abstract Beijing-Tianjin-Hebei (BTH) region in China is affected seriously by the hazy weather that has a large impact on human health. $PM_{2.5}$ is one of the most important reasons for hazy weather. Understanding the $PM_{2.5}$ emission characteristics from different types of heavy-duty trucks (HDTs) is valuable in policies and regulations to improve urban air quality and mitigate vehicle emission in China. The investigation and analysis on HDT population and $PM_{2.5}$ emission in BTH region are carried out. The results show that the population and $PM_{2.5}$ emission of HDTs in BTH has risen for the last four consecutive years, from 404 thousand and 1795 tons in 2012 to 551 thousand and 2303 tons in 2015. The $PM_{2.5}$ emission from HDTs in Hebei is about 10 times more than that of Beijing and 9 times more than that of Tianjin. The proportion of natural gas HDTs is about 5%; however, its $PM_{2.5}$ emission only accounts for 0.94% in 2015, which indicates the utilization of HDTs powered by natural gas facilitate $PM_{2.5}$ mitigation more than diesel in BTH. The tractor and pickup trucks are the main source of $PM_{2.5}$ emission from different types of HDT, while special and dump trucks are relatively clean. This study has provided insights for management method and policy-making of vehicle in terms of environmental demand.

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Introduction

With the rapid economic development of China, the vehicle population increases rapidly and motor vehicle emissions have become the most predominant source of air pollution in China, particularly in urban areas (Liang et al. 2014; Shen et al. 2014; Huo et al. 2012; Wen et al. 2016;Liang et al. 2012; Camuzeaux et al. 2015). Take an example of Beijing, there were 225 days with hazy weather, of which 46 days were severe pollution in 2015. $PM_{2.5}$, a particulate matter with an average diameter of 2.5 μm or less, is one of the most important reasons for hazy weather (Fann et al. 2012). Major components of $PM_{2.5}$ include sulfate, nitrate, ammonium, organic carbon, elemental carbon, and mineral dust. If there is no good weather condition, the heavy concentration of $PM_{2.5}$ has serious impact on human health and environment (Wu et al. 2015a; Lv et al. 2016). The emission from heavy-duty trucks is supposed to be a major contribution of ambient $PM_{2.5}$. Compared with light-duty vehicles, primary $PM_{2.5}$ emissions from heavy-duty vehicles can be over 1~2 orders of magnitude. Given such significant contribution to air pollution, it is of great importance to establish the vehicular emission inventory and study its characteristics. These would provide basis to control air pollution and develop mitigation strategies.

In order to minimize the emissions from the transportation sector, many studies have attempted to estimate the contribution of HDT on road transport. Several investigations on emissions of greenhouse gas (GHG), $PM_{2.5}$, PM_{10}, NO_x, SO_2, and other pollutants in Beijing, Tianjin, Shanghai, Guangzhou, Hebei, Macau, and Taiwan, were carried out in terms of MOBILE, IVE, and COPERT models. And then, the cases of control advice of vehicle emission were proposed after deep analysis. For example, policymakers should consider other effective technology options for vehicles to mitigate gaseous contaminant emissions and promote alternative fuel vehicles (Puttipong et al. 2015; Wu et al. 2016; Wu et al. 2015b; Zhang et al. 2014; Chen et al. 2007; Cao et al. 2016; Cheng et al. 2013). In addition, some researchers have monitored and tracked motor vehicles to analyze the composition, concentration and source of $PM_{2.5}$ (Shen et al. 2014a; Bishop et al. 2015).

American researchers pay more attention to energy consumption, air pollution, greenhouse effect, and health effect from different types of heavy truck (Tamayao et al. 2015; Henschel et al. 2015). In Europe, vehicle emissions of nitrogen were investigated and the trend of air quality development were also predicted (Beevers et al. 2012; Querol et al. 2014; Ehsan, B. and Vahid, H. 2016). In addition, the development prospects of light vehicles and natural gas vehicles' emission factors in India, Iran, Pakistan, and other Southeast Asia areas were analyzed (Nesamani, K.S. 2010; Khan, M. and Yasmin, T. 2014; Pramila, G. et al. 2013).

Among all different kinds of vehicles, heavy-duty truck is the most important source of pollutant emissions, and its influence on air quality is especially serious. So, figuring out the trend of population and $PM_{2.5}$ emission characteristics of heavy-duty trucks are crucial to adjust the energy structure and relevant policy in China.

In this paper, we select three different regions in China to measure HDT population and $PM_{2.5}$ emission. Beijing is the capital city of China. Tianjin is one of the four directly governed municipalities. Hebei is an important industrial province. Beijing-Tianjin-Hebei (BTH) region is the high-tech zone and the base of heavy industry in China with the largest vehicle stock shown. The problem of vehicular emission in this region is typical and representative in China.

The objective of this study is to investigate the $PM_{2.5}$ emission characteristics from different types of heavy-duty trucks in Beijing-Tianjin-Hebei during the period of 2012 to 2015. In the first place, the population and $PM_{2.5}$ emission of heavy-duty trucks in BTH are calculated and analyzed to estimate the development trend. In addition, the influences of fuel types on emission are investigated to indicate the emission characteristics of HDTs. At last, the emission characteristics from four types of HDT are analyzed to figure out emission reduction trend. The significant findings of this study would reflect market situation and development prospect in BTH. Furthermore, the study can help provide theoretical basis for policy-making scientifically.

Materials and methodology

$PM_{2.5}$ emission calculation

According to Eq. (1), the $PM_{2.5}$ emission of different municipalities or provinces in China was estimated utilizing the parameters of heavy-duty trucks population, $PM_{2.5}$ emission factor, and vehicle kilometer traveled (VKT) (Cai et al. 2007).

$$EQ_m = \sum_i \sum_j \left(P_{m,i,j} \times EF_i \times VKT_{m,j} \right) \quad (1)$$

where m represents the three areas (Beijing, Tianjin, Hebei); i means the type of fuels, including natural gas and diesel; j means the type of heavy-duty trucks, including the tractor unit, pickup truck, dump truck, and special concrete transport truck. EQ_m represents emission (g) of pollutant $PM_{2.5}$ in area m; $P_{m,i,j}$ is the population of type j heavy vehicle powered by fuel i in area m; EF_i is the emission factor (g/km) of $PM_{2.5}$ emitted from heavy-duty trucks with fuel i; $VKT_{m,j}$ is the average annual travel mileage (km) of type j heavy-duty trucks in area m.

Population and vehicle kilometer traveled

The retirement coefficient and average annual travel mileage are general and important parameters for heavy-duty trucks. There is no precise approach to estimate them currently, so the parameters are often set by local professional organizations in terms of different usage characteristics of heavy-duty trucks.

The investigation has been performed by China Automotive Technology and Research Center, Beijing Operations, which is an authoritative data research institute to obtain the retirement coefficients from four companies: Shaanxi Automobile Group Co., Ltd., Faw Jiefang Automotive Company, Dong Feng Commercial Vehicle Company, and China National Heavy Duty Truck Group Co, respectively. These four companies accounted for about 70% of the whole market share in 2015. According to the applications, heavy-duty trucks can be mainly classified into four types, which are tractor unit, pickup truck, dump truck, and special concrete transport truck. The retirement coefficient and average annual travel mileage of heavy-duty trucks from four companies in different applications are listed in Table 1.

We calculated HDTs' population based on a vehicle fleet model (Yan et al. 2011), which requires the estimates of average retirement coefficient and new registrations number. Detailed registration numbers of various types of trucks by calendar year in Beijing-Tianjin-Hebei were, respectively, provided by the Vehicle Administration Region. Meanwhile, based on the principle of minimum displacement, the minimum values of annual travel mileage are selected in Table 1.

Table 1 The key parameters of heavy-duty trucks (Xing et al. 2016)

	Tractor 	Pickup 	Special 	Dump 
Characteristics of usage	Fixed routes、good maintain etc.	Used by logistics company, high-frequency operation etc.	Short distance、 use within city etc.	Short distance、emergency shutdown、harsh working condition etc.
Average retirement coefficient（year）	8	10	10	3
Annual average kilometer（km）	150,000~200,000	≥200,000	30,000~60,000	80,000~100,000

$PM_{2.5}$ emission factor

Accurate emission factors of motor vehicles are essential for evaluating air pollutant emissions. COPERT is a Microsoft Windows software program which is developed as a European tool for calculation of emissions from the road transport sector.

Due to the emission standard of China adopting the European system, it is more suitable to use COPERT model to calculate emission factors in China (Fan et al. 2011). Some previous research had also proved that COPERT model was appropriate for vehicular emission evaluation in China (Wang et al. 2010; Ekström, M. and Sjödin, A. K. 2004). Sun have used COPERT model to estimate vehicle emission factors in Shandong, China from 2000 to 2014. Many types of pollutants (such as CO, NMVOC, NOx, PM_{10}, CO_2, CH_4, and N_2O) from each vehicle type (including passenger cars, light dutyvehicles, heavy-duty trucks, buses, and motorcycles) have been analyzed (Sun et al. 2016). José M has estimated for the evolution of CO, NOx, NMVOC, and PM emissions from on-road transportation in 1988–1999 in Spain by COPERT model (José et al. 2004).

Therefore, $PM_{2.5}$ emission factors of HDTs powered by diesel and natural gas in the BTH region were decided to calculate by this model. Some of the input data, such as climate parameters (temperatures, atmospheric pressure), fuel quality (mainly sulfur content) which is obtained from fuel standards, and average speed evaluation. From 2012 to 2015 all newly manufactured heavy-duty trucks must pass Chinese National Standard IV (European IV emission), as well as natural gas HDTs must pass Chinese National Standard V in BTH region.

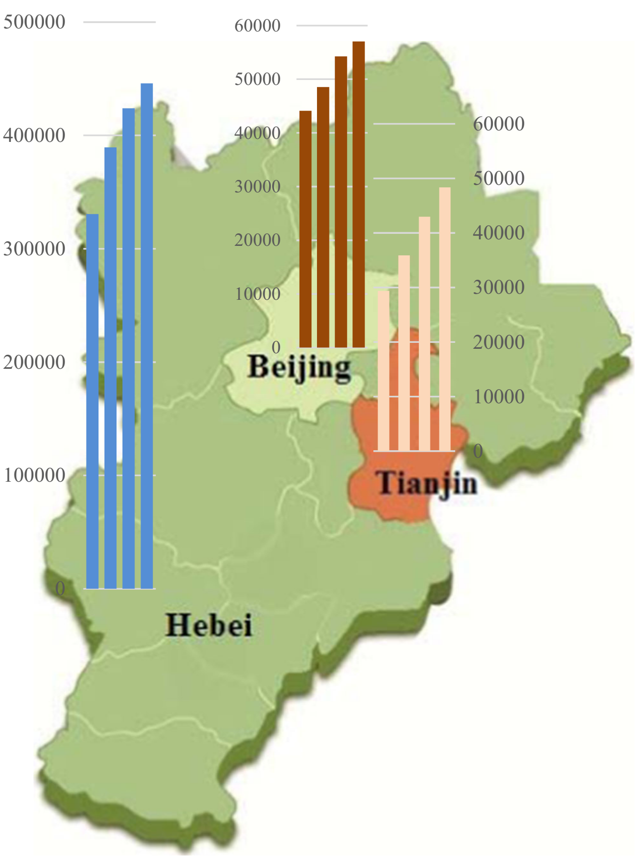

Fig. 1 The distribution of HDT population in 2015

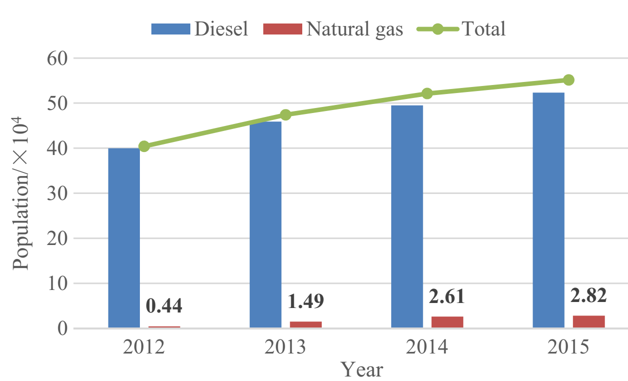

Fig. 2 Trend of heavy-duty truck population in BTH from 2012 to 2015

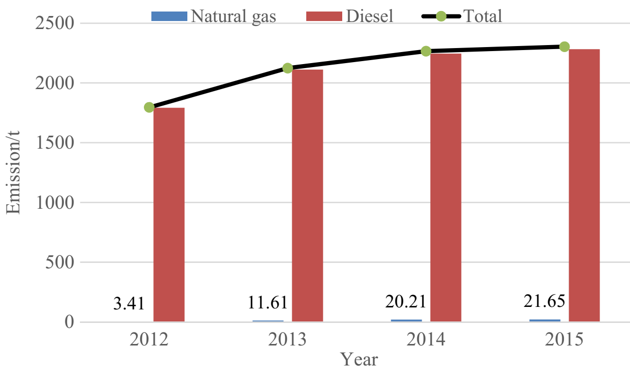

Fig. 3 Trend of heavy-duty truck $PM_{2.5}$ emission in BTH from 2012 to 2015

The emission factors of diesel HDTs are classified into different standards. From National Standard I to National Standard IV are 0.029, 0.027, 0.041, and 0.012 g/km, respectively. The value of National Standard III is relatively high. The reason is that compared to previous standard, the technology of catalytic converter in National Standard III is more difficult. This may cause the change of its emission factors. The results of different standard natural gas HDTs are exactly similar, so we adopt the same value of natural gas HDT emission factors in the following calculation, 0.0055 g/km. Besides, secondary PM is not accounted in this paper. Only the direct $PM_{2.5}$ emission of HDTs is taken into account in this article.

Results and discussion

The population of heavy-duty truck in BTH

Figure 1 shows the population of heavy-duty trucks in Beijing, Tianjin, and Hebei were 57 thousand, 48 thousand and 446 thousand in 2015 respectively. The population of heavy-duty trucks in Hebei occupied 81% in the whole BTH region in 2015, and is much higher than those of the other two regions, which is about 8 times more than that of Beijing and 9 times more than that of Tianjin.

Figure 2 illustrates the trend of population of heavy-duty trucks in Beijing-Tianjin-Hebei from 2012 to 2015. We can see that the total population has risen for the last four consecutive years. HDT population reached a high level of 551 thousand in 2015 and has risen 6% between 2012 and 2015. The population of diesel HDTs accounts for more than 90% during the fourth year. But the percentage of diesel HDTs has been decreased from 98.9% in 2012 to 94.9% in 2015. However, the HDT powered by diesel still occupied most of total population about 95%.

The $PM_{2.5}$ emission of heavy-duty truck in BTH

The trend of $PM_{2.5}$ emission of heavy-duty trucks in Beijing-Tianjin-Hebei from 2012 to 2015 has been estimated and shown in Fig. 3. During this period, the $PM_{2.5}$ emission of heavy-duty trucks has increased rapidly, from 1795 tons in 2012 to 2303 tons in 2015. But the change rate declines year by year and the annual average change rate were 15.15, 6.68, and 1.65% among 2012 to 2015, respectively. There are three main reasons to explain this trend. Firstly, the economic depression from 2012 leads to vehicle market decreases. In addition, the engine technology of natural gas vehicles has developed which could satisfy the customer's demand. At last, the natural gas price has no economic advantage since diesel price decreases a lot from the second half of 2014.

Figure 4 shows the $PM_{2.5}$ emission of heavy-duty trucks in Beijing, Tianjin and Hebei were 177.8 ton, 201.8 ton and

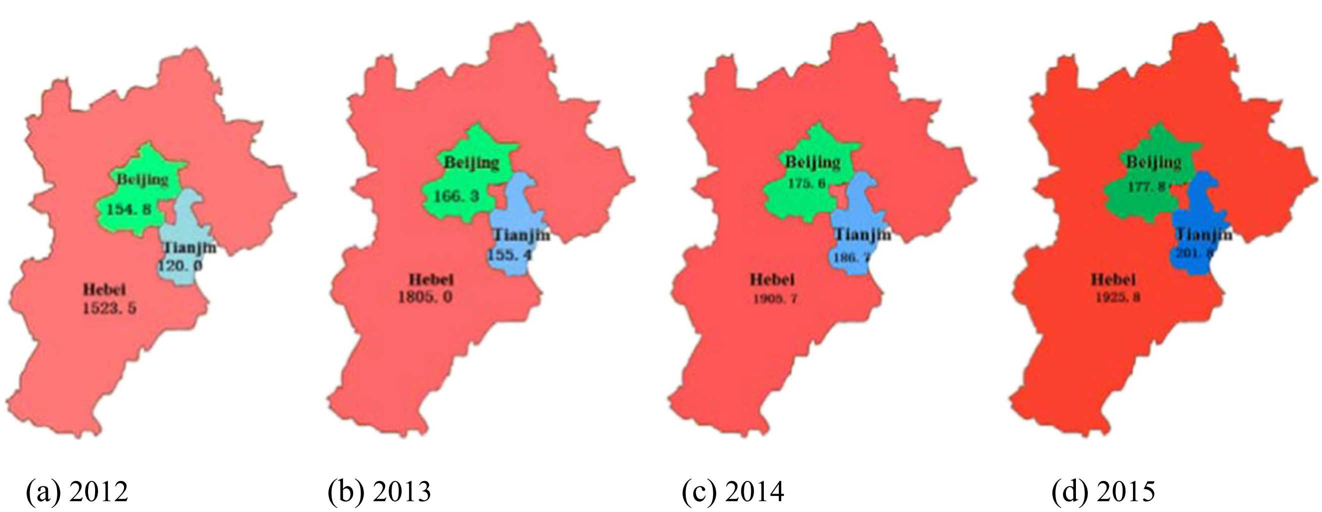

Fig. 4 The distribution of HDT $PM_{2.5}$ emission from 2012 to 2015

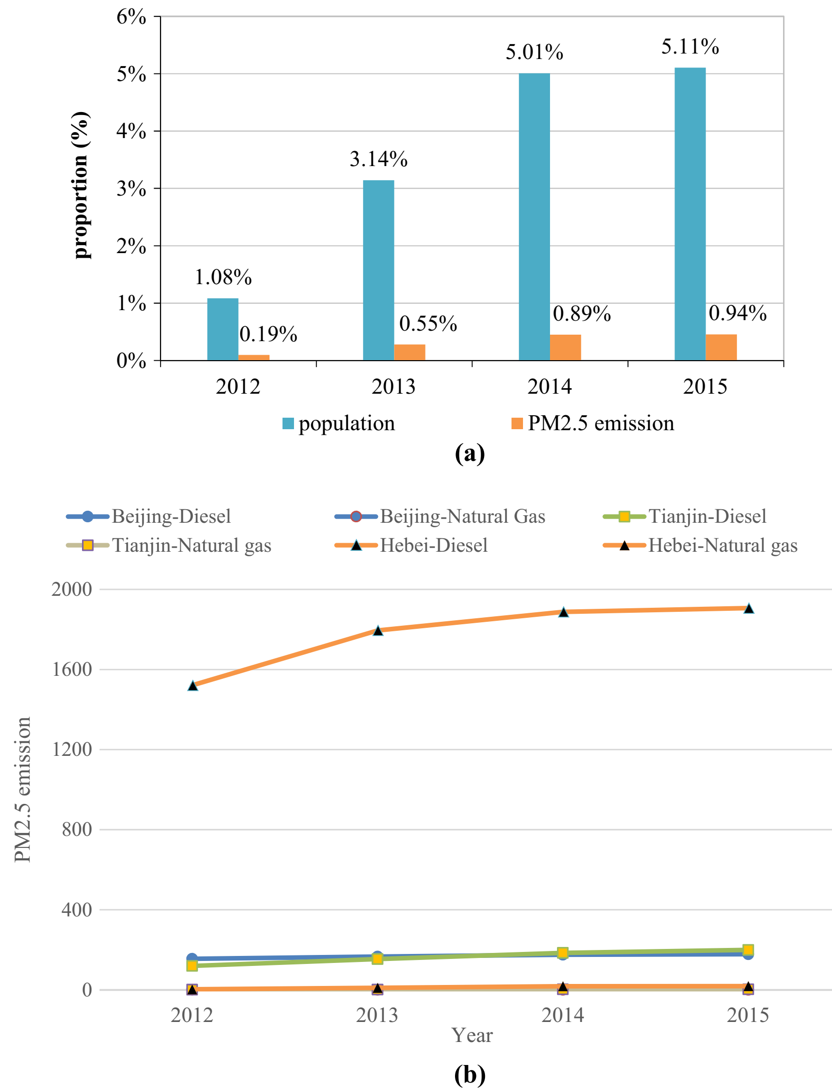

Fig. 5 The proportion of population and the amount of $PM_{2.5}$ emission of HDTs powered by natural gas in BTH

1925.8 ton in 2015, respectively. The $PM_{2.5}$ emission from HDT in Hebei is much higher than those of the other two regions, which is about 10 times more than that of Beijing and 9 times more than that of Tianjin. From 2012 to 2015, the percentage of $PM_{2.5}$ emission in Beijing and Tianjin has decreased gradually because of various policies on emission cutting, such as odd-and-even license plate rule, improvement of fuel standard (Li et al. 2014). Hebei mainly drives the air pollution in BTH region with its huge population, which accounts for over 80% of the overall $PM_{2.5}$ emission. In order to reduce the overall emission intensity of BTH region, there needs some measures to control $PM_{2.5}$ emission in Hebei.

The analysis of different fuel types of heavy-duty truck

The heavy-duty trucks are mainly powered by natural gas and diesel (Curran et al. 2014; Wang et al. 2008), and diesel motor vehicles contribute over 90% of the on-road PM emissions in China (Ministry of Environmental Protection of China, 2010). Fig. 5 shows the proportion of population and $PM_{2.5}$ emission of

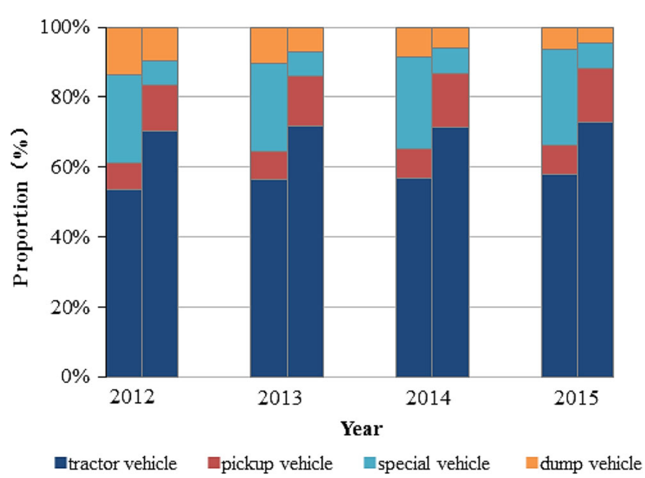

Fig. 6 The proportion of population and $PM_{2.5}$ emission of different types of HDTs in BTH

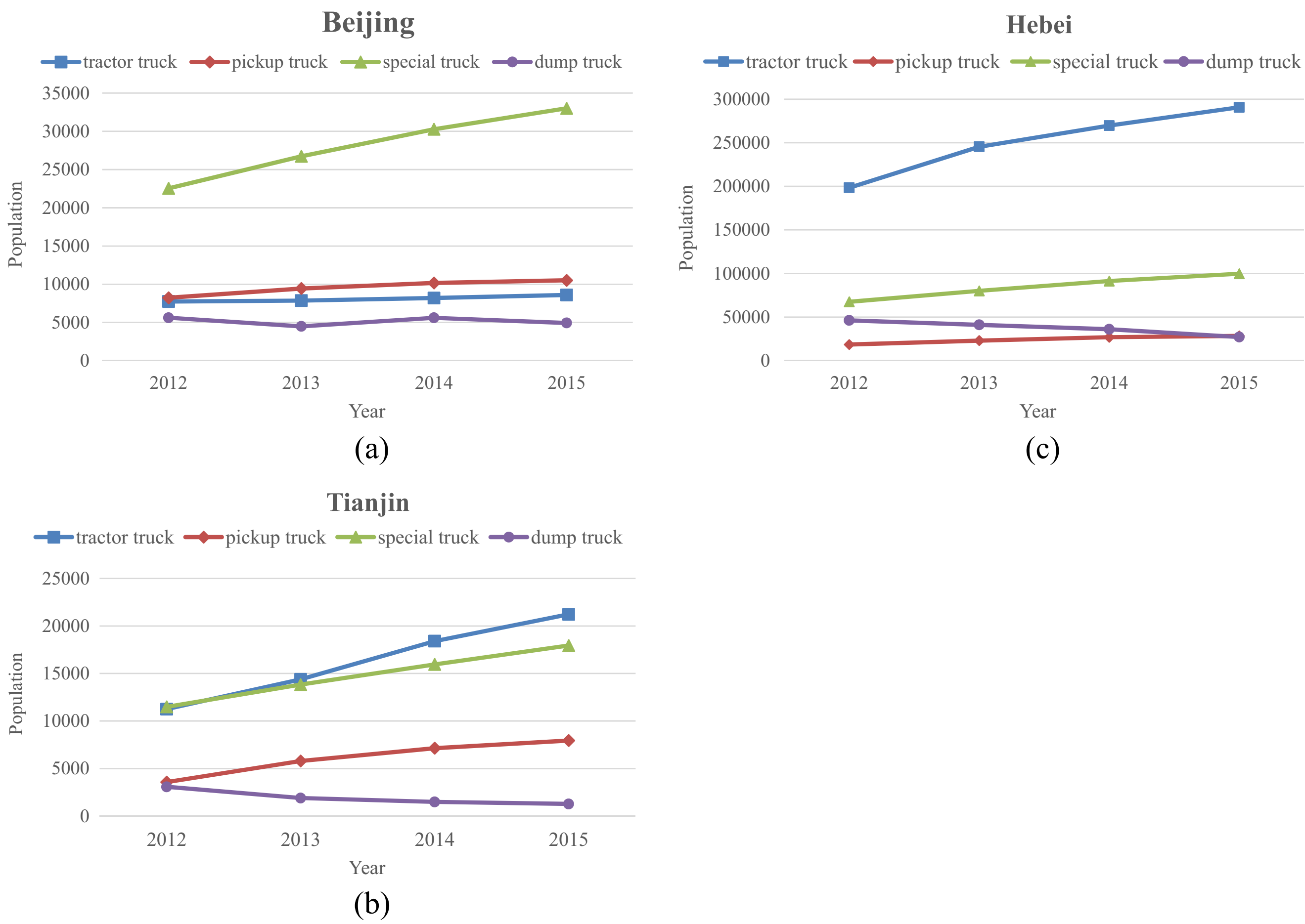

Fig. 7 The population of four types of HDT from 2012 to 2015

HDTs powered by natural gas in BTH from 2012 to 2015. We can see the population proportion of HDTs powered by natural gas exhibits a continuous growth trend from 1.08 to 5.11%, and the proportion of $PM_{2.5}$ emission from 0.19 to 0.94%. Conventional diesel trucks may mainly occupy the HDT market through 2050 (Askin et al. 2015). Combining with Fig. 1 and 3, we get the population of natural gas HDTs is 4.4 thousand, 14.9 thousand, 26.1 thousand and 28.2 thousand from 2012 to 2015; and the $PM_{2.5}$ emission was 3.41, 11.61, 20.21, and 21.65 tons, respectively. However, in urban areas of Beijing, only 43% of on-road $PM_{2.5}$ emissions come from diesel vehicles (Shen et al. 2014b). Because HDTs are tools of long-distance transportation, the values of VKT from HDTs are much higher on highways.

The growth of natural gas trucks may depend on some key economic and industrial uncertainties (Askin et al. 2015).The price of natural gas is the major factor that promotes the natural gas HDT market development. In 2012 and the first half of 2014, natural gas shows a lower price than diesel. As a result, the population of natural gas HDT turns up a growth rapidly. In the second half of 2014, the price of natural gas increased and diesel decreased, so HDTs powered by natural gas had no longer advantages in price. Thus, the population of natural gas trucks in 2015 is only 30 thousand more than 2014 with 0.1% increase shown in Fig. 5. Compared with its population and emission proportion in Fig. 5, $PM_{2.5}$ emission of natural gas HDTs accounts very small percentage. Therefore, HDTs powered by natural gas can effectively reduce $PM_{2.5}$ emission from comparison in Fig. 5. The results indicate that the utilization of HDTs powered by natural gas facilitate $PM_{2.5}$ mitigation more than diesel in BTH.

On the contrary, the population and $PM_{2.5}$ emission of heavy-duty trucks powered by diesel is much higher than natural gas. The population and $PM_{2.5}$ emission of diesel HDT was 523 thousand and 2281 tons in 2015, respectively.

The analysis of different types of heavy-duty trucks

Figure 6 displays the proportion of population and $PM_{2.5}$ emission of different types of heavy-duty trucks in Beijing-Tianjin-Hebei from 2012 to 2015. In the same year of the figure, the left histogram is the proportion of population and right is the proportion of $PM_{2.5}$ emission. We find the population of tractor, pickup, and special HDTs has increased every year since 2012, which has reached 320 respectively, and tractor vehicle takes a great proportion of the whole $PM_{2.5}$ emission.

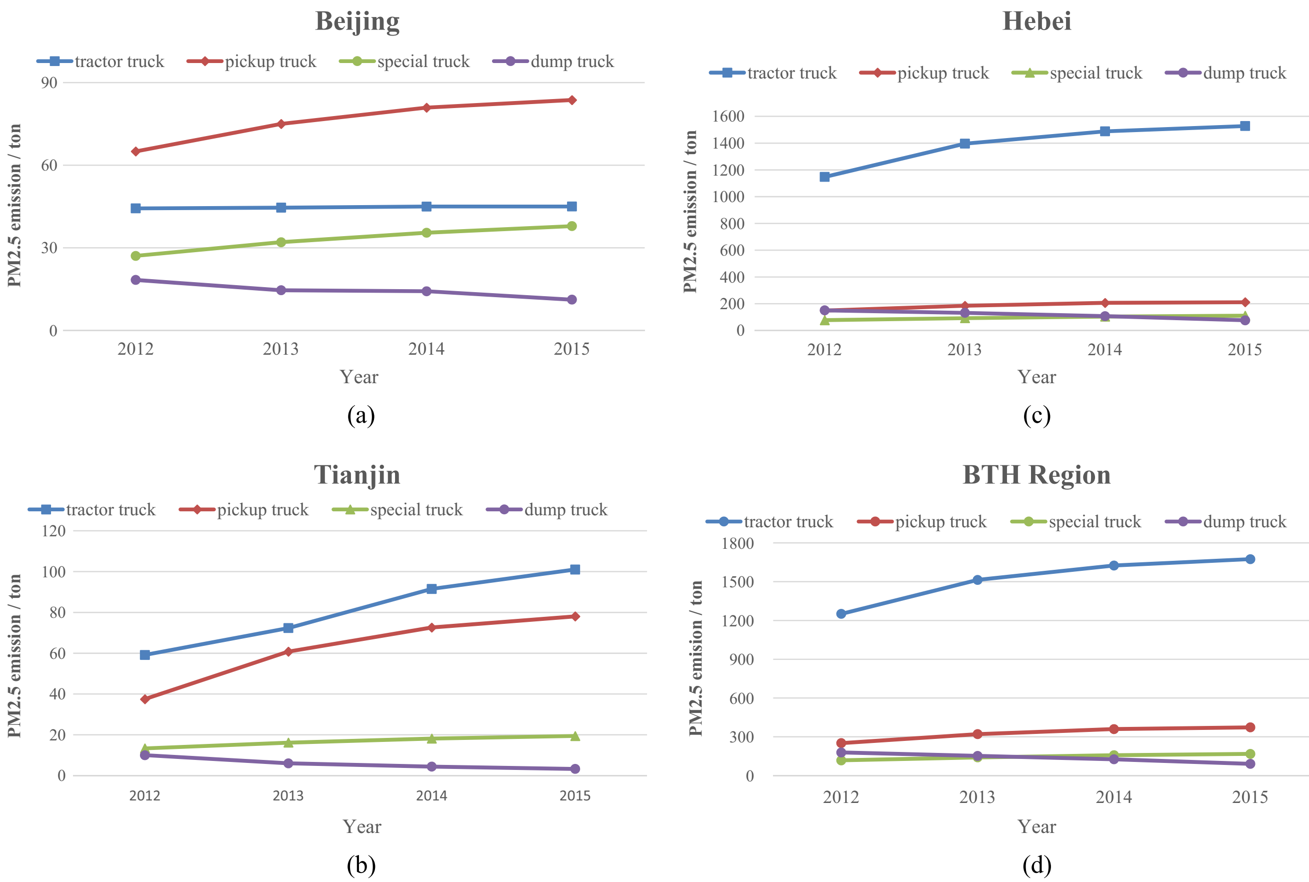

Fig. 8 $PM_{2.5}$ emission from four types of HDT from 2012 to 2015

Figure 7 shows four types of HDT population in Beijing, Tianjin, and Hebei of from year 2012 to 2015. In Beijing, the dominant HDT type was special vehicle about 33 thousands accounting for 57.86% of the whole market in 2015. In Tianjin, the population of market shares basically the same from tractor and special vehicle, representing 43.88% and 37.08% of total HDT market. In Hebei, Tractor vehicle occupies the main market share, accounting for 65.18%. The differences of the population proportions for various HDT types in Beijing, Tianjin and Hebei can also reflect the vehicle population constitution in different provinces/cities of China.

Figure 8 illustrates four types of HDT proportion of $PM_{2.5}$ emission in Beijing, Tianjin, and Hebei. In Beijing, pickup vehicle was the dominant source for $PM_{2.5}$ emission with a contribution of over 47% by the end of 2015. In Tianjin, tractor vehicle was the main source, and accounting for over 50% of the total HDT $PM_{2.5}$ emission in 2015. In Hebei, the tractor vehicle occupies the main emission share accounting for 73% in 2015.

From Figs. 6 to 8, we conclude that tractor and pickup vehicle are the main source of $PM_{2.5}$ emission from heavy-duty trucks, which has a great pollution on air condition. And special and dump vehicle is an effectively clean heavy-duty truck. Hebei has a significant effect on $PM_{2.5}$ emission in the total BTH region and should be governed seriously.

Uncertainty analysis

The uncertainty analysis is necessary because different emission factors for each species are under different fuel types. Emission factors come from the calculation through COPERT IV model. The estimated average annual mileage is from a practical investigation of four companies and is set as constant. Therefore, we set emission factors as variables. There are three procedures for calculating the uncertainty of each emission species. At first, the probability density function of emission factor is obtained by Eqs. (2) and (3).

$$f(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \frac{\exp\left(\frac{-(lnx-\mu)^2}{2\sigma x^2}\right)}{x} \tag{2}$$

$$\mu = \ln\left(\overline{x}\right) \tag{3}$$

x is the probability value of emission factors, f is the probability of x, μ is the logarithmic mean of input information, σ is the standard deviation of logarithmic x, and $\bar{x}$ is the value of the calculated emission factors. Besides, a Monte Carlo simulation with a 95% confidence interval has been carried out with the input of the probability density function of the emission factor.

The results indicate that the relative error for the uncertainty of $PM_{2.5}$ emissions is 21.47~29.53% with diesel and 73.67~81.32%with natural gas. The relative errors with natural gas HDTs are generally higher than those with diesel because the parameters of diesel HDTs are more accurate. Furthermore, the uncertainties of $PM_{2.5}$ emissions with natural gas HDTs are significant due to the difficulties of data acquisition.

As long as accuracy increases for the $PM_{2.5}$ emission factor with natural gas HDTs in the future, the results will become more reliable.

Conclusions

In recent years, BTH region is affected seriously by hazy weather, and there exists significant pressure to improve urban air quality and mitigate vehicle emission. This paper analyzed the trends of HDT population and $PM_{2.5}$ emissions of Beijing-Tianjin-Hebei region, as well as improved understanding of vehicle structure and emission characteristics.

The population and $PM_{2.5}$ emission of heavy-duty trucks in BTH has risen for the last four consecutive years, from 404 thousand and 1795 tons in 2012 to 551 thousand and 2303 ton in 2015, respectively. $PM_{2.5}$ emission from HDTs in Hebei is about 10 times more than that of Beijing and 9 times more than that of Tianjin.

From 2012 to 2015, HDTs powered by natural gas play an increasingly key role to meet global energy demand with population increase from 4.4 thousand to 28 thousand. Natural gas HDTs' proportion of $PM_{2.5}$ emission is much lower than its population, which indicates the utilization of natural gas HDT can effectively reduce $PM_{2.5}$ emission.

In Beijing, pickup trucks were dominant source for $PM_{2.5}$ emission, while Tianjin and Hebei was tractor trailer. Comparing the population and $PM_{2.5}$ emission proportion of four HDT types, we get tractor and pickup vehicle are the main source of $PM_{2.5}$ emission from heavy-duty trucks. On the contrary, special and dump vehicle are relatively clean.

This study has provided insights for management method and policymaking of vehicle in terms of environmental demand.

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