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Characterization of road freight transportation and its impact on the national emission inventory in China

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Abstract

Mobile source emission inventories serve as critical input for atmospheric chemical transport models, which are used to simulate air quality and understand the role of mobile source emissions. The significance of mobile sources is even more important in China because the country has the largest vehicle population in the world, and that population continues to grow rapidly. Estimating emissions from diesel trucks is a critical work in mobile source emission inventories due to the importance and difficulties associated with estimating emissions from diesel trucks. Although diesel trucks are major contributors of nitrogen oxide (NO_x) and primary particulate matter smaller than 2.5 µm ($PM_{2.5}$), there are still more obstacles on the existing estimation of diesel truck emissions compared with that of cars; long-range freight transportation activities are complicated, and much of the basic data remain unclear. Most of existing inventories were based on local registration number. However, according to our research, a large number of trucks are conducting long-distance inter-city or inter province transportation. Instead of the local registration number based approach, a road emission intensity-based (REIB) approach is introduced in this research. To provide efficient data for the REIB approach, 1060 questionnaire responses and approximately 1.7 million valid seconds of onboard GPS monitoring data were collected. Both the questionnaire answers and GPS monitoring results indicated that the driving conditions on different types of road have significant impacts on the emission levels of freight trucks.

We present estimated emissions of NO_x and primary $PM_{2.5}$ from diesel freight trucks for China in 2011. Using the REIB approach, the activity level and distribution data are obtained from the questionnaire answers. Emission factors are calculated with the International Vehicle Emission (IVE) model that interpolated local on-board measurement results in China according to the GPS monitoring data on different roads.

Depending on the results in this research, the largest differences among the emission factors (in g km^{-1}) on different roads exceed 70 and 50 % for NO_x and $PM_{2.5}$, respectively. The differences were caused by different driving conditions that we monitored

via GPS. The estimated NO_x and $PM_{2.5}$ emissions from diesel freight trucks in China were 5.0 (4.8–7.2) million t and 0.20 (0.17–0.22) million t, respectively, via the REIB approach in 2011. Another implication of this research is that different road infrastructure would have different impacts for NO_x and $PM_{2.5}$ emissions. A region with more inter-city freeways or national roads tends to have more NO_x emissions, while urban streets play a more important role in primary $PM_{2.5}$ emissions from freight trucks. Compared with former studies, which allocate emissions according to local truck registration number and neglect inter-region long distance transport trips, the REIB approach has advantages regarding the allocation of diesel truck emissions into the provinces. Furthermore, the different driving conditions on the different roads types are no longer overlooked with this approach.

1 Introduction

China has been facing severe air quality challenges in the past several years. Air pollution in China not only endangers the health of billions of people but also creates a substantial burden on the economy (Matus et al., 2012). The 2005 marginal welfare impact to China, considering only ozone and particular matter, was US$112 billion (1997 US$) (Hammitt and Zhou, 2006). Vehicular emissions form one of the greatest contributors to the air pollution in China, especially for NO_x and $PM_{2.5}$. According to the Ministry of Environmental Protection (MEP), vehicular emissions contributed 27.4 % of the total NO_x emissions in 2012 (MEP, 2012a). Vehicle emissions also contribute more than 30 % of $PM_{2.5}$ in Beijing, as announced by the Beijing government.

Preparing inventories is essential to the assessment and management of current atmospheric problems (Ohara et al., 2007; Streets et al., 2003; Beaton et al., 1995). Previous work has set up inventories for the different types of pollutants from the different sources. Among all the sources, the mobile source is one with the greatest uncertainty and ambiguity (Cai and Xie, 2007; Wang et al., 2008a). Among all the vehicles, diesel freight trucks contributed to a large portion of vehicular emissions. According to

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the MEP, diesel vehicles, mainly consisting of freight trucks, contributed 70 % of NO_x and 90 % of PM in the total vehicular emissions in 2012 (MEP, 2013). Most research in freight truck emissions, including both measurement and evaluation, was conducted in or focused on urban areas (Cheng et al., 2006; Wu et al., 2010; Liu et al., 2009; Chen et al., 2007; Huang et al., 2013). However, the fact is that in large cities, such as Shanghai, Beijing and Guangzhou, where most research is studied, restrictions over diesel trucks are notably tight; only a small number of permitted trucks, usually low emitters, are allowed to run in the urban area only during a certain time period, mostly late night. Therefore, the conclusions from former research may be partly biased by placing excessive emphasis on the urban emissions.

Another major impediment to developing a new approach to estimate freight truck emissions is that most inventories were based on the local registration numbers, which means there is an assumption that trucks are running within the province or city where they registered (Zheng et al., 2013). However, according to this research, many trucks are conducting long-distance inter-city or inter-province transportation trips. Therefore, a road-based estimate approach was introduced in this research instead of the former local registration number based approach. This simulation addresses more on the freight transportation system as a whole rather than a local emissions scale.

In summary, we attempt to identify and reduce the impact of the factors mentioned above by adopting a road-based approach with collected activity level data including both questionnaire answers and GPS records. In particular, this research serves to (i) provide more accurate activity level data for freight trucks including mileage traveled vs. age, activity regions and driving conditions, (ii) identify the different emission rates caused by different driving conditions on each type of road and (iii) provide a national emissions inventory that considers the road freight system as whole instead of separating it into different pieces according to the province divisions.

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2 Data and methodology

2.1 Data source

The data source of this research primarily consists of two major parts: (1) questionnaires that investigated the driving behavior of professional truck drivers, along with experiential data that related to their driving pattern. (2) Driving condition tests of trucks driving on different types of roads. Information about the questionnaires and GPS data, such as the sample numbers and location range, is shown in Table 1.

A series of questions related to driving pattern, fuel consumption, route selection, transport range, etc. were included in the questionnaires. All the investigated drivers are professional freight truck drivers. Because most of the freight truck drivers are not highly educated, all the questionnaires were conducted by college students, and a detailed explanation was required to make sure that the drivers understood the question correctly. To ensure the quality of the answers, related questions that validate each other are designed to wipe out careless or wrong answers. A total of 1060 samples from 16 provinces were investigated. Therefore, it is a large sample study according to the theory of statistics (Box et al., 2005). Previous studies on driver behavior in China also conducted questionnaire investigations. For example, 520 samples, which were targeted at all automobile drivers and not limited to trucks, were studied in 2002 to understand the behavior of drivers (Xie and Parker, 2002). Another 87 completed samples were used to make comparisons between China and Hong Kong in 2009 (Chan et al., 2009). Questionnaires are also used on truck drivers in Australia ($N = 433$), Germany ($N = 10\,101$), Brazil ($N = 4878$) and New Zealand (1065) for different purposes (Sullman et al., 2002; Lajunen et al., 2004; Moreno et al., 2006, 2004). Compared with other sample sizes of domestic and foreign studies on truck drivers, the number of samples in this study is adequate to describe the average level of freight truck activities.

According to weight, the trucks are classified into four types: Mini Trucks (MiniT) with weights less than 1.8 t, light duty trucks (LDT) with weights of 1.8–6 t, middle duty trucks (MDT) with weights of 6–14 t and heavy duty trucks (HDT) with weights greater

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than 14 ton. The classification follows how the National Bureau of Statistics reports the vehicle stock (CATARC, 2012). Because the MiniT population only consists of a very small proportion of the total truck fleet and the differences between MiniT and LDT are not significant, MiniTs and LDTs are grouped together in the calculation of emission factors.

Because the normal method to testing driving patterns focuses on driving in cities, this method can hardly be applied to freight trucks; a freight truck has significant operation differences with that of a private passenger car (Holguin-Veras et al., 2006; Kamakaté and Schipper, 2009). Freight trucks in China generally travel inter-cities and do not stop for extended time periods, except for a small portion that run inside cities for short distance freight transit or other special public service (like garbage collection or road sprinkler) (Hine et al., 1995). To obtain the real time driving patterns of freight trucks, a Global Positioning System (GPS) receiver and speed sensor were used. For many years, GPS has been used to monitor the driving conditions of vehicles in many emission related studies (Ochieng et al., 2003; Rakha et al., 2004; Canagaratna et al., 2004). A multifunction Columbus GPS data logger V-990 produced by GPSWebShop (Canada) Incorporation was used in this research. The data were collected every second when the engine of the investigated truck is on.

The investigated trucks were all driven by professional truck drivers during the tested time period. The GPS data logger was required to be used for at least one week to record the full driving pattern of the freight trucks. All drivers maintained their business as usual during the test time period. In total, 1 728 622 valid seconds from 16 trucks with different load capacities and functions were tested. All of the tested data were classified into five different types according to the road type they were on. The road type is identified by Google Map. The roads are divided into 5 classifications: urban roads, rural/town road, provincial roads, national roads and inter-city freeways. Typical speed tracks and routes of each type of the tested roads are shown in Fig. 1. To present the speed distribution in a same scale, only the first 4000 s of speed are shown in Fig. 1.

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For urban road, there are only 3989 s of data, and it represents the longest single trip in urban area that was monitored in this research.

2.2 Emission rates and emission factors

Vehicle-specific power (VSP) is a concept that is designed to describe the working conditions, such as aerodynamic drag, acceleration, rolling resistance and hill climbing, of a vehicle and is used in the evaluation of vehicle emissions (Jimenez-Palacios, 1998). VSP is now widely used in emission factor modeling, such as in the IVE and MOVES models. For the VSP calculation, the equation for heavy duty diesel trucks (HDDTs) from the MOVES model was applied in this study (Eq. 1).

$$\mathrm{VSP} = \frac{A}{m} \cdot v + \frac{B}{m} \cdot v^2 + \frac{C}{m} \cdot v^3 + a \cdot v + gv \cdot \sin\theta \tag{1}$$

where m is the vehicle weight, t; v is the instantaneous vehicle speed, $\mathrm{m\,s^{-1}}$; a is the instantaneous vehicle acceleration, $\mathrm{m\,s^{-2}}$; θ is the road grade, radians; A is the rolling resistance coefficient, $\mathrm{kW\,s\,m^{-1}}$; B is the rotational resistance coefficient, $\mathrm{kW\,s^{-2}\,m^{-2}}$; and C is the aerodynamic drag coefficient, $\mathrm{kW\,s^{-3}\,m^{-3}}$. The road-load coefficients (i.e., A, B and C) by each major category are shown in Table 2. The coefficients were estimated according to the typical weight type used in Motor Vehicle Emission Simulator (MOVES) model (Koupal et al., 2005).

Engine stress (ES), which includes 25 s historical VSP data, was introduced by emission models such as International Vehicle Emission (IVE) model to represent how early running conditions impact current emissions. ES is calculated in following equation (Eq. 2) from the IVE model (CE-CERT et al., 2008):

$$\mathrm{ES} = \mathrm{RPMIndex} + (0.08\,\mathrm{t\,kW^{-1}}) \times \mathrm{PreaveragePower} \tag{2}$$

where PreaveragePower is the average VSP during −5 to −25 s, $\mathrm{kW\,t^{-1}}$; RPMIndex is the $\mathrm{Velocity}_{t=0}$/SpeedDivider, unitless; and the minimum RPMIndex is 0.9. The detailed SpeedDivider is shown in Supplement Table S1.

Operating mode bins are identified according to the VSP and ES. One-second on-board measurement data from Liu et al., Wu et al. and the Vehicle Emission Control Center of China (VECC) was used to calculate a representative emission rate for each bin according to the IVE model (Liu et al., 2009; Zhang et al., 2013; Wang et al., 2012). With GPS monitoring data from tested trucks in this research, the second-by-second emissions rate for each vehicle technology can be calculated following earlier studies. The distance-specific emission factors can be calculated with the following equation (Eq. 3):

$$EF_{i,j} = \frac{1000 \cdot \sum_t ER_{i,j,t}}{\sum_t v_{i,j,t}} \quad (3)$$

where EF is the distance-specific emission factor, $g\,km^{-1}$; ER is the second-by-second emission rate, $g\,s^{-1}$; and v is the velocity. The subscripts i, j and t represent road type, type of tested truck and time, respectively.

2.3 Setting up the regional emission inventory

Top-down approaches are widely used in estimating anthropogenic emissions for a relatively large geographic range. According to the annual vehicle population numbers from the China's Automotive Industrial Statistics Yearbook (CATARC, 2012) and the survival curve from a former study (Hao et al., 2011), details about the existing vehicle population, such as the portion of trucks at different ages and weight, can be calculated. Following the Yearbook, the trucks were divided into 4 types according to their GVW (shown in Table 2). In addition, the annual VKT (vehicle kilometer traveled) of trucks at different ages is acquired from the investigation. Combining the fleet information and the VKT data together yields the total activity level number.

In this research, a new road emission intensity based (REIB) approach was introduced to calculate the regional emission inventory of diesel trucks. Instead of relying on local registration numbers, the road emission intensity served as the base of the REIB approach. The basic assumption for REIB is that for freight trucks, the driving conditions and truck flow were similar on the same type of road in different regions. The emission intensity of different types of road was calculated according to the activity distribution obtained from this research. Then, the emissions in each grid cell or province could be calculated according to the length of different types of road. Unlike former approaches that assumed that trucks ran limitedly in the region where they are registered, the REIB approach examines the road freight transportation as a whole nationwide system. The REIB approach is a better fit, given the fact that a large portion of trucks run across provinces. In the GPS monitoring conducted in this research, the longest single trip traveled across 8 provinces. The local registration based approach introduced great inaccuracy by overlooking the cross region trips of freight trucks.

Different types of truck were investigated to determine their traveling information. The drivers were asked to estimate the distance portion that they drive on different types of roads. In this study, the roads are classified into freeway, national roads, provincial roads, rural roads, urban roads and other special roads such as those within factories and ports. Then, the emission density of different types of roads was calculated according to following equation (Eq. 4):

$$\rho_i = \frac{\sum_{j,k} \overline{\mathrm{VKT}}_{j,k} \cdot \mathrm{NV}_{\mathrm{current\_year}\,k,j} \cdot \mathrm{SR}_{j,k} \cdot \mathrm{EF}_{i,j,k} \cdot \mathrm{DP}_{i,j}}{L_i} \tag{4}$$

where ρ_i is the emission density of i type road, $\mathrm{g\,km^{-1}\,year^{-1}}$; $\overline{\mathrm{VKT}}_{j,k}$ is the average VKT per vehicle, $\mathrm{km\,year^{-1}}$; $\mathrm{NV}_{\mathrm{current\_year}\,k,j}$ is the new vehicle population of type j k years ago; $\mathrm{SR}_{j,k}$ is the survival rate of a k year-old type j vehicle; $\mathrm{DP}_{i,j}$ is the distance portion for type j truck running on type i road; and L_i is the total length of type i road in China, km. The subscript k refers to the age of a vehicle. The remaining variables are the same as described above.

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With the emission density number, the national emissions inventory can be calculated according to the spatial distribution of different types of road. In this research, multi-dimensions of inventories have been created to present the spatial distribution of freight truck emissions.

3 Results and discussion

3.1 Activity level of freight trucks

Freight trucks with different ages were investigated in this research. According to a former study, the total distance that a passenger car traveled has a quadratic relationship vs. its age (Liu et al., 2008). This relationship means that as the passenger car ages, the mileage traveled per year decreases. According to the investigated samples in this study, the average total kilometers that a truck traveled also follow the similar pattern (shown in Fig. 2). With an R-square value of 0.9651, the empirical quadratic equation is adequate to describe the average activity level. The standard error in this research is relatively high, revealing large variation among the trucks of the same age. This significant variation is caused by the diversity of functions of different trucks, which makes the investigation in truck activity a tough task. However, this research founded an acceptable empirical summary for trucks at different ages. Moreover, unlike former research that used average mileage traveled for the entire fleet (Huo et al., 2012b; Fu et al., 2001), these results here represent the aging effect of trucks, which is that the annual mileage decreases as the truck grows older. By neglecting the annual mileage reduction as trucks age, the impact of old trucks may be exaggerated because they do not actually run as much as newer trucks. Therefore, this investigation will help to identify the contribution of trucks under different ages more accurately.

Moreover, a revision factor according to the vehicle type was introduced to identify the differences between each type of truck shown in Table 2. Heavier trucks tend to run more mileage on average because heavier trucks are more economic in long-distance freight transportation. Smaller and lighter trucks are more frequently used in short distance transport for their flexibility.

Both the mileage traveled and emission rates for trucks at different ages are different. Therefore, it is required to have the detailed age composition of truck fleet in the target year. The truck fleet composition is calculated following the Eq. (5):

$$\mathrm{FP}_{i,j} = \mathrm{NP}_{2011-i,j} \times \mathrm{SR}_{i,j} \quad (5)$$

where $\mathrm{FP}_{i,j}$ is the truck that came online i year ago in the current fleet; $\mathrm{NP}_{2011-i,j}$ is the new vehicle population of type j truck in $2011-i$ year, from the National Bureau of Statistics (CATARC, 2012); and $\mathrm{SR}_{i,j}$ is the survival rate of j type truck that has run i year, from nationwide vehicle survival pattern research (Hao et al., 2011).

The fleet composition and the total mileage traveled in 2011 by vehicle age are shown in Fig. 3a and b. The total diesel truck population in 2011 reached 193.3 million, of which 53 % came online during 2009–2011 and therefore meet the China 3 tailpipe emissions standard. Different from the vehicle population, the total mileage contributed by the China 3 trucks reaches 60 % because new trucks are more frequently used. A total of 1.47 trillion kilometers were conducted by diesel freight trucks in 2011. The large portion of new vehicles in both population number and mileage traveled indicates that the application of stricter emissions standards has great significance because China is experiencing a booming in its truck population. However, the application of the China 4 emissions standard on diesel vehicles has been delayed because oil companies in China were unable to supply diesel that met the standard (Zhang et al., 2012). Considering the booming increase of new diesel trucks and the large share of them in the total mileage traveled, the impact of the delay of upgrading the emissions standard would be highly significant.

One of the challenges in mapping the emissions of freight trucks is that it is hard to identify where the trucks are running. The problem is more challenging with trucks rather than other types of automotive because trucks are not limited to their registration region as cars are nor do they have fixed routes as buses do. In the questionnaires

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conducted in this research, the professional truck drivers estimated the length proportions they drive on different types of road. The length proportions of roads that trucks run on is summarized into different groups according to their GVW, as in Fig. 4. As Fig. 4 shows, we determined that different types of trucks tend to have different running patterns. It is obvious that heavier trucks are more likely to run on the high speed freeways; heavy duty trucks are generally employed for long distance transportation because it is more economical than lighter carriers. For long distance transportation, high speed freeways are the primary options for the drivers. On the contrary, inside an urban area, mini trucks and light duty trucks are more common given their flexibility and also possible constrictions on heavy duty trucks. This result is used to estimate the truck flow and fleet composition and to assign total kilometers traveled for each type of truck. The mileage and fleet information on each type of road are inputs for the calculation of emission intensity. The differences of fleet compositions between the different types of road have long been overlooked in past inventory work.

3.2 Different driving characters on different types of roads

Trucks with different weights usually serve different purposes. This consequently leads to different driving patterns of the different types of trucks. According to the research results, the annual mileage traveled and average speed have significant differences among the different types of trucks.

Generally, heavier trucks ran at higher speeds and traveled greater mileage than lighter trucks. This behavior is due to the varying main function of trucks with different load capacities. Heavier trucks are usually used for long-distance transportation to reduce average cost, which means heavier trucks operate more on high-speed roads. Lighter trucks run more on urban roads given their flexibility. The differences in the time portions from running on each type of road by the different levels of trucks are shown in Fig. 4. These differences will lead to different driving patterns for the different types of trucks. As shown in Fig. 1, the speed records on selected routes for each type of road were quite different from each other. For the tested route on the G93 Freeway, the

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average speed was maintained at approximately 70 km h^{-1}, and the stop times (when the speed reaches zero) were rare. It indicated that the traffic flow on the G93 Freeway during the tested time was very fluent. For the tested routes on the G309 National Road and S343 Provincial Road, the speed hardly exceeded 70 km h^{-1}, and the stops and sudden drops in speed were more frequent than on the G93 Freeway. Although the speed distributions on the G309 and S434 looked similar, the speed on the S434 obviously fluctuated more frequently than that on the G309. This revealed that the driving conditions on these two roads were similar, while traffic flow on the G309 was more fluent. For the urban road in Changsha City, Hunan, it was difficult for the truck to reach 40 km h^{-1} during the tested time. Stops were much more frequent than on former roads potentially due to traffic lights and traffic jams within the city. As for the country road between two villages in Shandong, the driving conditions were the worst among all the roads. The maximum speed during the tested time period was 40 km h^{-1}, and 85.5 % of time the speed stayed below 20 km h^{-1}. In summary, as what we can see from the selected examples of the different types of roads, the driving conditions were distinctly different.

To demonstrate that the differences were not special cases, a statistic summary was made to see whether significant differences could be found in the large amount of data that we collected. The velocity and acceleration distributions for the total monitored data on urban roads (226 290 valid seconds) and freeways (583 922 valid seconds) are shown in Fig. 5 as selected examples to illustrate the differences between the running conditions on these two types of roads. (Monitoring data on other roads are shown in Supplement Fig. S1–S3.) Velocity and acceleration are divided into several bins, and the frequency of each bin is calculated. Velocity is divided into 30 bins from 0–30 m s^{-1}, and acceleration is divided into 7 bins from –1.5 to 2 m s^{-2}.

The results show two obvious different running conditions on the urban roads and inter-city freeway. The average speed and the maximum speed on the urban road are much lower than that on the inter-city freeways. Additionally, the urban road has much greater low-speed-running and idling time. If the high peak of the low-speed zone is

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removed, the speed distribution on the urban road is relatively flat with the range from 5 to 20 $m\,s^{-1}$. On the other hand, the situation on the inter-city freeway is quite different. There are two peaks on the inter-city freeway: a smaller peak in the lower speed zone and a larger peak in the high speed zone. The percentage of the middle speed is very low. From the results, it shows that the difference is still significant considering all the collected data from different roads and trucks. Because both velocity and acceleration will affect the vehicle specific power and engine stress, different velocity and acceleration distributions will lead to different emission results. Without considering the differences in emission factors caused by the different driving conditions, uncertainties and inaccuracy were introduced to former vehicular emissions inventory research. In the upcoming section, the differences in emission factors on the different roads will be discussed.

3.3 Emission differences caused by different driving cycles on each type of road

As discussed in the previous section, different driving cycles on the different types of road lead to different emission factors for the different roads. The IVE model is a widely accepted tool to estimate vehicle emissions, and former research in China has already localized the IVE model so that it applies to the Chinese vehicles. The IVE model uses velocity and VSP as two inputs and classifies the driving conditions into different bins. For each bin, a measured typical emission factor is used to represent the average emission level. The distribution of bins on each type of road is shown in Fig. 4, and the emission factors that are derived for each type of the road using the IVE model are shown in Table 2. As introduced in Sect. 2.2, on-board measurement data in China was used to calculate the average emission factor on the different types of road with real time monitoring GPS data. The results are shown in Fig. 6.

From the results, it can be concluded that different running conditions on different types of road lead to significant differences in the emission factors. Generally, rural or town areas tend to have the worst conditions for diesel freight trucks. In almost all

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the cases, the emission factors for both NO_x and $PM_{2.5}$ on rural or town roads are the largest among the 5 types of roads. This is mainly due to the long idling time without shutting down the engine on the rural or town roads while loading or unloading. Generally, the highest emission factor is 73.5 and 51.2 % higher than the lowest one for NO_x and $PM_{2.5}$, respectively. These significant differences will lead to equivalent scaling errors in the total emissions of freight trucks. Generally, the emission factors are tested on urban or suburban roads where the driving conditions are relatively worse, leading to a higher emission factor. However, inter-city national, provincial road and freeway are also important places where many freight trucks run, especially those with heavier gross vehicle weights. This means the former study has over-estimated the emissions from freight trucks, because when running on inter-city roads or freeways, trucks have a lower emission factor due to better running conditions.

3.4 Emission inventory of freight trucks

According to this research, the total NO_x from freight trucks in 2011 was 5 000 000 t. This NO_x number is a little higher than the MEP's estimation of 3 900 000 t NO_x emissions from trucks in 2011 (MEP, 2012b). The difference was mainly caused by the failure to control NO_x emissions of freight trucks in China. Although the emissions standard in China has been improved to China 3, which is equivalent to Euro 3, on-board NO_x measurements indicated that the emission factor for diesel trucks had not improved significantly compared with China 2 (Wu et al., 2012; Liu et al., 2009). If the emission factors from foreign models such as IVE and MOBILE model were used, the emissions of NO_x will be underestimated. In fact, NO_x reduction from diesel trucks was not as successful as expected.

On the other hand, the primary $PM_{2.5}$ emissions from diesel trucks in 2011 were 200 000 ts. According to the MEP, the total $PM_{2.5}$ emissions from the truck fleet were 460 000 t in 2011 (MEP, 2012a). Compared with these results, the $PM_{2.5}$ emissions calculated in this research are significantly lower. A major reason for this lower result is that we included the decreasing trend of mileage traveled by trucks per year in this calculation. In addition, $PM_{2.5}$ emissions from older trucks (Euro 0 and Euro 1) are significantly higher than those from newer trucks. If the average mileages traveled by trucks with different age were fixed, the calculated $PM_{2.5}$ emissions would increase 50 %, exceeding 300 000 ton. In China, overloading was common for commercial trucks. This accelerated the deterioration of trucks, which means older trucks had to run less due to deteriorated performance and more frequent repair and maintenance. This is not such a large problem for NO_x because the NO_x emission factor did not improve as significantly as that for $PM_{2.5}$. Without considering the reduction of annual mileage as trucks age, the emissions from old trucks were exaggerated.

Figure 7 shows the NO_x and $PM_{2.5}$ emissions from trucks of different ages in the 2011 fleet. For both NO_x and $PM_{2.5}$, heavy duty trucks accounted for over 70 % of the total emissions despite only counting for 26 % of the total population. Hence, focus should be placed on controlling the emissions from heavy duty trucks. If the age of trucks is considered, the trucks that went into the market during 2009–2011 accounted for 40 % of the total population and 60 % of the total mileage traveled due to the mushrooming sales and the greater activity of new vehicles. This means the tightening of the emissions standard for new vehicles plays a critical role in the vehicular emissions control section. Moreover, the Yellow Label Vehicle, which means the pre-China 3 emissions standard diesel vehicles, has a more significant contribution to primary $PM_{2.5}$ emissions than NO_x.

Figure 8 shows the emissions distribution calculated according to the emission intensity of the different types of roads in the eastern part of China, where the major emissions occurred, with a resolution of $0.5^{\circ} \times 0.5^{\circ}$ per cell. Unlike approaches that are based on the local registration numbers of trucks, the approach applied in this research relies on the assumption that the traffic volume of freight trucks on each type of road remains similar. This approach views the freight transport in the nation as a whole system. From the emissions map and the emission intensity comparison, the freeways and national roads, where most of the freight transportation in China is conducted, have large emission intensities and emission impacts on their surroundings.

From Fig. 8, freight transportation has the strongest impact in locations where the economy is well developed and the population has high density. The Beijing-Tianjin-Hebei (Jing-Jin-Ji) district, Yangzi River Delta and Pear River Delta, the three biggest economic circles in China, are also the regions with highest emission density. From another perspective, 12 out of the 13 key control regions listed in the 12th Five Year Plan (FYP) of Air Pollution Control in China have relatively high emission densities, as shown in Fig. 8 (MEP et al., 2012). (The remaining key region, Urumqi and its surroundings in the Xinjiang province, which is not shown in the East China map, is also a hot spot of freight emission.) Therefore, the significance of controlling emissions from diesel freight trucks is greater considering the high impact on the air quality and human health in the key regions.

Figure 9 shows more detailed emissions inventories of diesel freight trucks in the three biggest economic circles, Jing-Jin-Ji, Yangzi River Delta and Pearl River Delta, with a resolution of $0.1^{\circ} \times 0.1^{\circ}$ per cell. The emission map indicated that cities with developed road networks and their surroundings suffered the greatest from the emissions of freight trucks. The distributions in the three districts were not the same. Pearl River Delta had the highest density of emissions. The high emissions area is close to Guangzhou and Shenzhen, the core cities in PRD. Meanwhile in Yangzi River Delta, the emissions are much more dispersive due to the large numbers of cities with high economic growth and well developed road networks. From the differences in the emission distribution, we can conclude that emissions from freight trucks in PRD are more aggregate. Therefore, controlling diesel freight truck emissions in YRD would be more challenging because more cities are needed to be involved in the control strategy.

The provincial level NO_x and $PM_{2.5}$ emissions from road freight transportation are shown in Fig. 10a and b, respectively. For both NO_x and $PM_{2.5}$, Shandong and Guangdong, where most of the freight transportation in China is conducted, take the leading positions in freight truck emissions. The NO_x and $PM_{2.5}$ emissions in these two provinces exceeded 600 000 t and 25 000 t, respectively.

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In the report published by MEP (2012a), the largest contributor of both NO_x and $PM_{2.5}$ in China during 2011 was Hebei province. However, Shandong contributed the most road freight emissions in 2011 according to this research. This difference was caused by the methodology on which the inventory was based. As discussed earlier, the registration number based approaches have a significant bias because trucks are not limited to the province where they are registered. Therefore, a province with the largest registration number of trucks might not have the most freight transportation. According to the China Statistics Bureau, Shandong has the greatest cargo volume and cargo turnover volume in the road transportation sector (Bureau, 2012). These data verified our assumption from a different perspective. Therefore, the former approach would be inaccurate without considering that the real range of truck activities might be different from the place where they are registered.

Observing the amount of emissions for the different provinces in China, the rankings for NO_x and $PM_{2.5}$ are not the same. This means that the differences in driving conditions could lead to different results in NO_x and $PM_{2.5}$ emissions. For example, Henan is the 3rd largest province in NO_x emissions, but it ranks 5th in $PM_{2.5}$ emissions among all the provinces, exceeded by the Jiangsu and Hebei provinces. Other similar provinces, such as Inner Mongolia (IMAR), Hubei and Guangxi, are significant contributors in the NO_x emissions sector but not the $PM_{2.5}$ sector. There are also provinces that are the opposite. $PM_{2.5}$ emissions from freight trucks in Shanxi, Heilongjiang and Jilin rank obviously higher than they do for NO_x emissions. Different running conditions on the different types of road will influence the emission factors for NO_x and $PM_{2.5}$ differently. Therefore, the road infrastructure structure will affect local emissions. Places that have more inter-city roads, such as inter-city freeways or national roads, are inclined to contribute more to NO_x emissions because the better running conditions means complete combustion, which brings up the NO_x level. A region that has a larger portion of urban roads than others tends to contribute more to $PM_{2.5}$ because incomplete combustion of the truck's engine on urban roads increases the formation of $PM_{2.5}$. In former inventories which calculated the emission on the basis of the local registration number of trucks, the ranks for the different pollutants in different provinces were the same. The registration number based inventories were unable to differentiate the distribution patterns for the different pollutants.

3.5 Uncertainty analysis

Monte Carlo simulation is used to quantify the uncertainty in both NO_x and primary $PM_{2.5}$ emissions from diesel freight trucks. Monte Carlo methods are widely used in identifying uncertainties in emission inventories (Hammersley and Handscomb, 1964; Sawyer et al., 2000; Wang et al., 2008b). The simulation is based on activity data and emission factors variety distribution. The statistical distributions of the input parameters are determined according to the data collection in this research or related published literature (Zhang et al., 2013; Huo et al., 2012a). The uncertainties of the input parameters are listed in Table 3. The distribution of the inputs follows normal distribution. The trials of the simulation were set to 100 000 times.

The overall uncertainties in this inventory are estimated at −24.1 to 44.7 % for NO_x emissions and −16.3 to 31.3 % for primary $PM_{2.5}$ emissions. The uncertainty is significant compared with other types of anthropogenic emissions because the uncertainties in both activity level and emission factor of mobile sources are more significant than other types of sources. The greatest uncertainties in the simulation are the uncertainties of emission factors of freight trucks. The uncertainties were significant during the test procedure. The emission data from the on-board measurement of diesel freight truck emissions has significant variances, which even reached 100 % in some cases (Huo et al., 2012a). In this research, comprehensive research into the activity levels of freight trucks was conducted to minimize the uncertainties in activity level. The new REIB approach also reduced the uncertainties in the distribution of freight truck activity. Further improvements can be achieved by more accurate measurements on emission factors.

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4 Conclusions

We presented a REIB approach to estimate NO_x and $PM_{2.5}$ emissions in China, 2011. The estimated emissions inventory may be used to forecast and evaluate the impact of road freight transportation on air quality in China. Unlike approaches that are based on the local registration numbers of trucks, the REIB approach views the freight system as a whole nationwide system. The activity of freight trucks is distributed according to the development and infrastructure of the local road system. The REIB approach is feasible in the freight transportation sector, because in many cases, freight trucks conduct long-distance trips across several provinces, neglecting where they are registered. The distribution of emissions among the different provinces has significant differences compared with the former research that was based on local registration numbers. However, the REIB approach would be less efficient when applied to the passenger car sector because private cars tend to have a more local range of activity.

According to the GPS monitoring results, the driving conditions on the different types of road are different for trucks. These differences would lead to significant variances in emission factors. According to the simulation results by the IVE model that were interpolated with local on-board test data in China, the differences between the emission factors from different types of trucks of same emissions standard could reach as high as 70 and 50 % for NO_x and $PM_{2.5}$, respectively. Uncertainties in emission factors are the major drivers of the total uncertainty in the emissions inventory of diesel freight trucks. The improvements of emission factors on the different roads reduce the uncertainty and inaccuracy of diesel freight truck emissions.

In 2011, the diesel truck fleet emitted 5.0 (4.8–7.2) million t NO_x and 0.20 (0.17–0.22) million t primary $PM_{2.5}$ in China. Moreover, places with the highest diesel freight truck emission density are the regions that have most severe air quality problem. In addition, 12 out of the 13 key air quality control areas listed in the 12th FYP of Air Pollution Control in Key Regions have high densities of truck emissions. Therefore, controlling diesel truck emissions plays a critical role in the air quality control plan in China.

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According to our emission distribution in 2011 of the fleet by vehicle age, promoting more stringent emission standard on new trucks is more efficient than eliminating the old Yellow Label Trucks. However, the fact is that the Chinese government postponed the application of the China 4 diesel truck emissions standard nationwide several times in the past few years.

Our research also indicates the uncertainties in freight truck emissions are approximately −24.1 to +44.7 % for NO_x and −16.3 to +31.3 % for $PM_{2.5}$. The uncertainties mainly come from the uncertainties in the emission factors from on-board measurements. Via improvements in specifying the emission factors to road type levels, this research reduced the uncertainties in freight truck inventories.

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References

Beaton, S. P., Bishop, G. A., Zhang, Y., Ashbaugh, L. L., Lawson, D. R., and Stedman, D. H.: On-road vehicle emissions: regulations, costs, and benefits, Science, 268, 991–993, 1995.

Box, G. E., Hunter, J. S., and Hunter, W. G.: Statistics for Experimenters, Wiley, New York, 2005.

Cai, H. and Xie, S.: Estimation of vehicular emission inventories in China from 1980 to 2005, Atmos. Environ., 41, 8963–8979, 2007.

Canagaratna, M. R., Jayne, J. T., Ghertner, D. A., Herndon, S., Shi, Q., Jimenez, J. L., Silva, P. J., Williams, P., Lanni, T., and Drewnick, F.: Chase studies of particulate emissions from in-use New York City vehicles, Aerosol Sci. Tech., 38, 555–573, 2004.

CATARC: China Automotive Industry Yearbook, China Industry Press, Beijing, 2012.
Chan, A. P., Lam, P. T., Chan, D. W., Cheung, E., and Ke, Y.: Drivers for adopting public private partnerships – empirical comparison between China and Hong Kong special administrative region, J. Constr. Eng. M. ASCE, 135, 1115–1124, 2009.
Chen, C., Huang, C., Jing, Q., Wang, H., Pan, H., Li, L., Zhao, J., Dai, Y., Huang, H., and Schipper, L.: On-road emission characteristics of heavy-duty diesel vehicles in Shanghai, Atmos. Environ., 41, 5334–5344, 2007.
Cheng, Y., Lee, S., Ho, K., and Louie, P.: On-road particulate matter ($PM_{2.5}$) and gaseous emissions in the Shing Mun Tunnel, Hong Kong, Atmos. Environ., 40, 4235–4245, 2006.
Fu, L., Hao, J., He, D., He, K., and Li, P.: Assessment of vehicular pollution in China, J. Air Waste Manage., 51, 658–668, 2001.
Hammersley, J. M. and Handscomb, D. C.: Monte Carlo Methods, Springer, Chapman and Hall, London, 1964.
Hammitt, J. K. and Zhou, Y.: The economic value of air-pollution-related health risks in China: a contingent valuation study, Environmental and Resource Economics, 33, 399–423, 2006.
Hao, H., Wang, H., Ouyang, M., and Cheng, F.: Vehicle survival patterns in China, Science China Technological Sciences, 54, 625–629, 2011.
Hine, J., Barton, A., Guojing, C., and Wenlong, W.: The scope for improving the efficiency of road freight transport in china, 7th World Conference on Transport Research, Sidney, Australia, July 1995, 1995.
Holguin-Veras, J., Wang, Q., Xu, N., Ozbay, K., Cetin, M., and Polimeni, J.: The impacts of time of day pricing on the behavior of freight carriers in a congested urban area: implications to road pricing, Transport. Res. A-Pol., 40, 744–766, 2006.
Huang, C., Lou, D., Hu, Z., Feng, Q., Chen, Y., Chen, C., Tan, P., and Yao, D.: A PEMS study of the emissions of gaseous pollutants and ultrafine particles from gasoline- and diesel-fueled vehicles, Atmos. Environ., 77, 703–710, doi:10.1016/j.atmosenv.2013.05.059, 2013.
Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., and He, K.: On-board measurements of emissions from diesel trucks in five cities in China, Atmos. Environ., 54, 159–167, doi:10.1016/j.atmosenv.2012.01.068, 2012a.
Huo, H., Zhang, Q., He, K., Yao, Z., and Wang, M.: Vehicle-use intensity in China: current status and future trend, Energ. Policy, 43, 6–16, doi:10.1016/j.enpol.2011.09.019, 2012b.
CE-CERT (Center for Environmental Research and Technology, College of Engineering, University of California at Riverside), GSSR (Global Sustainable Systems Research), ISSRC

(the International Sustainable Systems Research Center): IVE Model User Manual: Version 2.0 Attachment B and Attachment C. available at: www.issrc.org/ive (last access: 1 May 2014), 2008.
Jimenez-Palacios, J. L.: Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing, Massachusetts Institute of Technology, Cambridge, 1998.
Kamakaté, F. and Schipper, L.: Trends in truck freight energy use and carbon emissions in selected OECD countries from 1973 to 2005, Energ. Policy, 37, 3743–3751, 2009.
Koupal, J., Landman, L., Nam, E., Warila, J., Scarbro, C., Glover, E., and Giannelli, R.: MOVES2004 energy and emission inputs (Draft report). Prepared for US Environmental Protection Agency, EPA-420-P-05-003, Washington, DC, 2005.
Lajunen, T., Parker, D., and Summala, H.: The Manchester Driver Behaviour Questionnaire: a cross-cultural study, Accident Anal. Prev., 36, 231–238, doi:10.1016/S0001-4575(02)00152-5, 2004.
Liu, H., He, K., and Wang, Q.: Vehicular emissions inventory and influencing factors in Tianjin, Journal-Tsinghua University, 48, 370 pp., 2008.
Liu, H., He, K., Lents, J. M., Wang, Q., and Tolvett, S.: Characteristics of diesel truck emission in China based on portable emissions measurement systems, Environ. Sci. Technol., 43, 9507–9511, 2009.
Matus, K., Nam, K.-M., Selin, N. E., Lamsal, L. N., Reilly, J. M., and Paltsev, S.: Health damages from air pollution in China, Global Environ. Chang., 22, 55–66, 2012.
Moreno, C., Carvalho, F., Lorenzi, C., Matuzaki, L., Prezotti, S., Bighetti, P., Louzada, F., and Lorenzi-Filho, G.: High risk for obstructive sleep apnea in truck drivers estimated by the Berlin questionnaire: prevalence and associated factors, Chronobiol. Int., 21, 871–879, 2004.
Moreno, C., Louzada, F., Teixeira, L., Borges, F., and Lorenzi-Filho, G.: Short sleep is associated with obesity among truck drivers, Chronobiol. Int., 23, 1295–1303, 2006.
Ochieng, W., Polak, J., Noland, R., Park, J.-Y., Zhao, L., Briggs, D., Gulliver, J., Crookell, A., Evans, R., and Walker, M.: Integration of GPS and dead reckoning for real-time vehicle performance and emissions monitoring, GPS Solut., 6, 229–241, 2003.
Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, Atmos. Chem. Phys., 7, 4419–4444, doi:10.5194/acp-7-4419-2007, 2007.

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Rakha, H., Ahn, K., and Trani, A.: Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions, Transport. Res. D-Tr. E., 9, 49–74, 2004.

Sawyer, R. F., Harley, R. A., Cadle, S. H., Norbeck, J. M., Slott, R., and Bravo, H. A.: Mobile sources critical review: 1998 NARSTO assessment, Atmos. Environ., 34, 2161–2181, doi:10.1016/s1352-2310(99)00463-x, 2000.

Streets, D., Bond, T., Carmichael, G., Fernandes, S., Fu, Q., He, D., Klimont, Z., Nelson, S., Tsai, N., and Wang, M. Q.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, J. Geophys. Res.-Atmos., 108, GTE30.1–GTE30.23, 2003.

Sullman, M. J. M., Meadows, M. L., and Pajo, K. B.: Aberrant driving behaviours amongst New Zealand truck drivers, Transport. Res. F-Traf., 5, 217–232, doi:10.1016/S1369-8478(02)00019-0, 2002.

Wang, H., Chen, C., Huang, C., and Fu, L.: On-road vehicle emission inventory and its uncertainty analysis for Shanghai, China, Sci. Total Environ., 398, 60–67, doi:10.1016/j.scitotenv.2008.01.038, 2008a.

Wang, H., Chen, C., Huang, C., and Fu, L.: On-road vehicle emission inventory and its uncertainty analysis for Shanghai, China, Sci. Total Environ., 398, 60–67, 2008b.

Wang, X., Westerdahl, D., Hu, J., Wu, Y., Yin, H., Pan, X., and Max Zhang, K.: On-road diesel vehicle emission factors for nitrogen oxides and black carbon in two Chinese cities, Atmos. Environ., 46, 45–55, doi:10.1016/j.atmosenv.2011.10.033, 2012.

Wu, Y., Wang, R., Zhou, Y., Lin, B., Fu, L., He, K., and Hao, J.: On-road vehicle emission control in Beijing: past, present, and future†, Environ. Sci. Technol., 45, 147–153, doi:10.1021/es1014289, 2010.

Wu, Y., Zhang, S. J., Li, M. L., Ge, Y. S., Shu, J. W., Zhou, Y., Xu, Y. Y., Hu, J. N., Liu, H., Fu, L. X., He, K. B., and Hao, J. M.: The challenge to NO_x emission control for heavy-duty diesel vehicles in China, Atmos. Chem. Phys., 12, 9365–9379, doi:10.5194/acp-12-9365-2012, 2012.

Xie, C.-Q. and Parker, D.: A social psychological approach to driving violations in two Chinese cities, Transport. Res- F-Traf., 5, 293–308, 2002.

Zhang, Q., He, K., and Huo, H.: Policy: cleaning China's air, Nature, 484, 161–162, 2012.

Zhang, S., Wu, Y., Wu, X., Li, M., Ge, Y., Liang, B., Xu, Y., Zhou, Y., Liu, H., and Fu, L.: Historic and future trends of vehicle emissions in Beijing, 1998–2020: a policy assessment for the most stringent vehicle emission control program in China, Atmos. Environ., 89, 216–229, doi:10.1016/j.atmosenv.2013.12.002, 2013.

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Zheng, B., Huo, H., Zhang, Q., Yao, Z. L., Wang, X. T., Yang, X. F., Liu, H., and He, K. B.: A new vehicle emission inventory for China with high spatial and temporal resolution, Atmos. Chem. Phys. Discuss., 13, 32005–32052, doi:10.5194/acpd-13-32005-2013, 2013.

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Table 1. Data information.

Data	Sample numbers	Region	Test Time
Questionnaires	1060	16 provinces	Aug 2012–Aug 2013
GPS data	16 trucks/1 728 622 valid seconds	15 provinces	Aug 2013–Oct 2013

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Table 2. Summary of road-load coefficient values for calculating VSP of each major HDDT category.

Vehicle type	MiniT LIGHT	LDT LIGHT	MDT HEAVY	HDT HEAVY
GVW (tonne)	≦ 1.6	1.6 and 6	6 and 14	> 14
Mileage Correction Factor	0.145	0.475	1.278	2.713
Typical GVW (tonne)	3.3	10.2	17.6	
A/m	0.102	0.0875	0.0661	
B/m	0.00131	0	0	
C/m	0.000322	0.000248	0.000207	

Note: with reference to the MOVES model, those vehicle types and coefficients are estimated according to the typical gross vehicle weight (GVW) (Koupal et al., 2005). The classification of truck type is explained in Sect. 2.3.

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Table 3. Uncertainties scales of inputs.

Stock	Annual Kilometer	Emission Factor		Mileage
	Traveled	NO_x	$PM_{2.5}$	Distribution
2 %	15 %	−41 to +79 %	−31 to +58 %	5 %

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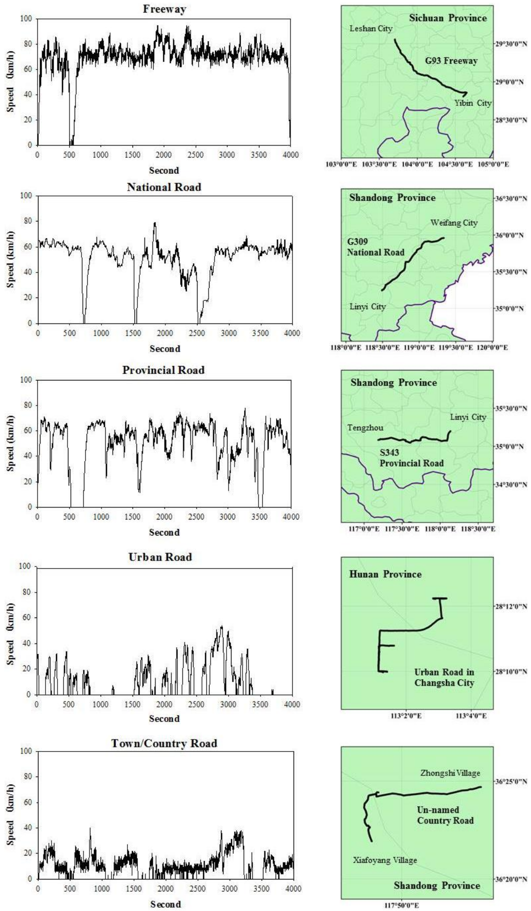

Figure 1. Speed and route of different types of tested roads.

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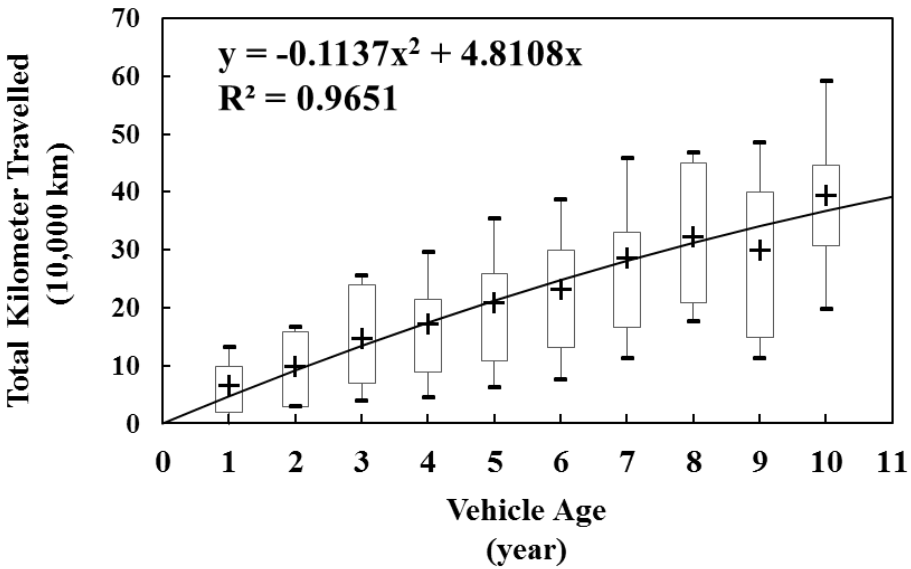

Figure 2. Accumulated traveled distance of trucks under different ages. (The boxes show the 1st and 3rd quartiles of the total investigated numbers and the bars show the standard errors.)

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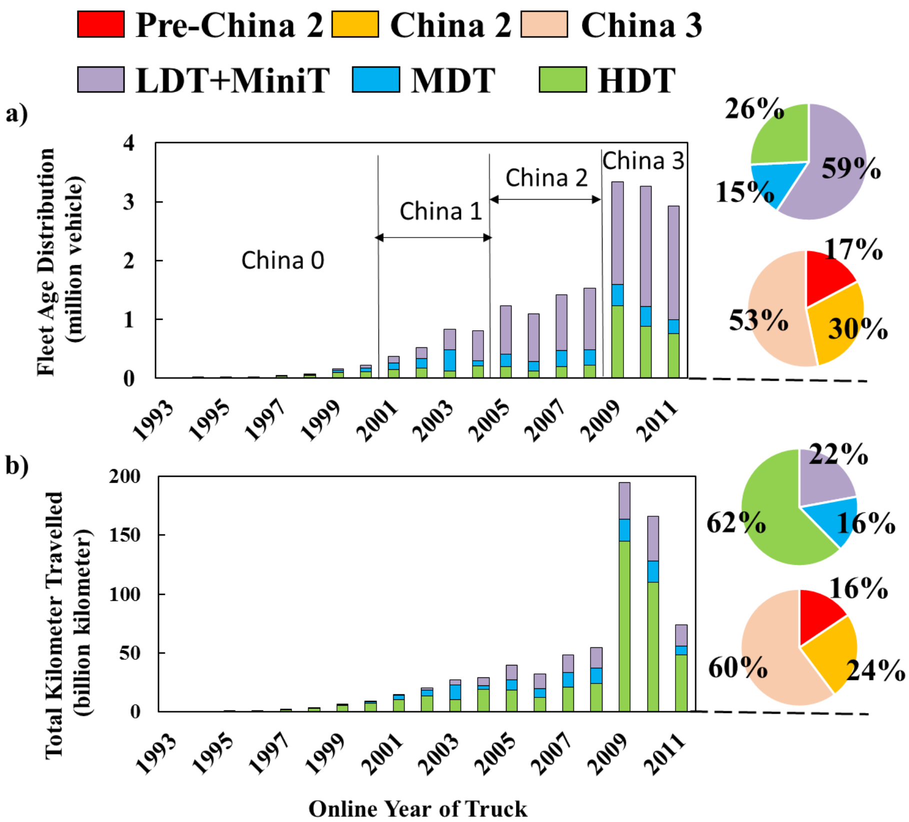

Figure 3. Age and total mileage traveled distribution of the diesel truck fleet in 2011, China: **(a)** vehicle population; **(b)** to tal mileage.

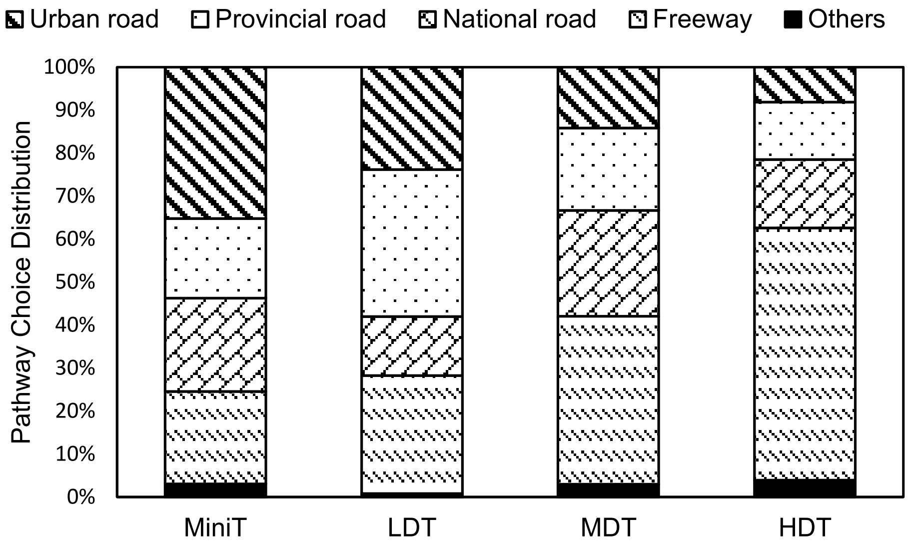

Figure 4. Proportion of running time on different types of roads.

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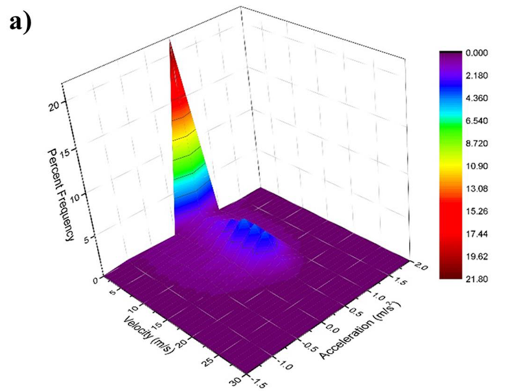
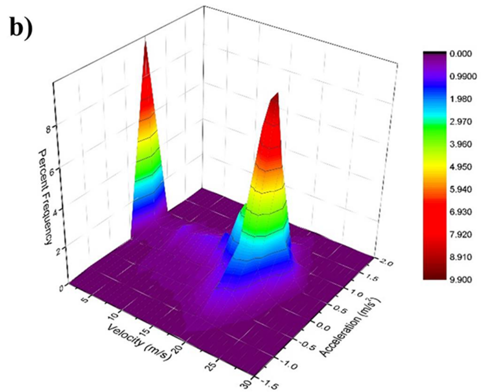


a） Velocity and Acceleration Distribution on Urban Roads



b） Velocity and Acceleration Distribution on the Inter-city Freeway

Figure 5. Velocity and VSP distribution on each type of roads: **(a)** urban roads **(b)** inter-city freeway.

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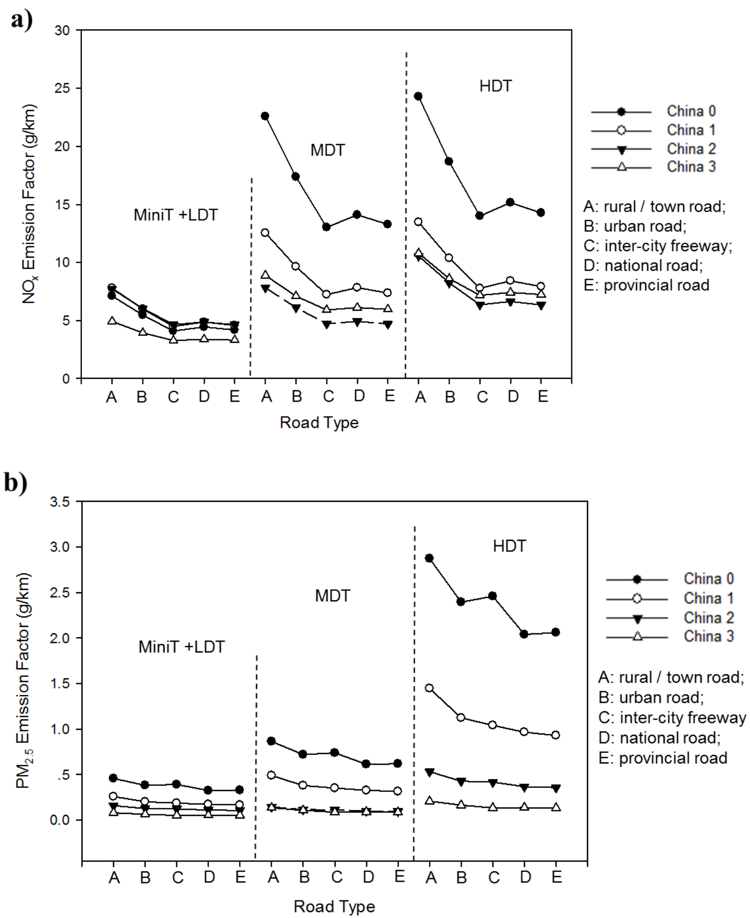

Figure 6. Emission factors on different roads **(a)** NO_x emission factors; **(b)** $PM_{2.5}$ emission factors.

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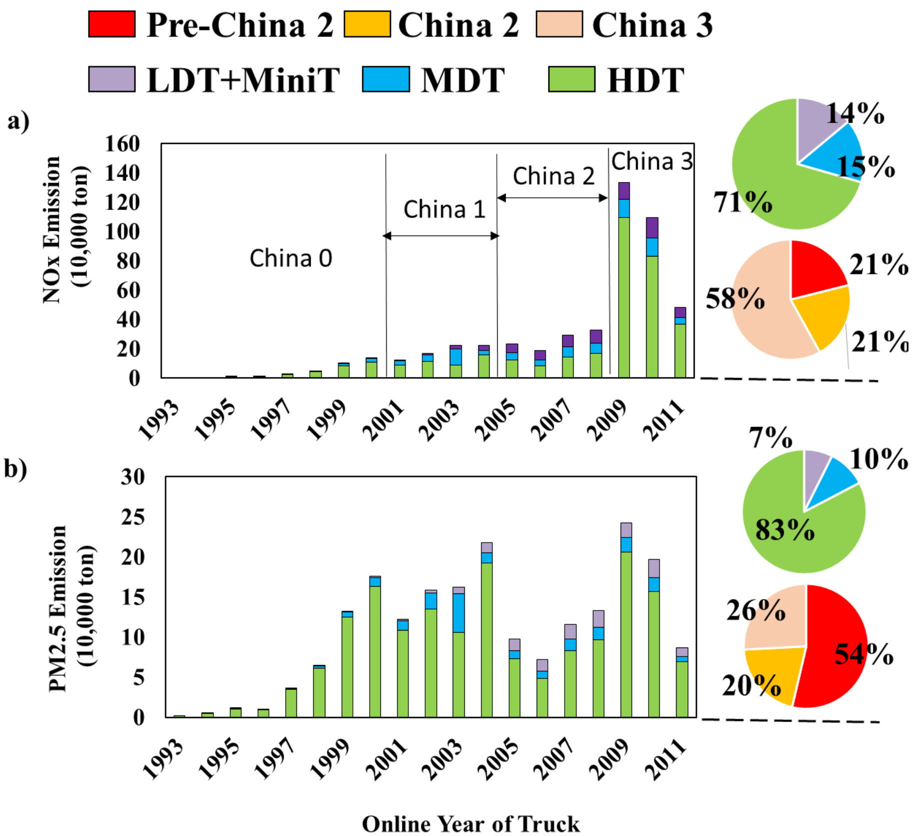

Figure 7. Emissions from diesel truck fleet in 2011, China **(a)** NO_x emission; **(b)** $PM_{2.5}$ emission.

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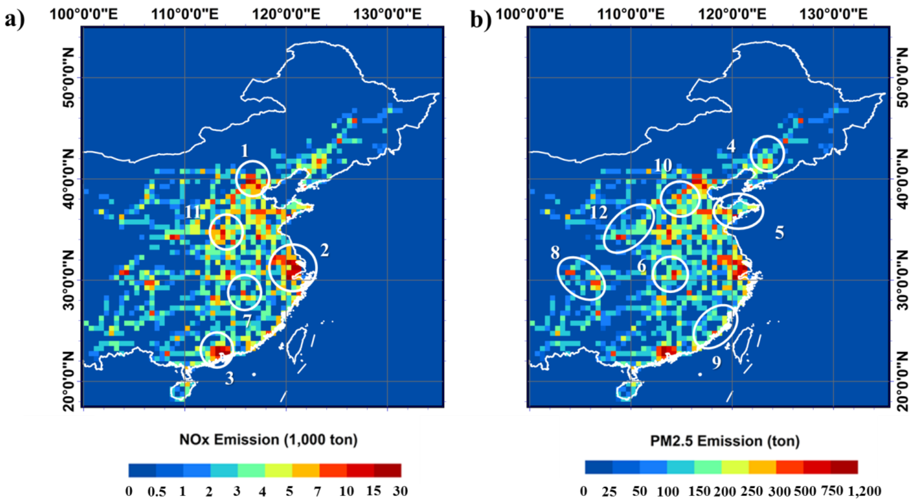

Figure 8. Maps of NO_x and $PM_{2.5}$ emissions from freight trucks in the eastern part of China 2011: **(a)** NO_x emission; **(b)** $PM_{2.5}$ emission. (Key control areas in 12th Five Year Plan of Air Pollution Control: 1. Jing-Jin-Ji; 2. Yangzi River Delta; 3. Pearl River Delta; 4. central part of Liaoning Province; 5. Shangdong Province; 6. Wuhan City and its surroundings; 7. Changsha-Zhuzhou-Changde; 8. Chengdu and Chongqing; 9. west side of the Taiwan Strait; 10. central and north part of Shanxi Province; 11. Guanzhong region in Shaanxi; 12 Gan-Ning region is Gansu and Ningxia.)

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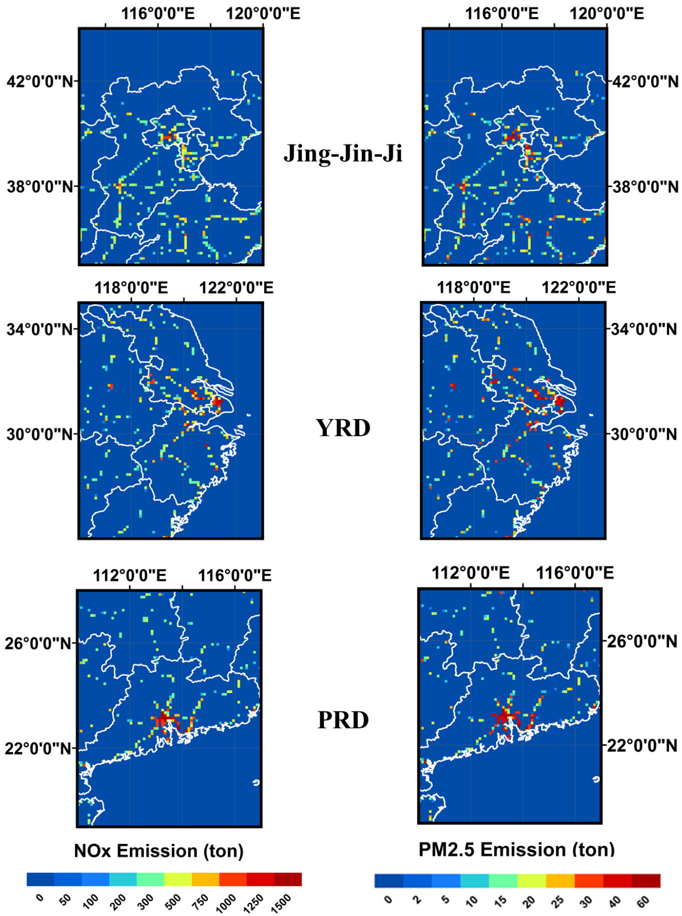

Figure 9. Maps of NO_x and $PM_{2.5}$ emissions from freight trucks in east part of China 2011.

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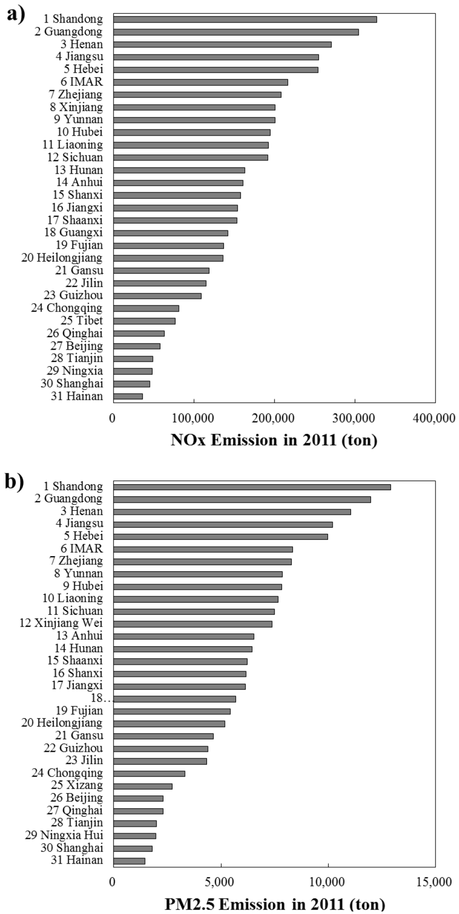

Figure 10. Provincial emissions from diesel fueled trucks in 2011. **(a)** NO_x emissions ranks; **(b)** $PM_{2.5}$ emissions ranks.

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