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Primary Air Pollutants Emissions Variation Characteristics and Future Control Strategies for Transportation Sector in Beijing, China

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Abstract: Air pollutant emissions from vehicles, railways, and aircraft for freight and passenger transportation are major sources of air pollution, and strongly impact the air quality of Beijing, China. To better understand the variation characteristics of these emissions, we used the emission factor method to quantitatively determine the air pollutant emissions from the transportation sector. The emission intensity of different modes of transportation was estimated, and measures are proposed to prevent and control air pollutants emitted from the transportation sector. The results showed that air pollutant emissions from the transportation sector have been decreasing year by year as a result of the reduction in emissions from motor vehicles, benefiting from the structural adjustment of motor vehicles. A comparison of the emission intensity of primary air pollutants from different modes of transportation showed that the emission level of railway transportation was much lower than that of road transportation. However, Beijing relies heavily on road transportation, with road freight transportation accounting for 96% of freight transportation, whereas the proportion of railway transportation was low. Primary air pollutants from the transportation sector contributed significantly to the total emissions in Beijing. The proportion of NO_x emissions increased from 54% in 2013 to 58% in 2018. To reduce air pollutant emissions from the transportation sector, further adjustments and optimization of the structure of transportation in Beijing are needed. As for the control of motor vehicle pollutant emissions, vehicle composition must be adjusted and the development of clean energy must be promoted, as well as the replacement of diesel vehicles with electric vehicles for passenger and freight transportation.

Keywords: transportation; air pollution; pollution prevention and control; motor vehicle; emissions contribution

1. Introduction

As a megacity, Beijing has a large permanent resident population and a high demand for transportation, food, and consumer products, resulting in a large number of motor vehicles and a high volume of passenger and freight transportation [1]. Motor vehicles, trains, and airplanes generate a large quantity of atmospheric pollutants such as nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) during the fuel combustion process, which has a strong impact on the atmospheric environment and human health [2–5]. According to analysis of PM_{2.5} sources in Beijing, the pollution contribution from mobile sources such as motor vehicles

increased from 31% in 2013 to 45% in 2018 [6,7]. Air pollution prevention in the transportation sector is significant for future air quality improvement [8–10].

The reduction of air pollution from the transportation sector depends on adjusting the structure of transportation networks and prioritizing to transportation methods with fewer pollutant emissions. The vehicle composition for each mode of transportation must be adjusted to reduce total fuel consumption and pollutant emissions [11–13]. Scholars in China and other countries have researched the quantification of motor vehicle pollutant emissions and their impact on air quality [14–19]. Cheng et al. comprehensively analyzed multi-source traffic data, such as the fine trajectory of vehicles, road traffic conditions, and road networks, to establish a high-temporal-resolution emission inventory of heavy-duty diesel vehicles in Beijing and to identify their emission patterns [14]. Cell phone global positioning system (GPS) data was used by Gately et al. to quantify motor vehicle congestion and its impact on air pollution in eastern Massachusetts, USA [17]. Some scholars proposed adjusting transportation structure [20–24]. For instance, Kelly et al. stated that it is necessary to fundamentally change urban transportation systems to improve air quality [22]. However, there are few studies on the quantitative assessment of air pollutant emissions from the transportation sector and emission comparisons for different types of transportation.

We aimed to better understand the current status of air pollution emissions from the transportation sector and the emission contributions of different modes of transportation in Beijing. The emission factor method was used to quantify the effect of changes in activity levels, including fuel consumption in the transportation sector, the stock of vehicles, and the number of aircraft trips, thus identifying the variation characteristics in air pollutant emissions from Beijing's transportation sector. Correlation analysis was performed with changes in air pollutant emissions recorded at certain transportation and atmospheric environment monitoring stations in Beijing. Considering changes in passenger and freight transportation volume, the differences in emission levels and the economic costs of different modes of transportation were compared. On the basis of these analyses, suggestions are proposed for reducing air pollution in the transportation sector and adjusting and optimizing transportation structure and vehicle composition. This could provide support for atmospheric environmental management and for the regulation of control measures.

2. Materials and Methods

2.1. Research Objectives

The transportation sector in Beijing mainly includes motor vehicles (gasoline, diesel, and other passenger vehicles and trucks), railways (fossil-fuel-burning internal combustion engines and electric locomotives), and airplanes (fossil fuel-burning aircraft) [25]. The spatial distribution of motor vehicle roads, railway lines, and airports is shown in Figure 1. According to data from the Beijing Statistical Yearbook 2019 [26], there were approximately 5.73 million fossil fuel motor vehicles in Beijing, and the consumption of gasoline and diesel was approximately 6.2 million tons in 2018. The operating mileage of the railway in Beijing is approximately 130,000 km, accounting for about 1% of the total mileage across the country, which is much higher than its ratio of land area. Railway resources are relatively abundant in Beijing but are not fully used for freight. As the electrification of railways has accelerated, the amount of fossil fuels used for railway transportation has decreased. In 2018, the fuel consumption of railway internal combustion engines was 76,000 tons. There are two civil airports in Beijing, and air traffic has increased year by year, with annual trips approaching 6.6 billion.

Due to the large population and high residential density of Beijing, the demand for passenger transportation is high. In addition, due to economic development, residents have a large demand for energy, food, and consumer products, resulting in a large volume of freight transportation. A large quantity of air pollutants is generated by motor vehicles, trains, and aircraft engines during the fuel combustion process, which affects the atmospheric environment and human health. Therefore, the transportation sector is a significant source of air pollution.

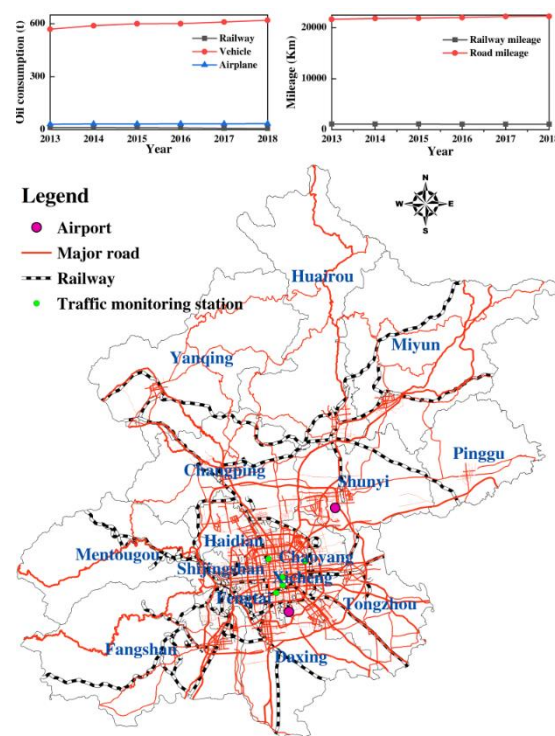


Figure 1. Distribution of roads, railways, and airports in Beijing.

2.2. Emission Evaluation Method

Emissions of atmospheric pollutants from road vehicles, railway internal combustion engines, and airplanes in the transportation sector were calculated using the emission factor method. As air pollutants are mainly emitted from the fuel combustion process, non-exhaust particulate emissions were not included in this study [27,28]. Road vehicles were divided into three categories based on vehicle types (freight, passenger, and motorcycles), fuel types (gasoline, diesel, and natural gas), and emission levels (pre-National I, National I, National II, National III, National IV, and National V). Details of the emission evaluation method can be seen in our previous study [29].

$$E = \sum_i P_i \times EF_i \times VKT_i \quad (1)$$

where P is the stock of motor vehicles; EF represents the emission coefficient based on mileage, as recommended by the technical guidelines for the compilation of an air pollutant emission inventory for road motor vehicles, which was based on practical emission monitoring; VKT represents vehicle kilometers of travel for a year; and i represents the type of vehicle. The internal combustion engines of railway vehicles were analyzed based on their fuel quantity, and airplanes were analyzed based on the number of take-off and landing cycles. The specific formula is:

$$E = A \times Ef \quad (2)$$

where A is the number of take-off and landing cycles of the airplanes or the fuel consumption of the railway vehicles' internal combustion engines based on statistical data, and Ef is the pollutant emission factor. See previous studies for discussions of specific emission factors [29].

2.3. Traffic and Atmospheric Environment Monitoring Stations and Data

The official air quality monitoring system in Beijing consists of 35 monitoring stations, which are divided into 4 categories: background, suburban, urban, and traffic stations. There are currently five

stations for monitoring the impact of road traffic pollution on ambient air quality: Yongdingmen, Qianmen, South Third Ring Road, East Fourth Ring Road, and Xizhimen North. These monitoring stations may also be affected by other atmospheric pollution sources such as heating boilers and dust, but they mainly measure the effects of road traffic pollution emissions. Each monitoring station is equipped with automatic monitoring instruments for SO_2 , NO_2 , CO , O_3 , PM_{10} , and $\text{PM}_{2.5}$; their concentrations in the air are published in real-time (<http://zx.bjmemc.com.cn>).

The environmental pollution concentration levels from the five road traffic monitoring stations from 2013 to 2018 were compared with the average concentrations of the city (Figure 2). The concentrations of the four pollutants (SO_2 , NO_2 , PM_{10} , and $\text{PM}_{2.5}$) at the traffic stations were all higher than the averages in the city. The concentration of NO_2 was the highest, which was related to the large NO_x emissions from road vehicles.

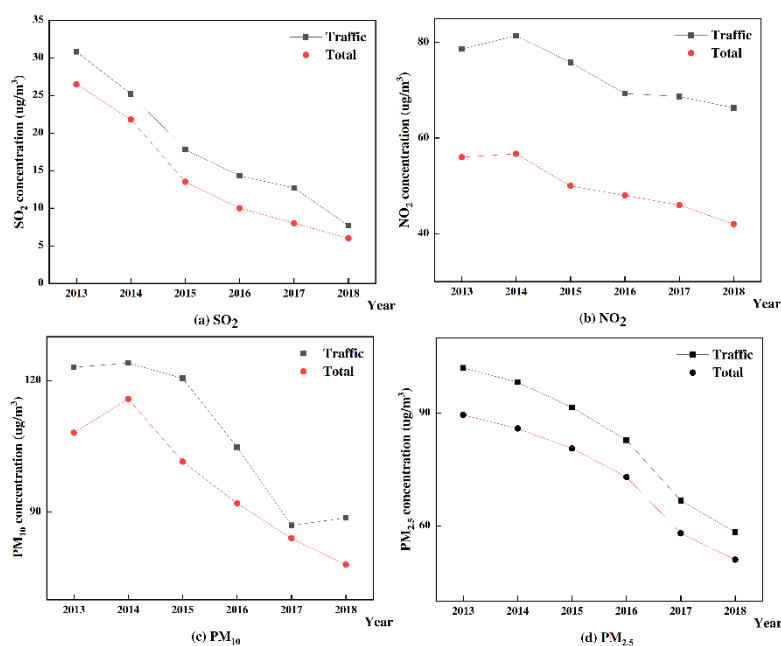


Figure 2. Ambient air pollutant concentrations of all monitoring stations and traffic monitoring stations from 2013 to 2018.

3. Results and Discussion

3.1. Changing Trends in Emissions from the Transportation Sector

The emissions of the four air pollutants from Beijing's transportation sector from 2013 to 2018 and the contribution ratios of the different transportation types are shown in Figure 3. The emissions of the major pollutants in the transportation sector exhibited a downward trend, falling by 51.4% from 2013 to 2018, which was mainly related to a decline in emissions from motor vehicle pollution. With the implementation of the Beijing Municipal Government's clean air action plan [30], the number of motor vehicles and the emissions from new motor vehicles are strictly controlled. In addition, the adjustment of the composition of motor vehicles was accelerated through the retirement of old high-emission vehicles. From 2013 to 2017, 2.167 million old motor vehicles were phased out. The compositions of buses, taxis, dirt trucks, garbage trucks, and freight trucks were also adjusted. Diesel vehicles and vehicles that met National III standards or lower were retired. The replacement vehicles and newly added vehicles were mostly new-energy vehicles. The transition to electric vehicles among industrial vehicles was also accelerated to effectively promote pollutant emission reductions and to adjust the composition of industrial motor vehicles.

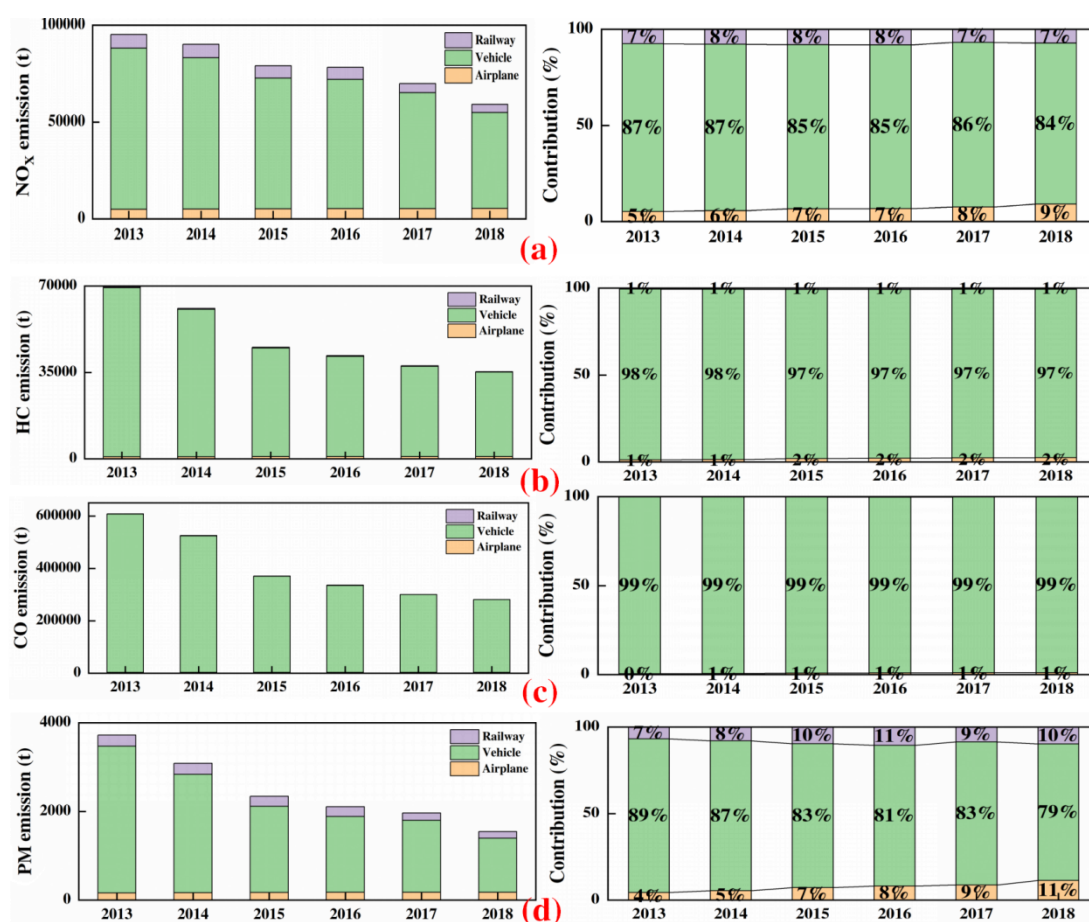


Figure 3. Changes in the major air pollutant emissions and contributions from the transportation sector in Beijing, 2013–2018: (a) NO_x; (b) HC; (c) CO; (d) PM.

The impact of the reduction in motor vehicle pollutant emissions on the improvement of air quality was also confirmed by the data from the road traffic pollution monitoring stations. The concentrations of NO₂, PM_{2.5}, and CO at the five traffic monitoring stations decreased by 15.6%, 42.8%, and 47.0%, respectively. The NO₂ concentration decreased from 78.6 µg/m³ in 2013 to 66.3 µg/m³ in 2018. Compared with road vehicles, airplanes and railways contributed less to emissions from the transportation sector. Each of these forms of transportation contributed 4% to the NO_x emissions from the transportation sector. Driven by economic development, the number of air passengers and the amount of freight traffic continued to increase, and pollution emissions also increased. Railway transportation volume continued to increase, but the pollution emissions were mainly from fossil fuel internal combustion locomotives. As the proportion of electric locomotives increased, the fuel volume for passenger and freight trains decreased year by year, as did railway pollution emissions. The NO_x emissions fell from 7133 tons in 2013 to 4241 tons in 2018—a drop of 40%.

The highest proportion of emissions in the transportation sector was from motor vehicles, which contributed the vast majority of the HC, CO, and PM_{2.5}. The NO_x emission contributions were also relatively large, at 84–87%. This contribution was related to the large volumes of road passengers and road freight transportation, which accounted for 65.4% and 80.3% of the total passenger and freight transportation, respectively. In terms of energy consumption, the fuel consumption of motor vehicles, airplanes, and railways was 6.72 million, 345,000, and 76,000 tons, respectively. The consumption of gasoline and diesel by motor vehicles was large, at 19 and 88 times the consumption by airplanes and railways, respectively.

3.2. Contribution to Total Emissions and Impact on Environmental Quality

Pollutant emissions from the transportation sector contributed significantly to total air pollutant emissions in Beijing. According to NO_x emissions of Beijing from 2013 to 2018 published in the Beijing Statistical Yearbook 2019, the proportion of NO_x from the transportation sector increased significantly as a proportion of Beijing's total emissions, increasing from 54% in 2013 to 58% in 2018. CO accounted for approximately 60% of total emissions and HC emissions contributed 15–21% of the total, mainly from motor vehicle exhaust and fuel evaporation (Figure 4).

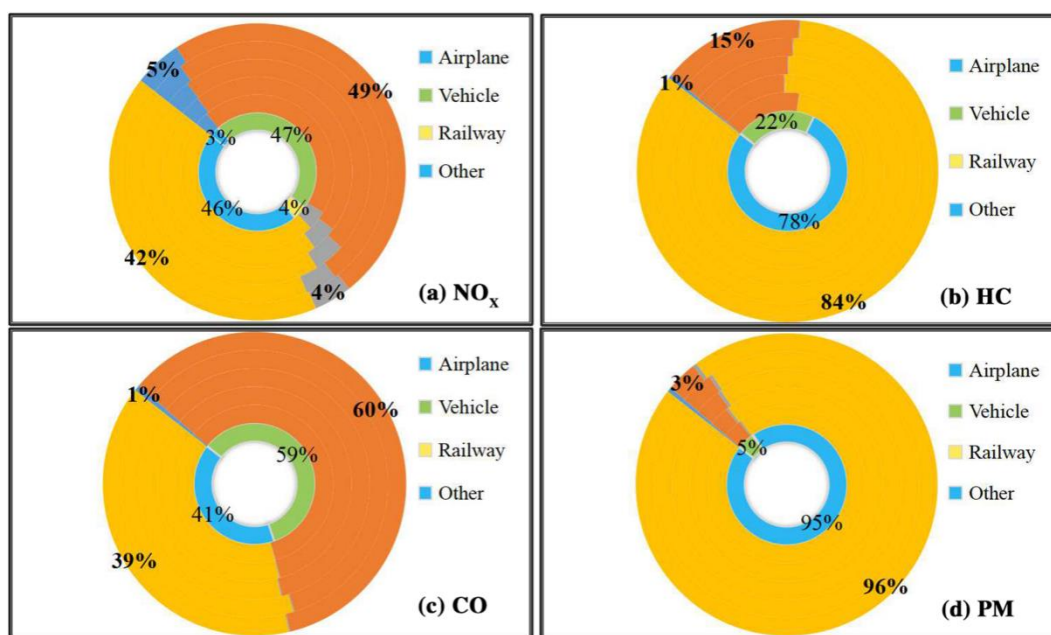


Figure 4. Changes in the contribution of air pollutant emissions from the transportation sector to total emissions, 2013–2018: (a) NO_x ; (b) HC; (c) CO; (d) PM.

Based on the air quality data from traffic monitoring stations, vehicle emissions from the transportation sector also had a large impact on air quality. According to the concentration of ambient air pollutants at five traffic environmental monitoring stations in Beijing from 2013 to 2018, the 6-year average NO_2 , PM_{10} , and $\text{PM}_{2.5}$ concentrations at the stations were 1.5, 1.1, and 1.2 times the average concentrations in the city, respectively.

3.3. Comparison of the Emissions from Different Modes of Transportation

We observed obvious differences in the pollution emissions for different modes of transportation (Figure 5). The emission intensities of the four types of air pollutants per unit mileage of road freight and passenger transportation were the highest, at 4.2 and 2.3 g/person·km, respectively. These numbers were 28 and 33 times the railway freight and passenger transportation numbers, respectively, and 17 and 57 times the air freight and passenger transportation numbers, respectively. The intensity of the air freight pollutant emissions was greater than that of the railways, but that of the air passenger pollutant emissions was less than that of railway passenger transportation.

Specific to each pollutant, the NO_x emission intensities from passenger and freight road transportation were still dozens of times higher than those of railways and airplanes, but the multiples were lower than that of other pollutants. The CO, HC, and PM emissions of railways and airplanes were relatively small, related to the higher combustion efficiency of their engines compared to trucks. From the comparison of the pollution emission intensities of the different transportation types, we found obvious environmental benefits from railway freight and air passenger transportation.

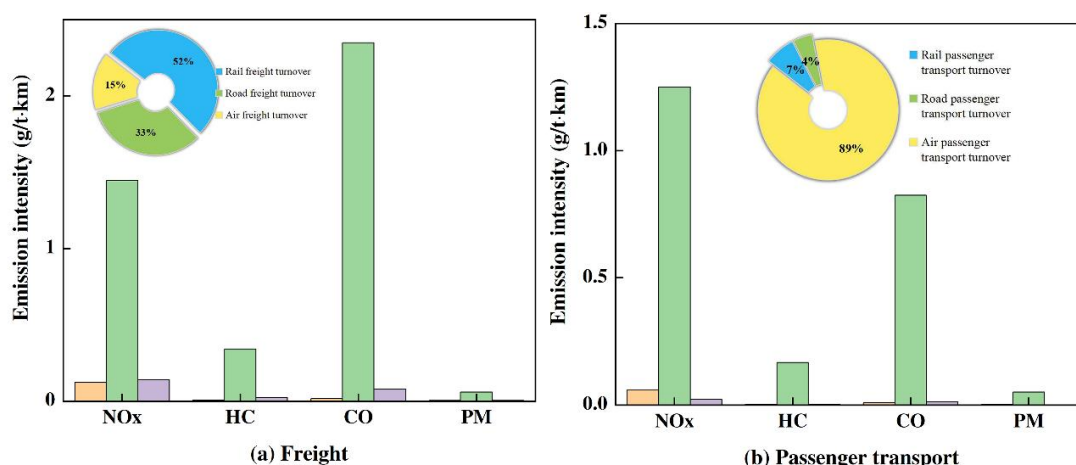


Figure 5. Pollutant emission intensity for different modes of transportation (a) Freight; (b) Passenger transport.

From comparison of the economic costs of unit mileage for the different types of transportation (Table 1) based on field investigations, it was observed that the cost of road freight transportation was the lowest, at 0.07 dollars per ton-kilometer, with the advantages of fast transportation and convenience [31]. These are the reasons for the high proportion of road freight transportation in Beijing. Railway freight transportation is more suitable for bulk freight and the transportation cost is approximately three times that of road freight. Railway connections from factories to departure stations and between arrival stations and destinations have not been developed. Road freight is needed for these connections, which restricts the volume of railway freight. The cost of air freight is approximately 10 times higher than that of road transportation, which is a limiting factor for the growth of its volume. In terms of passenger transportation, the costs of different transportation methods are relatively close, but they show the same trend as freight transportation. The cost of road passenger transportation is slightly lower than that of railways, and the cost of air passenger transportation is again the highest.

Table 1. Comparison of the economic costs of different types of transportation.

Type of Transportation		Transportation Cost	Unit
Freight	Railway	0.18	Dollar/ton-kilometer
	Road	0.07	
	Air	0.67	
Passenger	Railway	0.07	Dollar/person-kilometer
	Road	0.06	
	Air	0.11	

3.4. Control Strategies for the Transportation Sector

Considering the characteristics and contribution of air pollutant emissions from the transportation sector, the transportation structure must be adjusted and optimized and the prevention and control of pollution must be strengthened to reduce the emissions from the transportation sector. Specific emission reduction measures and recommendations are as follows:

1. The structure of transportation should be improved. As can be seen from the results of variation trends in emissions from the transportation sector, the transportation structure in Beijing is relatively simple and relies too much on road transportation. The proportions of railway freight and air freight are relatively low. These two methods have relatively low pollution emission intensities. Therefore, it is necessary to adjust and optimize the transportation structure and formulate overall plans to promote the construction of multiple types of transportation

network, to coordinate the use of existing railway transportation resources, and to promote the priority use of railways to transport bulk freight for key industrial enterprises, logistics parks, and industrial parks.

2. The composition of road freight transportation vehicles needs to be adjusted and optimized. Diesel vehicles are still the main form of road freight transportation, emitting large amounts of NO_x and PM based on calculations of emission intensity from different vehicle types. However, for short-distance freight transportation, road transportation is to some extent irreplaceable. The vehicle structure can nevertheless be adjusted to promote the replacement and update of diesel trucks that fall below the National III standard. The use of energy-saving, environmentally friendly, and new-energy trucks should be promoted by prioritizing them in related policies such as road accessibility.
3. Road passenger vehicles should be electrified. According to the comparison of emissions from different modes of transportation and motor vehicle types in Section 3.3, passenger vehicles, such as buses, taxis, and coaches, greatly contribute to HC and CO emissions due to their intensive use. Increasing the replacement of these passenger vehicles by electric vehicles can reduce their pollution emissions. These types of electric vehicle models are more mature in technology, and their battery life and supporting infrastructure are constantly being improved. As the technology continues to progress, the cost is decreasing.
4. The supervision and enforcement of emission standards need to be strengthened. Remote sensing monitoring, remote emission management terminals, and other methods can be used to monitor the emissions of freight transportation vehicles, thus effectively and quickly identifying excessive emissions. A closed-loop management system for maintenance and inspection should be established to ensure that vehicles with excessive emissions are repaired and rectified in a timely manner. Daily maintenance should be strengthened to ensure that emissions standards are met during actual use and to effectively reduce pollutant emissions.

4. Conclusions

As they are a major source of air pollution, reducing the emissions of primary air pollutants in the transportation sector would play an important role in improving Beijing's air quality in the future. We estimated the emission variation characteristics for the transportation sector from 2013 to 2018 and their impacts on total emissions and air quality. We also compared and analyzed the emission intensity and economic costs of different types of transportation. On this basis, suggestions for reducing air pollution from the transportation sector were proposed.

Although the absolute value of primary air pollutant emissions from road transportation decreased with the optimization of the motor vehicle composition in Beijing, the transportation sector's contribution to total emissions increased because its rate of reduction was lower than that of total emissions. The air pollutant concentrations measured by road traffic monitoring stations were much higher than those measured in other places, showing that road transportation had a greater impact on air quality. By comparing the emission intensities of various modes of transportation, we also observed that the pollutant emissions from passenger and freight transportation on roads were much higher than those of railway and air transportation.

As for future policy implications, reasonably arranging and optimizing the transportation structure, improving the capacities of railway and air transportation, and reducing the proportion of road transportation would all be conducive to pollution reduction and air quality improvement. Controls upon vehicle emissions need to be further strengthened. The introduction of strict supervision, the elimination of high-emission diesel vehicles through emission standards, and the replacement of fuel vehicles with electric vehicles have all played essential roles in decreasing emissions from the transportation sector.

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