Analysis on the Evolution, Causes, and Countermeasures of Urban Haze Components in Beijing

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Abstract. Based on the results of PM2.5 sources analysis, this paper analyzes the component evolution, formation causes, and governance countermeasures of urban haze in Beijing. The proportion of coal burned in sources of PM2.5 in Beijing has gradually declined, and motor vehicle exhaust has become the largest source of pollution. The formation of haze pollution in Beijing is related to the change in energy structure, the increase in the number of motor vehicles, the increase of urban construction area, and the cross-regional transmission of pollutants in Hebei, Tianjin, and other places. Beijing's urban haze control measures include reducing vehicle emissions, optimizing industrial structure, adjusting energy structure, building an eco-city, and implementing cross-regional coordinated governance.

1. Introduction

Haze pollution causes traffic accidents and respiratory diseases, which becomes the main air pollution problem in developing countries, such as China. As the capital of China, the urban haze pollution of Beijing has always attracted widespread. The haze control of Beijing will be of great significance to the development of such mega city. In order to improve the reliability of control measures, the evolution and formation mechanism of urban haze pollution need to be clarified.

At present, the causes and control of haze have been studied by many researchers. Gorge [1] points out that air pollution is cross-regional, and each treatment measure cannot be independent of each other. Haze pollution should be monitored in real-time. Peng [2] believes that unfavorable meteorological conditions are the main cause of haze pollution in Beijing, and air pollutants are secondary. It is imperative to control Beijing's motor vehicle and coal-fired pollution. Xie [3] divides the influencing factors of haze weather into two categories, pollution sources contribute to haze components, and meteorological conditions affect component transmission. Hu[4] believes that the increase in the number of motor vehicles, including automobiles, is the main cause of haze pollution. Wang [5] points that the cause of PM2.5 in north China is the concentrated embodiment of environmental problems accumulated by China's rapid industrialization and urbanization process. Eugene [6] proposed that clean production and recycling of substances should be carried out, and waste should not be treated by incineration and landfill. Stephen [7] believes that attention should be paid to the effective evaluation of haze polluation control measures. Walter et al. [8-10] mainly focus on optimizing governance methods, and further strengthens environmental research from the perspective of governance. They propose a cross-regional collaborative governance model for haze control. Sajor et al. [11-12] noted that the failure of the "one-size-fits-all" model was due to not taking into account the heterogeneity, complexity, and motivations behind pollutant emissions across regions. In summary, haze pollution control policies should be formulated based on the composition of local pollution sources.

The aim of this study is to clear out the evolution, causes, and countermeasures of urban haze in Beijing. Based on the analysis results of PM2.5 sources in Beijing, this paper analyzes the component evolution and formation causes of haze pollution in Beijing. On the basis of summarizing the main influencing factors of haze pollution in Beijing, cross-regional collaborative governance policy suggestions are proposed.

2. Evolution trajectory of urban haze components in Beijing

For the analysis of PM2.5 sources in Beijing, most of the experimental studies before 2012 were conducted by individual scholars, lacking official unified authoritative data, the scope of research was not extensive, the research was intermittent, and the data were not continuous enough. In 2013, Beijing carried out the first PM2.5 source analysis, followed by the second and third PM2.5 source analyses in 2017 and 2020. Table 1 lists the available analysis results of PM2.5 sources for different observation times in Beijing.

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Table 1 Analysis of PM2.5 sources in Beijing

Researcher	Observation time	Result of source analysis
Fumo YANG	1999-2000	burning coal, soil dust, motor vehicle exhaust
Yu SONG	2000-2001	coal combustion, dust, construction dust, biomass combustion, motor vehicle exhaust
Jing XU	2003-2004	dust, coal, marine aerosols, motor vehicle exhaust, steel industry production
Jun TAO	2009-2010	transportation of coal-fired and motor vehicle exhaust and regional pollution sources
Monitoring Center	2013	motor vehicle exhaust, coal combustion, industrial production, dust
Monitoring Center	2017	Motor vehicle exhaust, dust, industrial production, living surface, coal combustion
Monitoring Center	2020	Motor vehicle exhaust, dust, industrial production, living surface, coal combustion

Table 1 shows that with the development of society, the characteristics of haze pollution in Beijing have also changed accordingly. From 1999 to 2001, dust and coal burning were the most important sources of atmospheric PM2.5 in Beijing, and biomass combustion was also an important source of PM2.5 pollution in Beijing during this period, while the impact of motor vehicle emissions was relatively small. From 2001 to 2004, China's industry developed rapidly, and the steel industry used a large amount of coal, which had the greatest impact on PM2.5 pollution in Beijing. Since 2000, the contribution rate of coal combustion to PM2.5 sources in Beijing has been declining, while the contribution rate of motor vehicle exhaust to PM2.5 sources has been increasing. In 2010-2017, with the continuous optimization of energy structure, coal energy was replaced by clean energy in industrial production, and the impact of coal combustion on air pollution is getting smaller and smaller. But with the increase in the number of motor vehicles, motor vehicle exhaust has become the primary source of pollution. By 2020, coal and biomass combustion had largely withdrawn from the ranks of Beijing's major sources of atmospheric PM2.5 pollution.

Figure 1 shows the comprehensive analysis results of PM2.5 sources in Beijing in 2013, and the sources of pollutants mainly come from two aspects. On the one hand, from the local emission of pollutants. On the other hand, from the transmission of other areas, the overall proportion of local emissions of pollutants is relatively high. Local emissions come from the combustion of fossil fuels, of which energy such as gasoline and diesel is consumed by motor vehicles, and pollutants from coal combustion account for the absolute majority of local pollutants. Motor vehicles accounted for the largest share of emissions, at 31.1%, and coal burning followed with 22.4%.

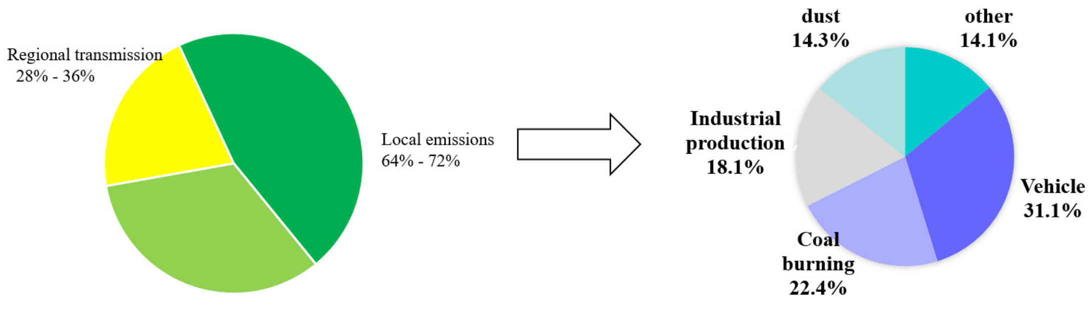

Figure 1 Analysis results of $PM_{2.5}$ sources in Beijing in 2013

Figure 2 shows the relationship between local emissions and regional transmission of PM2.5 sources in Beijing in 2017, 42% of the annual PM2.5 pollution sources in Beijing in 2017 came from the regional transmission, compared with the results shown in Figure 1, the proportion of air pollutants produced by regional transmission increased, and so did the harm of air pollution in Beijing gradually. Figure 3 shows the main sources of PM2.5 local emissions in Beijing in 2017. In 2017 the proportion of mobile sources of air pollutants was the highest with a percentage of 45%, while coal-fired sources decreased significantly compared with 2013. In 2012-2013, coal-fired air pollutants accounted for the second place in local emissions of pollutants with a percentage of 22.4%. By 2017, through these years of governance, the contribution rate of coal-fired sources fell to 3%. The probability of haze pollution caused by coal burning is greatly reduced.

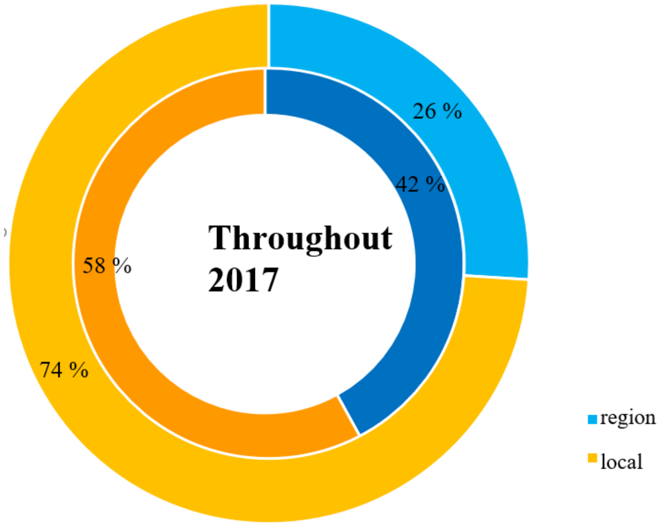

Figure 2 Relationship between local emissions and regional transport in PM2.5 sources in Beijing in 2013 (outer ring) and 2017 (inner ring)

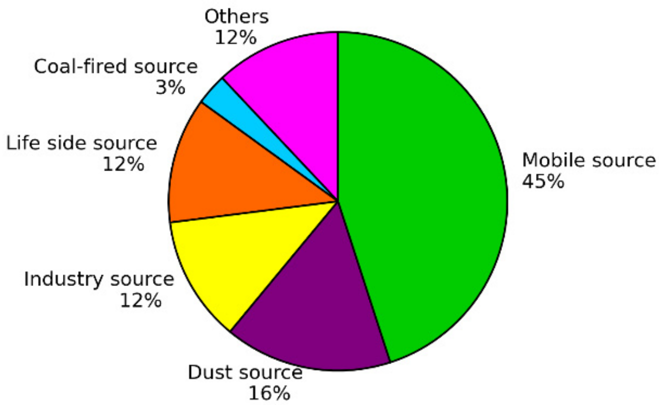

Figure 3 Main sources of local PM2.5 emissions in Beijing in 2017

In 2020, local emissions accounted for 58% of Beijing's main sources of PM2.5, as shown in Figure 4, which was basically the same as in 2017. Among the local emissions, mobile sources, domestic sources, dust sources, industrial sources, and coal-fired sources accounted for 46%, 16%, 11%, 10%, and 3% respectively. And Other sources such as agriculture and natural background account for about 14%. Combined with the analysis results of PM2.5 sources in Beijing in 2013, 2017, and 2020, it can be seen that since 2013, the control effect on coal combustion and industrial pollution sources has been the most prominent. And the absolute contribution value of coal combustion to all pollutant sources in 2020 has been far lower than that of other pollution sources, from more than 20% in 2013 to less than 5% in 2020. The proportion of mobile source emissions has increased. Because of the development of society and the improvement of living standards, the number of motor vehicles has increased significantly, resulting in an increase in motor vehicle exhaust emissions. Compared with 2017, the proportion of major sources of PM2.5 emissions in Beijing remained stable in 2020. Among them, mobile sources are the first major source of local atmospheric PM2.5 pollution, and living sources have become the second largest source, showing the typical pollution characteristics of megacities. In 2020, regional transmission accounted for 42% and 58% of the sources of PM2.5 in Beijing, indicating that cross-regional coordinated emission reduction in Beijing-Tianjin-Hebei is the key to the next stage of Beijing's haze pollution control.

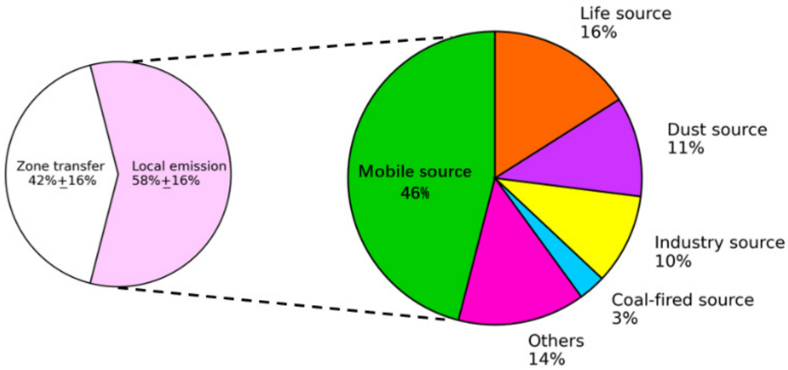

Figure 4 Analysis results of PM2.5 sources in Beijing in 2020

3. Analysis of socio-economic causes of urban haze pollution in Beijing

Haze is essentially aerosol pollution. Human activities produce harmful particulate matter, which undergoes a series of physical and chemical reactions under high humidity conditions, coupled with special climatic conditions, forming haze [13]. The formation of haze pollution in Beijing is the result of a combination of meteorological factors and sociological factors. Socio-economic factors are the root cause of the formation of haze due to the high levels of sulfur dioxide, nitrogen oxides, and total suspended particulate matter in the atmosphere [14-15]. Meteorological factors are complex and random, and man-made is uncontrollable. Relatively speaking, climatic conditions in a certain area are relatively stable in the short term. So this paper does not take meteorological factors as the research object, but studies the causes of urban haze in Beijing from the sociological perspectives such as energy structure, transportation structure and pollutant transmission.

Table 2 shows the trend of energy structure change in Beijing from 2002 to 2020. Fossil fuel consumption in Beijing has been at a high level, and the consumption of coal increased faster in 2004-2007, much higher than oil and gas. Since 2008, Beijing's coal consumption has declined rapidly, and the consumption of clean energy such as natural gas has increased significantly. And by 2020, oil consumption has exceeded coal consumption. As the proportion of coal in Beijing's energy structure continues to decrease, the contribution rate of coal combustion to Beijing's PM2.5 sources decreases, while the contribution rate of oil-fueled vehicle emissions to Beijing's PM2.5 sources continues to increase, becoming the primary source of pollution.

Table 2 Trends of energy structure change in Beijing from 2002 to 2020

Year	Coal/10^4t	Oil/10^4t	Natural gas/10^8m^3
2002	2719	106	10
2003	2675	138	16
2004	2531	152	21
2005	2674	165	21
2006	2939	198	27
2007	3068	235	32
2008	3055	278	40
2009	2984	324	46
2010	2740	339	60
2011	2664	363	69
2012	2530	362	74
2013	2283	380	73
2014	2179	405	92
2015	2019	423	98
2016	1736	440	113
2017	1165	462	145
2018	847	470	160
2019	485	489	162
2020	489	521	180

With the development of the economy and society, the number of motor vehicles in Beijing keeps increasing. Table 3 shows the trend in the number of the motor vehicle and construction areas in Beijing from 1985 to 2020. Since 1985, the number of motor vehicles in Beijing has always been on the rise. The combustion of gasoline in motor vehicles emits large amounts of air pollutants and at the same time, it causes dust on the road during driving, which together has led to the mobile source of motor vehicles becoming the largest source of PM2.5 in Beijing. Since 1985, the construction area of the city has been increasing, and after 2010, the construction area has grown more rapidly. Since not all construction companies can strictly abide by the environmental protection system during the construction process, this leads to an increase in the emission of air pollutants caused by construction. It is worth noting that the dust source in Beijing is not a simple crustal source of dust. People's production and life also have a certain impact on the dust on the ground in Beijing. And the pollution particles formed by human activities such as industry and motor vehicles enter the ecosystem through the natural cycle, which has an impact on the haze pollution in Beijing.

Table 3 Treends of motor vehicle ownership and construction area in Beijing from 1985 to 2020

Year	Motor vehicle ownership/10^4vehicles	Construction area/10^4m^2
1985	9.8	1952.1
1986	12.1	2351.9
1987	16.0	2802.7
1988	18.6	2760.7
1989	19.3	2578.0
1990	22.2	2642.2
1991	24.8	2450.8
1992	27.1	2864.9
1993	29.7	2818.0
1994	34.1	3126.8
1995	41.6	3607.5
1996	48.1	4460.9
1997	58.9	5524.3
1998	62.2	5633.2
1999	78.4	5819.4
2000	89.8	6496.1
2001	95.1	6556.5
2002	157.8	7246.8
2003	169.9	8919.3
2004	189.9	10240.9
2005	212.4	11971.7
2006	229.6	13019.5
2007	258.3	15417.6
2008	287.6	16202.0
2009	312.8	18224.6
2010	350.4	19537.0
2011	401.9	22720.6
2012	480.9	29440.4
2013	498.3	36506.9
2014	520.0	41660.3
2015	543.7	49259.0
2016	559.1	56477.1
2017	561.9	59776.7
2018	571.7	61097.5
2019	590.9	65290.1
2020	608.4	71969.3

Table 4 shows the changes in sulfur dioxide emissions in Beijing, Tianjin, and Hebei, respectively. As can be seen from Figure 8, during the statistical period, Beijing's sulfur dioxide emissions generally showed a downward trend year by year, but fluctuated around 2012, and the sulfur dioxide pollutant emissions decreased significantly in 2017. From 2008 to 2017, Tianjin's sulfur dioxide emissions decreased slightly every year, but the extent was not obvious. In 2018, Tianjin's sulfur dioxide emissions were significantly reduced, and the emission reduction effect was obvious. Due to the lack of strong emission reduction measures, sulfur dioxide emissions in Hebei Province did not show a significant downward trend from 2002 to 2014, and even showed several relatively large increases, which is completely different from the year-by-year decline in sulfur dioxide emissions in Beijing. After 2015, with the increase in air pollutant emission reduction, sulfur dioxide emissions in Hebei Province showed a significant downward trend. On the whole, due to the inconsistency of emission reduction measures in Beijing, Tianjin, and Hebei, the emission reduction effect of Tianjin and Hebei before 2016 was not obvious, and even rebounded abnormally, which led to the accumulation of air pollutants in Hebei, Tianjin, and other places, and aggravated Beijing's haze pollution through regional transmission.

Table 4 Trends of sulfur dioxide emissions in Beijing-Tianjin-Hebei from 2006 to 2020

Year	Beijing/10^4t	Tianjin/10^4t	Hebei/10^4t
2006	19.1	22.7	142.8
2007	19.1	26.5	149.5
2008	17.6	25.5	154.5
2009	15.2	24.5	149.2
2010	12.3	24.0	134.5
2011	11.9	23.7	125.3
2012	11.5	23.5	123.4
2013	9.8	23.0	141.2
2014	9.4	22.4	134.1
2015	8.7	21.6	128.4
2016	7.9	20.9	118.9
2017	7.1	18.5	110.8
2018	3.3	7.0	78.9
2019	2.0	5.5	60.2
2020	1.1	4.5	49.0

In view of the sociological causes of haze pollution in Beijing, we screened the main influencing factors of haze pollution in Beijing through correlation analysis and causality test. The in-depth inspection results show that there is a long-term and stable relationship between energy consumption per unit of GDP, coal consumption, crude oil consumption, greening coverage, sulfur dioxide emissions in Beijing, dust emissions in Beijing, sulfur dioxide emissions in Hebei, and sulfur dioxide emissions in Tianjin and haze pollution in Beijing, which are the main influencing factors of haze pollution in Beijing. Therefore, in order to achieve the next stage of effective control of haze in Beijing, it is necessary to carry out macro control of the Beijing-Tianjin-Hebei region as a whole. Specifically, according to the development characteristics of each region, relevant pollutant quality control should be carried out to reduce the emission of various pollutants in Beijing and its surrounding areas from the source, fully mobilize the enthusiasm of all regions, and constantly optimize and adjust production, life, ecology, and other aspects, so as to finally solve the problem of haze pollution in Beijing.

4. Policy recommendations for urban haze pollution control in Beijing

4.1 Optimization of industrial structure

In the past, the development model of overemphasizing the speed of industrial development and ignoring pollutant emissions led to more and more serious haze pollution in Beijing. To achieve the fundamental control of haze pollution in Beijing, it depends on the optimization of the industrial structure. Industrial restructuring is the key to coordinating high-quality economic development and environmental protection.

The Beijing municipal government can introduce relevant preferential policies to encourage more enterprises to migrate from Beijing to surrounding small and medium-sized cities, which can increase local employment opportunities and promote economic development. It is necessary to strengthen the infrastructure construction of small and medium-sized cities in the Beijing-Tianjin-Hebei region, and reduce the regional income gap by establishing a reasonable regional compensation mechanism. For the enterprises themselves, they should update their production equipment and replace fossil fuels such as coal with clean energy such as natural gas and electricity. The government should also introduce relevant policies to strictly eliminate invalid and backward production capacity.

In recent years, Beijing has made some progress in industrial structure upgrading, but the effect of industrial structure upgrading on haze control is not working well. The reason is that the industries in Tianjin and Hebei are still dominated by the extensive traditional manufacturing industry, and the high-tech industry is still not developed enough to support energy conservation and emission reduction under the current industrial structure. Increasing investment in high-tech industries and supporting the development of high-tech industries can not only promote the control of haze in Beijing, but also greatly benefit the integrated development of Beijing-Tianjin-Hebei.

4.2 Adjustment of the energy mix

According to the development level of Beijing and even the Beijing-Tianjin-Hebei region, it is not possible to completely eliminate primary energy such as fossil fuels in the short term, and the dependence on primary energy in the future is still high. Therefore, scientifically adjusting the proportion of energy use and vigorously developing new energy sources with low air pollutant emissions and relatively friendly to the environment is of great significance for haze control.

At present, Beijing and its surrounding areas still rely extensively on coal energy for industrial production, heat energy supply, chemical industry, electricity, and people's livelihood. In order to change the problem of haze pollution caused by a large amount of coal combustion, it is necessary to: (1) Changing the energy structure dominated by coal. According to the characteristics of different regions, the use of other clean energy such as natural gas and gas is promoted in stages to replace the traditional way of providing the main energy with coal, gradually control the use of coal, and at the same time increase the use and promotion of renewable energy, such as wind energy, geothermal energy, solar energy, and other energy sources, and fundamentally reduce the use of coal; (2) Improving the quality of coal. According to the characteristics of different regions, appropriately improve the quality of coal, research and promote more advanced coal cleaning technology, and remove compounds formed by excessive sulfur, nitrogen, and other elements in coal through selection, finishing, and other processes, so as to reduce the pollutants produced during coal combustion; (3) Developing and promoting more advanced combustion equipment and purification equipment. Improve the combustion conditions of coal, improve the utilization rate of coal, so as to effectively reduce the particulate matter and harmful gases generated due to incomplete combustion, strengthen the treatment of waste gas after coal combustion, and effectively block pollutants in the exhaust gas into the atmosphere through purification equipment.

4.3 Build ecological city

In the natural ecosystem, the continuous transmission and circulation between matter and energy, and the various parts of the ecosystem restrict and promote each other, so as to achieve a balanced state and enable the long-term development of the ecosystem. Beijing's rapid urbanization has destroyed the original ecosystem structure, and human activities have increasingly demanded various types of energy, and the extraction of energy is accompanied by a large emission of various air pollutants, which has led to the gradual imbalance of the originally stable ecosystem. Therefore, building an urban ecosystem is crucial to Beijing's haze control. The establishment of urban ecosystems can make the material and energy cycles within the city operate in a certain degree of coordination, thereby reducing the impact of human activities on the ecosystem and ensuring the overall stability of the ecological environment. To build an ecological city, we must abandon the old model of high input, low output, high emission, and high pollution, and establish a new model of the internet of everything, innovation, service sharing, common destiny, and beautiful life. Increasing urban green coverage is a low-cost and effective way to build ecological cities, and the increase of green coverage can promote the circular operation of urban ecosystems, improve urban micro-area ecosystems, and have a positive impact on haze control.

4.4 Implement cross-regional coordinated governance in the Beijing-Tianjin-Hebei region

The analysis of PM2.5 sources in Beijing has shown that the problem of haze pollution in Beijing can not be fundamentally improved by relying on the strict control of Beijing, so it is necessary to raise the public's awareness of the importance of cross-regional collaborative governance, not only Beijing, Tianjin, Hebei and other places should also increase the control of haze pollution, and all cities in the Beijing-Tianjin-Hebei region must coordinate and link, so as to maximize the effect of haze control.

Due to the large gap in the economic development level of various regions in the Beijing-Tianjin-Hebei region, in the process of cross-regional coordinated management of haze, it is necessary to take corresponding economic promotion and compensation measures according to the economic development characteristics of each region and local conditions, so as to avoid economic losses and personnel unemployment caused by industrial structure adjustment in some regions, and form a community of interests in the Beijing-Tianjin-Hebei region. The cross-regional coordinated governance of the Beijing-Tianjin-Hebei haze should be subordinate to the overall situation of serving the coordinated development of the country's Beijing-Tianjin-Hebei region.

In order to realize the cross-regional coordinated control of haze pollution in the Beijing-Tianjin-Hebei region, multi-level, cross-departmental, and cross-regional institutional arrangements should be formed, and precise policy plans and detailed implementation plans should be determined to ensure the efficient advancement of haze control. In the process of haze control, we should also pay attention to the cost-sharing of pollution control, eliminate the conflict of interest between regions in the process of haze control, and stabilize collaborative cooperation. The specific measures for cross-regional coordinated governance in the Beijing-Tianjin-Hebei region include the preparation of a unified regional air quality plan, the establishment and improvement of a regional air pollution joint prevention and control mechanism, the improvement of regional air pollution joint prevention and control policies, the construction of a scientific and technological linkage mechanism for regional pollution control, and the creation of a strong atmosphere for the whole society to participate in prevention and control.

5. Conclusions

Based on the source analysis of PM2.5 for Beijing, the component evolution, formation mechanism and governance countermeasures of urban haze were discussed. The conclusions are as follow:

(1) The evolution of PM2.5 components in Beijing was mainly affected by the change in haze pollution sources. In recent years, the contribution rate of motor vehicle exhaust for PM2.5 in Beijing was increasing. Meanwhile, the contribution rate of coal and industrial emissions was declining. Motor vehicle exhaust has become the primary source of PM2.5 pollution in Beijing.

(2) The formation of urban haze in Beijing is related to the change in energy structure, the rapid increase of motor vehicle ownership and urban construction areas, and the transmission of air pollutants across regions. Due to the undesirable emission reduction of air pollutants in Hebei and Tianjin, the transmission of air pollutants through regional transmission aggravated the haze pollution in Beijing.

(3) Urban haze pollution control policies for Beijing included reducing motor vehicle exhaust emissions, optimizing industrial structure, adjusting energy structure, building ecological cities and implementing cross-regional coordinated governance. In order to achieve cross-regional coordinated management of haze pollution, it is necessary to establish the joint prevention system of haze pollution in the Beijing-Tianjin-Hebei region.

In the future, relevant prediction method, such as artificial neural network and machine learning, should be applied to quantitatively evaluate the effects of different polices on the control of urban haze pollution.

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