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A Study on a Health Impact Assessment and Healthcare Cost Calculation of Beijing–Tianjin–Hebei Residents under $PM_{2.5}$ and O_3 Pollution

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Abstract: Excessive fine particulate matter ($PM_{2.5}$) and ozone (O_3) are invisible killers affecting our wellbeing and safety, which cause great harm to people's health, cause serious healthcare and economic losses, and affect the sustainable development of the social economy. The effective evaluation of the impact of pollutants on the human body, the associated costs, and the reduction of regional compound air pollution is an important research direction. Taking Beijing–Tianjin–Hebei (BTH) as the research area, this study constructs a comprehensive model for measuring the healthcare costs of $PM_{2.5}$ and O_3 using the Environmental Benefits Mapping and Analysis Program (BenMAP) as its basis. First, this study establishes a health impact assessment model and calculates the number of people affected by $PM_{2.5}$ and O_3 exposure using the health impact function in the BTH region. Then, the willingness to pay (WTP) and cost of illness (COI) methods are used to estimate the healthcare costs inflicted by the two pollutants upon residents from 2018 to 2021. The calculation results show that the total healthcare costs caused by $PM_{2.5}$ and O_3 pollution in BTH accounted for 1%, 0.7%, 0.5%, and 0.3% of the regional GDP in 2018, 2019, 2020, and 2021, respectively. Based on the research results, to further reduce these high healthcare costs, we propose policy suggestions for $PM_{2.5}$ and O_3 control in the BTH region.

Keywords: $PM_{2.5}$ and O_3; healthcare cost; Beijing–Tianjin–Hebei; BenMAP

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1. Introduction

With China's rapid industrialisation, the consumption of coal, oil, and other energy sources has increased. Many pollutants, including $PM_{2.5}$, O_3, nitrogen oxide (NO), and sulphur dioxide (SO_2), produced by the combustion of fossil fuels, are discharged into the air, which places a great burden on the atmospheric environment and seriously endangers the life, health, and quality of life of residents [1–3]. The government of China has placed great importance to this and carried out national environmental quality monitoring since 2010. After nearly ten years of air pollution control, the concentration of air pollutants in China has been declining, but it is still not ideal [4]. According to the Bulletin on the Ecological Environment of China in 2021 [5] issued by the Ministry of Ecology and Environment, only 64.3% of the cities in China will meet the environmental air quality standards in 2021. On days when the pollutant concentration in 339 cities exceeded the standard, the proportion of $PM_{2.5}$ as the primary pollutant was 39.7%, O_3 as the primary pollutant was 34.7%, PM_{10} as the primary pollutant was 25.2%, NO_2 as the primary pollutant was 0.6%, and CO as the primary pollutant was less than 0.1%. $PM_{2.5}$ and O_3 are the two main pollutants of air pollution in China [6]. $PM_{2.5}$ enters the human body through breathing and is considered to cause diseases in the respiratory, cardiovascular, and immune systems. O_3 causes heart failure, myocardial infarction, and other diseases, increases hospitalisation and premature death rates, and harms human health [7,8]. Excessive emissions of $PM_{2.5}$ and O_3 would seriously damage the ecological environment and endanger human health while restricting the sustainable development of China's social economy. Therefore, it is of great practical significance to strengthen the collaborative management of $PM_{2.5}$ and O_3 to improve air quality and enhance the health of residents.

The BTH region is one of the most polluted areas in China [9,10]. According to the Bulletin on the Ecological Environment of China, in 2021, the proportion of days with excellent air quality in 13 cities in the BTH region ranged from 60.3% to 79.2%, with an average of 67.2%. The average number of days exceeding the standard was 32.8%, of which 24.0% were labelled as having light pollution, 5.7% moderate pollution, 2% severe pollution, and 1.2% serious pollution. The BTH region still faces serious air pollution problems that restrict the coordinated development of the region and the construction of an ecological civilisation. Therefore, the Chinese government has placed considerable importance on the prevention and control of air pollution in the BTH region. In 2020, President Xi Jinping proposed strengthening ozone pollution control and promoting the coordinated control of $PM_{2.5}$ and O_3 in the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of Vision Goals for 2035 [11]. Various regions have gradually paid attention to the problem of compound pollution and carried out related research and practice.

The health impact of air pollution has been widely concerned by academic circles and has achieved a series of research results [12–14]. For example, Mirzaei et al. [15] statistically analysed the $PM_{2.5}$ concentration in Tehran from 2016 to 2018 and outlined the possible reasons why the $PM_{2.5}$ concentration exceeded the WHO guidance level and estimated the number of deaths caused by ischemic heart disease and lung cancer using AirQ+ v.2.0 and BenMAP-CE. Cao et al. [16] quantified the long- and short-term effects of air pollution on the mental health of urban residents in China. Yang et al. [17] investigated the impact of exposure to $PM_{2.5}$ on health and welfare in winter and summer in typical cities in northern China from 2013 to 2016. Moreover, they evaluated the economic losses and medical expenses of premature death caused by related diseases. Most existing studies take countries (such as the United States [18], Mexico [19], and East Africa [20]) and provinces [21,22] as research subjects to explore the impacts of atmospheric contamination on residents' health. Moreover, the United States and European countries started studies on the health effects of air pollution and the formulation of pollution prevention and control policies early, achieving notable results.

At present, research on the BTH region in China has mainly focused on the impact of particulate matter on economic benefits, largely ignoring the healthcare costs associated with ozone exposure [23,24]. As for the assessment methods of the impacts on health, Bai et al. [25] divided the methods of accounting for the healthcare costs of air pollutants into dynamic and static models. The computable general equilibrium (CGE) model is a commonly used dynamic estimation method that reflects the internal relationships between social and economic systems and can calculate the cumulative effect of economic losses over time. Therefore, it has been gradually applied to assess the health effects caused by air pollution in recent years [26,27]. Compared with dynamic models, static models are the most used healthcare cost accounting methods because of their simpler calculations and stronger applicability. Static methods primarily include the value of a statistical life (VSL) method, willingness to pay (WTP), and cost of illness (COI). For example, Lu et al. [28] used VSL to calculate the adverse health effects and economic losses caused by pollutants based on the concentration data of particulate matter (PM_{10} and $PM_{2.5}$) retrieved with satellites from 2004 to 2013. Qin et al. [29] used the cost of illness method to calculate the economic losses caused by PM in Wuhan, China.

Additionally, at present, the development of air quality assessment model systems is based on geographic information systems. The Environmental Benefits Mapping and Analysis Program (BenMAP) model is regarded as an effective tool for evaluating the health effects of one or more air pollutants [30,31]. The advantage of the BenMAP model is that it can take two pollutants as research objects and comprehensively evaluate the health impacts and corresponding economic losses on the exposed population, baseline incidence or mortality of diseases, health impact function, and value estimation model [32,33]. With scientific and comprehensive characteristics, this model has become a more advanced air pollution health assessment model in the world [34–36]. For example, Liang et al. [37] used BenMAP, an environmental benefit evaluation model developed by the US Environmental Protection Agency, to calculate avoidable all-cause mortality by rolling back the maximum 8 h daily average concentration of ozone to different values and used the WTP method to calculate the economic benefits brought about by controlling ozone concentration. Therefore, this study adopted BenMAP, an environmental benefit evaluation model developed by the US Environmental Protection Agency, to conduct a health impact assessment.

Overall, the existing research has made notable progress, but there is still much room for improvement. First, existing studies have focused on the impact of air pollutants on economic benefits, and there is less research on how they affect our health. Second, most existing studies focused on $PM_{2.5}$ or O_3, but collaborative investigations of these two closely related pollutants are lacking. Finally, most studies of $PM_{2.5}$ and O_3 focused on a national scale or single city, lacking the targeted research of key areas. To fill the gaps in existing research, this study uses the BenMAP model to evaluate the effects of $PM_{2.5}$ and O_3 on residents' health in BTH according to the health impact function, further monetising and quantitatively estimating the long- and short-term health effects using the WTP method and cost of illness method, respectively, while also calculating the healthcare costs of residents caused by the pollution of the two pollutants. The calculated results intuitively demonstrate the economic impacts of $PM_{2.5}$ and O_3 pollution and provide a basis for proposing policies for $PM_{2.5}$ and O_3.

2. Data and Methods

2.1. Data Sources

2.1.1. Monitoring Data of $PM_{2.5}$ and O_3

The concentration data of $PM_{2.5}$ and O_3 used in this study comprised historical monitoring data from air quality monitoring stations in the BTH region from 2018 to 2021. There are 97 state-controlled monitoring stations with all available data in the BTH region, including 18 in Beijing; 21 in Tianjin; 12 in Shijiazhuang; 7 in Baoding; 6 in Handan; 5 in Zhangjiakou, Chengde, and Tangshan; 4 in Qinhuangdao, Cangzhou, and Xingtai; and 3 in Langfang and Hengshui. A distribution map of the air quality monitoring stations in the BTH region is shown in Figure 1.

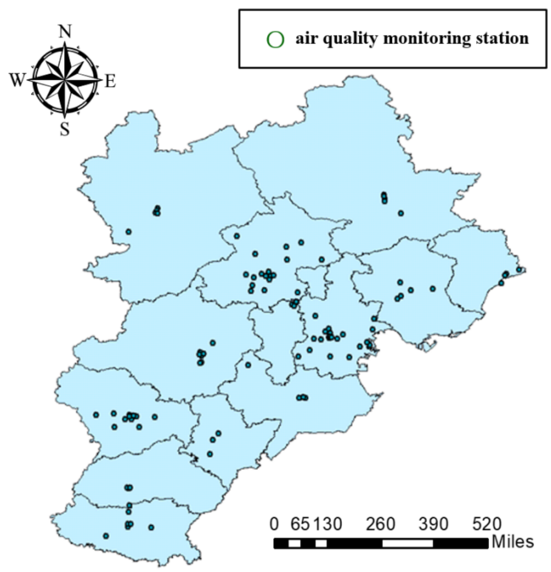

Figure 1. Distribution of air quality monitoring stations in Beijing–Tianjin–Hebei.

According to the concentration data of $PM_{2.5}$ and O_3 monitored by 97 state-controlled air quality monitoring stations in the Beijing–Tianjin–Hebei region from 2018 to 2021, we plotted a 2018–2021 distribution of $PM_{2.5}$ and O_3 concentrations in Beijing–Tianjin–Hebei based on BenMAP, respectively, as shown in Figures 2 and 3.

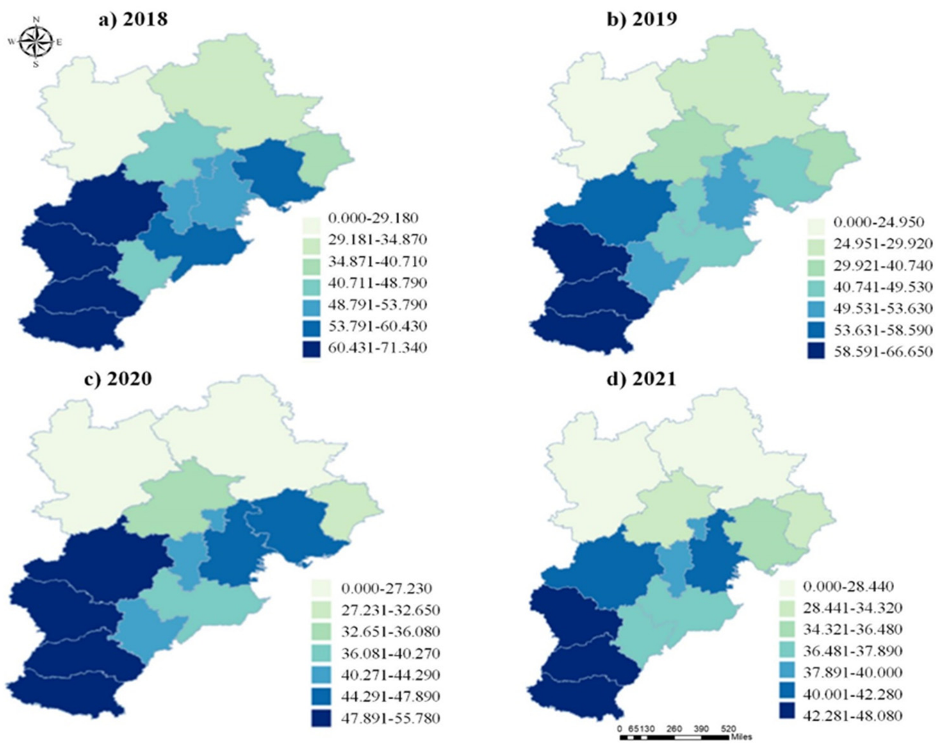

Figure 2. Distribution of $PM_{2.5}$ concentration in Beijing–Tianjin–Hebei in 2018–2021.

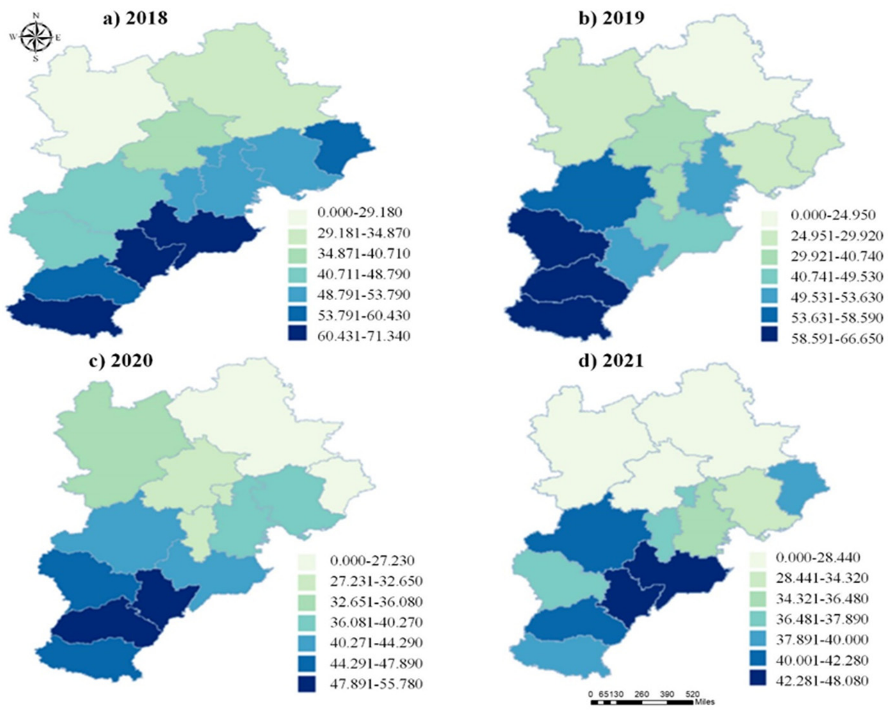

Figure 3. Distribution of O_3 concentration in Beijing–Tianjin–Hebei in 2018–2021.

2.1.2. Population Data

The permanent residents living in the BTH region belong to the exposed population. Because of the large population flow in the BTH region, the permanent population can represent the resident population more effectively than the registered population. Therefore, the permanent residents living in the BTH region were taken as the exposed population. The data were obtained from the statistical yearbooks of Beijing, Tianjin, and Hebei from 2018 to 2021 [38–40].

2.1.3. Health Effect Terminal

This study selected the health impact terminal based on an epidemiological study on the relationship between $PM_{2.5}$, O_3, and health in China. The selection criteria were as follows: only health impacts related to $PM_{2.5}$ and O_3 that were reported in China were selected. The relationship between pollutant concentration and health impacts can be quantitatively expressed using the exposure–response coefficient. Morbidity or mortality data for health terminals impacts can be obtained from relevant statistical yearbooks or reports in China.

2.1.4. Baseline Mortality and Morbidity Data

The relevant data came from the China Health Statistics Yearbook from 2019 to 2022 [41]. Because the corresponding mortality and morbidity data are not given for the prefecture-level cities in Hebei Province, the health impact data of 11 prefecture-level cities in Hebei Province were replaced by the data of Hebei Province.

2.1.5. Baseline Concentrations of $PM_{2.5}$ and O_3

The baseline concentration of pollutants refers to the minimum concentration of a pollutant that poses a threat to the health of residents. The baseline concentration of pollutants has an impact on the measurement results of the health impact and is an important variable in the health impact assessment model. In this study, the primary concentration (35 $\mu g/m^3$) in China's Ambient Air Quality Standard (GB3095-2012) [42] and primary concentration (100 $\mu g/m^3$) of O_3_8 h were used as the baseline thresholds for $PM_{2.5}$ and O_3, respectively.

2.1.6. Exposure Reaction Coefficient

The exposure–response coefficient (β), which can be gained from the studies on epidemiology in China, is a key factor in health impact assessment and reveals the quantitative relationship between the change in pollutant concentration and terminal morbidity or mortality of population health [43,44]. Considering the differences in race, sex, incidence rate, and other parameters of the target population in domestic and foreign research, this paper used the Meta method to carry out statistical analysis on the results of domestic epidemiological studies when determining the β value. In addition, this paper selected the exposure–response coefficient according to the following principles: ① select the literature published from 2015 to 2022 with BTH as the research object, followed by the literature in North China and areas with a similar pollution status to the BTH region; ② select research results under the single pollution model; ③ determine the average morbidity or mortality and 95% confidence interval (or standard error) of health impact terminals. We selected 29 articles using the CNki, WanFang Data, Web of Science, PubMed, and other platforms. The selected literature covered a wide range of fields, and the publication dates of the studies were close to 2018 [45–49]. See Tables 1 and 2 for details.

Table 1. Exposure–response coefficient of long-term health impact terminal.

Pollutant	Long-Term Health Effects	
	Health Terminal	**β (95%CL)**
$PM_{2.5}$	Premature deaths	1.74% (1.25%, 2.23%)
	Chronic bronchitis	5.68% (3.37%, 7.99%)
O_3	Death from respiratory diseases	0.53% (0.21%, 0.85%)
	Cardiovascular disease death	0.5% (0.2%, 0.8%)

Table 2. Exposure–response coefficient of short-term health impact terminal.

Pollutant	Short-Term Health Effects	
	Health Impact Terminal	**β (95%CL)**
$PM_{2.5}$	Asthma disease	3.85% (1.98%, 5.72%)
	Hospitalization of respiratory system disease	2.84% (1.79%, 3.89%)
	Hospitalization of cardiovascular diseases	0.66% (0.35%, 0.96%)
	Respiratory system disease outpatient	0.52% (0.36%, 0.67%)
	Cardiovascular disease outpatient	0.47% (0.45%, 0.49%)
O_3	Hospitalization of respiratory system disease	0.73% (0.26%, 1.21%)
	Hospitalization for cardiovascular system disease	0.01% (0, 0.01%)
	Respiratory system disease outpatient	0.42% (0.31%, 0.52%)

2.2. Research Method

2.2.1. Construction of Health Impact Assessment Model

To quantitatively characterise the impact of pollutants on human health, this study estimated the number of premature deaths and morbidity caused by $PM_{2.5}$ and O_3 pollution by constructing a health impact function including the exposure–response coefficient. The exposure–response coefficient is derived from cohort studies in epidemiology, revealing the impact of long-term exposure on human health. A standard health impact function should contain the following four components: excessive concentration of pollutants, population exposure level, baseline incidence of health terminal, and exposure–response coefficient. The linear logarithmic health impact function constructed in this study is as follows:

$$\Delta \mathrm{Pop} = \left(1 - e^{-\beta \Delta Q}\right) \times \mathrm{incidence} \times \mathrm{Pop} \quad (1)$$

In Formula (1), ΔPop refers to the health impact caused by an excessive concentration of pollutants (person) (increase in the number of patients or deaths), β represents the exposure–response coefficient, ΔQ refers to the excessive concentration of air pollutants, incidence represents the baseline incidence of each health terminal (i.e., mortality and morbidity), and Pop refers to the exposure level of the population (person) (i.e., the number of permanent residents in the BTH region at the end of the year, in this paper).

2.2.2. Long-Term Healthcare Cost Calculation Model

This study used the value of a statistical life (VSL) method to estimate the healthcare costs of death terminals caused by pollutant exposure. VSL stands for economic value, and it is calculated in investigations and studies to evaluate individuals' willingness to pay (WTP) for reducing the risk of mortality [50]. It is mainly determined by gross national product and consumer price index, and it increases with an increase in residents' income. The health benefit of total deaths in year i was calculated using Equations (2) and (3).

$$E_{d,i} = \Delta \mathrm{Pop}_{d,i} \times e_{d,i} \quad (2)$$

$$E_i = \sum E_{d,i} \quad (3)$$

where E_i represents the healthcare cost of all health terminals in i year, $E_{d,i}$ is the healthcare cost of a health terminal in year i, $\Delta Pop_{d,i}$ is the influence of pollutant concentration change on the health terminal population in year i, and $e_{d,i}$ is the unit economic loss of the health terminal in year i, that is, the VSL value corresponding to each health terminal.

This study first estimated the statistical life value of Beijing residents in the target year according to Beijing's GDP and CPI from 2018 to 2021, and the calculation formula used is outlined in Equation (4).

$$VSL_{bj,i} = VSL_{bj,k} \times (1 + \%\Delta P + \%\Delta G)^{\alpha} \tag{4}$$

where $VSL_{bj,i}$ is the VSL value (CNY 10,000) of Beijing in year i, $VSL_{bj,k}$ is the VSL value of Beijing residents in year K, %ΔP and %ΔG are the growth rate of CPI and GDP in Beijing from year K to i, respectively, and α is the income elasticity coefficient. This paper took α as 0.8. Owing to the different economic levels and residents' ideas in Tianjin and Hebei, the VSL of residents differed by location. Therefore, this study calculated the VSL values of residents in other cities in the BTH region using the benefit conversion method. The basic calculation formula used is outlined in Equation (5).

$$VSL_{n,i} = VSL_{bj,i} \times \left(I_{n,i}/I_{bj,i}\right)^{e} \tag{5}$$

where $VSL_{n,i}$ is the VSL value (CNY 10,000) of BTH city n in year i, $VSL_{bj,i}$ is the VSL value of Beijing in year i, $I_{n,i}$ is the per capita disposable income of BTH city n in year i, $I_{bj,i}$ is the per capita disposable income of Beijing, and e is income elasticity (generally taking e value as 1). Table 3 lists the calculated VSL values for the BTH region in each year.

Table 3. VSL value of BTH from 2018 to 2021 (CNY 10,000).

City	2018	2019	2020	2021
Beijing	238.09	251.38	251.46	273.58
Tianjin	150.83	157.32	158.82	173.08
Handan	88.26	94.13	97.49	106.83
Xingtai	76.56	82.87	86.09	93.47
Hengshui	75.86	81.87	85.2	94.4
Zhangjiakou	83.34	89.63	92.98	102.07
Chengde	75.12	80.98	84.1	93.6
Tangshan	115.72	122.73	126.29	137.37
Qinhuangdao	93.75	99.86	102.91	112.16
Langfang	113.7	120.96	124.43	136.23
Cangzhou	88.85	94.31	97.38	106.31
Baoding	82.88	88.18	91.28	103.05
Shijiazhuang	102.47	108.83	112.1	122.4

2.2.3. Short-Term Healthcare Cost Calculation Model

The disease cost method is often used to estimate the additional cost of treating chronic diseases caused by excessive pollutant concentrations. This study used this method to estimate two health terminals, inpatient and outpatient, and the calculation formula is as follows:

$$C_{i,k} = \left(C_{pi,k} + GDP_{pi} \times T_{pi,k}\right) \times \Delta Pop_{i,k} \tag{6}$$

where $C_{i,k}$ is the hospitalisation or outpatient cost of health terminal k in year i, $C_{pi,k}$ is the unit hospitalisation or outpatient cost of health terminal k in year i, GDP_{pi} is the daily average of per capita GDP in year i, $T_{pi,k}$ is the lost time d caused by the hospitalisation of health terminal k in year I, and the lost time caused by outpatient services was calculated as 0.5 d. $\Delta Pop_{i,k}$ is the influence of pollutant concentration changes on health impact terminal K in year i.

Because the relevant statistics do not distinguish the outpatient expenses of different diseases in detail and because single outpatient expenses are relatively small, this study did not distinguish them. This study considered the annual per capita outpatient expenses of Beijing, Tianjin, and Hebei in the China Health Statistics Yearbook from 2019 to 2022 as the outpatient expenses for respiratory and cardiovascular diseases (Table 4).

Table 4. Average outpatient expenses and sick expenses in the BTH region from 2018 to 2021.

Year	Unit Outpatient Expenses/CNY			Unit Outpatient Day/Day	Average Cost per Unit of Asthma Disease/CNY
	Beijing	Tianjin	Hebei Province		
2018	572.04	356.265	251.475	0.5	15,396.465
2019	589.47	380.415	269.325		15,733.515
2020	716.205	480.165	304.395		16,093.035
2021	713.79	475.02	307.965		16,800.84

This study referred to previous estimation methods [51] to obtain hospitalisation expenses and lengths of stays. The average hospitalisation expenses and hospitalisation days for respiratory system diseases were replaced with the average medical expenses and average hospitalisation days for the main respiratory system diseases, such as bronchitis, pulmonary tuberculosis, and pulmonary heart disease. Similarly, the average hospitalisation expenses and days of cardiovascular system diseases were replaced with the average hospitalisation expenses and days of major cardiovascular diseases, such as congestive heart failure and myocardial infarction (Table 5).

Table 5. Hospitalization expenses and days in BTH from 2018 to 2021.

Year	Unit Hospitalization Days/Days		Unit Hospitalization Expenses/CNY	
	Respiratory System Diseases	Cardiovascular System Diseases	Respiratory System Diseases	Cardiovascular System Diseases
2018	10.7	8.9	8533.924	17,584.2
2019	10.17	8.3	8720.532	18,529.73
2020	10.2	10.3	8991.392	18,665.4
2021	10.4	10.5	9433.409	19,440.17

According to the results of the fifth and sixth National Health Service Surveys, the average indirect outpatient expenses account for 5% of the per capita outpatient medical expenses, and the average indirect hospitalisation expenses account for 7% of the average hospitalisation expenses. Therefore, the unit outpatient expenses were 1.05 times the per capita outpatient medical expenses, and the unit hospitalization expenses were 1.07 times the per capita hospitalization medical expenses.

3. Results and Discussion

3.1. Analysis of Health Impact Assessment Results in BTH

3.1.1. Health Effects of $PM_{2.5}$

Figure 4 shows the long-term health effects of $PM_{2.5}$ in BTH from 2018 to 2021. Shijiazhuang, Handan, Baoding, and Tianjin were the areas most affected by long-term exposure. In 2018, the number of people affected by long-term $PM_{2.5}$ exposure was 108,100. With the continuous reduction in the $PM_{2.5}$ concentration in 2019–2021, the number of people affected by negative long-term health effects in BTH decreased by 23.2%, 32.8%, and 53.6%, respectively, and the decline rate increased annually. The areas with the greatest decline in long-term health effects were Tangshan, Beijing, and Cangzhou. Based on the proportion of long-term health effects, the proportion of the two kinds of effects in each year was basically the same: patients with chronic bronchitis accounted for approximately 80%, and those who died prematurely accounted for 20%. Therefore, the long-term impact of $PM_{2.5}$ on human health is mainly reflected in the onset of chronic bronchitis.

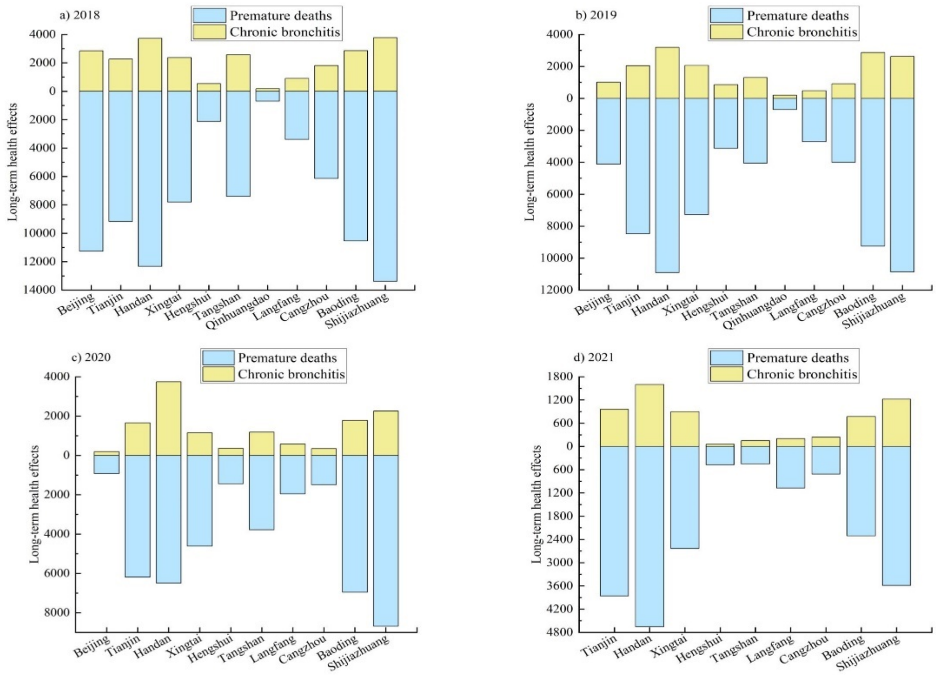

Figure 4. Long-term health effects of $PM_{2.5}$ in BTH from 2018 to 2021.

Table A1 shows the short-term health effects of $PM_{2.5}$ in BTH from 2018 to 2021. The number of people affected by short-term health effects was greater than that affected by long-term health effects. In 2018, the number of people with short-term exposure in the BTH region was 3,564,100, which continually decreased from 2019 to 2021, with decreasing rates of 10.51%, 45.38%, and 54.06%, respectively. Short-term effects began to decline rapidly in 2020, which was related to a significant reduction in pollutant concentrations in 2020. From the perspective of the proportion of short-term health impacts, the number of outpatients was accounted for the most at approximately 93.2%, while hospitalisation accounted for 4.6% (hospitalisation mainly caused by respiratory system diseases) and asthma for 2.2%. From the perspective of cities, the areas most affected by long- and short-term exposure were Shijiazhuang, Handan, Beijing, and Baodin.

3.1.2. Health Effects of O_3

Figure 5 presents the long-term health effects of O_3 in the BTH region from 2018 to 2021. The total number of regional deaths caused by O_3 decreased annually, and the number of people affected by long-term health effects in 2018–2021 was 7391, 6717, 5673, and 4282, respectively. Among these, the death toll from cardiovascular disease accounted for approximately 68% of the long-term impact, which is the health impact most affected by ozone exposure, and excessive O_3 concentrations increased the death rates correlated with cardiovascular diseases. From the perspective of cities, the cities most affected by long-term health effects were Beijing, Tianjin, Shijiazhuang, and Baoding, and their health effects accounted for more than 48% of the total health effects in BTH.

Table A2 presents the short-term health effects of O_3 in BTH from 2018 to 2021. The short-term health effect of O_3 exposure decreased from 5,405,800 in 2018 to 3,225,300 in 2021, which is a decrease of 40.34%, reflecting the achievements of the BTH region in the treatment of O_3. However, the short-term health effects of O_3 exhibited an unbalanced distribution. Beijing, Tianjin, Shijiazhuang, and Handan were the most affected by short-term ozone exposure, and the health effects here accounted for approximately 50% of the total health effects in BTH. In contrast to the long-term health effects, among the short-term health effects of O_3, respiratory system health terminals (including inpatient and outpatient services for respiratory system diseases) were the most affected, accounting for approximately 95% of the total short-term health effects. Therefore, in the short term,

O_3 mainly causes respiratory system diseases by acting on the human respiratory tract; oppositely, in the long term, O_3 reacts with cells and tissues to affect the cardiovascular system.

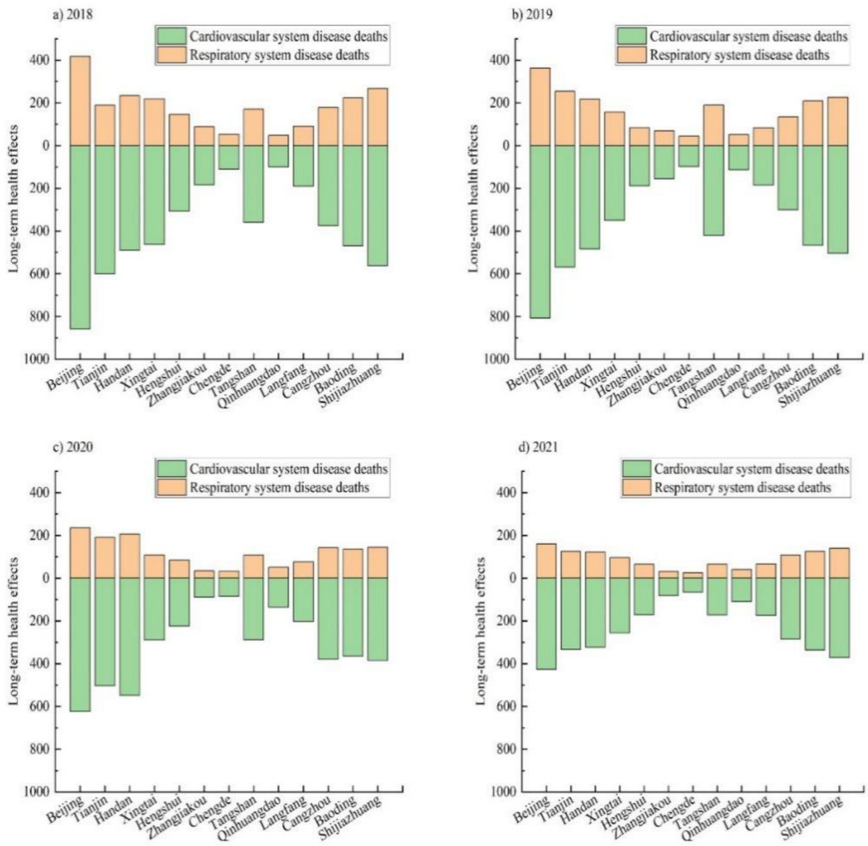

Figure 5. Long-term health effects of O_3 in BTH from 2018 to 2021.

3.2. Calculation of Healthcare Costs in BTH

3.2.1. Long-Term Healthcare Cost Calculation

(1) Long-term Healthcare Costs of $PM_{2.5}$

This study used the VSL value of BTH to estimate the economic impact of death. For chronic bronchitis, treatment is slow and affects people's quality of life and spirit; therefore, it is difficult to estimate its healthcare cost through medical expenses such as hospitalisation and outpatient services. Referring to the recommendation of the World Bank [52], this study assumed that residents' willingness to pay to avoid chronic bronchitis was equivalent to 32% of the local VSL. Figure 6 shows the long-term healthcare costs of $PM_{2.5}$ exposure in BTH from 2018 to 2021.

The healthcare cost attributed to long-term $PM_{2.5}$ pollution in BTH showed a downward trend from 2018 to 2021. Regional healthcare costs decreased from CNY 59.775 billion in 2018 to CNY 15.023 billion in 2021 and as a proportion of GDP from 0.76% to 0.16%, which is a decrease of 79.3%. With the annual increase in VSL, healthcare costs continue to decrease; owing to the effective control of $PM_{2.5}$, the number of patients who die prematurely and suffered from chronic bronchitis has decreased. The cities where the decline in healthcare costs is lower than the regional average decline are Tianjin, Handan, Xingtai, Langfang, Baoding, and Shijiazhuang, which are heavily polluted areas; therefore, they are the key areas for $PM_{2.5}$ pollution control in the BTH region.

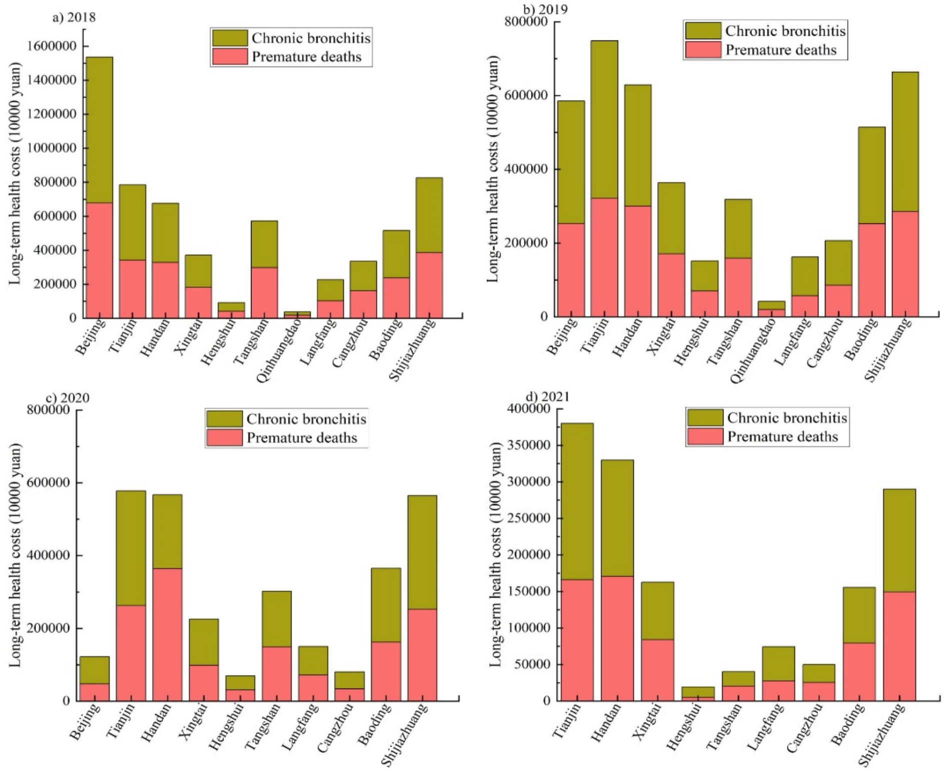

Figure 6. Long-term healthcare costs of $PM_{2.5}$ exposure in 2018–2021 (CNY 10,000).

(2) Long-term Healthcare Costs of O_3

Figure 7 shows the long-term healthcare costs associated with O_3 exposure in the BTH region from 2018 to 2021. According to the estimation results, regional healthcare costs decreased from CNY 9.064 billion in 2018 to CNY 5.975 billion in 2021, which is a decrease of 45.85%, being slightly lower than that of $PM_{2.5}$. From the perspective of cities, Beijing, Xingtai, Hengshui, Zhangjiakou, and Tangshan fell below the regional average. Except for Xingtai, the healthcare costs of other heavily polluted cities decreased gradually. Among the deaths caused by the long-term exposure to O_3, the healthcare costs of death from cardiovascular diseases were higher because the number of deaths from cardiovascular diseases was higher than that from respiratory diseases. Therefore, in the long term, O_3 exposure is harmful to the human cardiovascular system and results in higher healthcare costs.

3.2.2. Short-Term Healthcare Cost Calculation

(1) Short-term Healthcare Costs of $PM_{2.5}$

Table A3 shows the short-term healthcare costs of $PM_{2.5}$ exposure from 2018 to 2021. Short-term healthcare costs decreased from CNY 4.472 billion in 2018 to CNY 1.072 billion in 2021 and as a proportion of GDP from 0.06% to 0.01%, which is a decrease of 80%. Cities with a lower-than-average decline and more serious pollution were Handan, Xingtai, and Shijiazhuang, which were similar to those that were below the average regarding the short-term exposure healthcare costs of $PM_{2.5}$. In terms of the composition of healthcare costs, the healthcare costs caused by respiratory system diseases accounted for approximately 75% of the total short-term healthcare costs, which was three times greater than the hospitalisation and outpatient expenses for cardiovascular diseases. Therefore, for long- and short-term health effects, $PM_{2.5}$ pollution is more harmful to the human respiratory system, and its healthcare costs mainly come from the loss of life value and the treatment expenses of related diseases caused by deaths due to respiratory system diseases.

(2) Short-term Healthcare Costs of O_3

Table A4 shows the short-term healthcare costs associated with O_3 exposure in the BTH region from 2018 to 2021. According to the estimation results, the short-term healthcare costs of O_3 exposure were low and their proportion of the regional GDP was less than 0.05%. In contrast to long-term exposure, short-term exposure to O_3 is harmful to the human respiratory system. O_3 enters the human respiratory tract through breathing and reacts with the respiratory epithelium and surface liquid in a short time, causing respiratory system diseases, which in turn leads to an increase in the number of respiratory system outpatients.

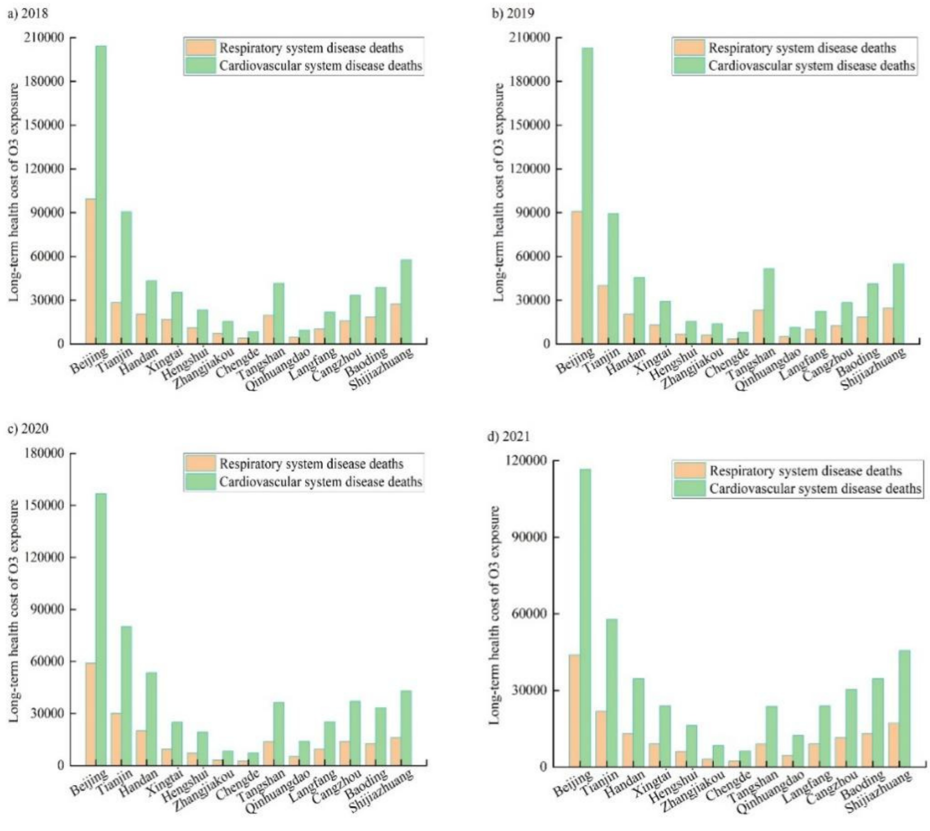

Figure 7. Long-term healthcare costs of O_3 exposure from 2018 to 2021 (CNY 10,000).

3.2.3. Total Healthcare Costs of $PM_{2.5}$ and O_3 in BTH

By summing up the long-term and short-term healthcare costs of $PM_{2.5}$ and O_3 in the BTH region, we obtained the healthcare costs of the two pollutants from 2018 to 2021, as shown in Table 6.

As shown in Table 6, the healthcare cost caused by $PM_{2.5}$ in the BTH region decreased annually from CNY 64.246 billion in 2018 to CNY 16.095 billion in 2021, which is a decrease of 74.9%. The healthcare costs of O_3 also decreased annually. In 2018–2021, the healthcare costs regarding ozone exposure decreased by only 33.3%, which is far lower than the healthcare costs of $PM_{2.5}$. This is because the BTH region is mainly polluted by $PM_{2.5}$, and the number of people affected by the long-term health effects of $PM_{2.5}$ is higher. On the other hand, the number of people affected by the short-term health effects of O_3 is higher, but the long-term healthcare costs are much higher than the short-term healthcare costs. In turn, $PM_{2.5}$ healthcare costs in the BTH region are mainly caused by $PM_{2.5}$ pollution, which are approximately 3.5 times greater than the healthcare costs caused by O_3 pollution. Meanwhile, regarding the control of $PM_{2.5}$ pollution, it is necessary to continue strengthening O_3 pollution control. It is worth noting that the total healthcare costs caused by $PM_{2.5}$ and O_3 pollution in the BTH have shown a downward trend from 2018 to 2021. Regional healthcare costs decreased from CNY 77.085 billion in 2018 to CNY 24.652 billion in 2021, and as a proportion of the GDP from 0.98% to 0.26%. The BTH region has achieved remarkable results in the pollution control of $PM_{2.5}$ and O_3. To intuitively understand the changes in $PM_{2.5}$ and O_3 healthcare costs in the BTH region, a spatial distribution map of healthcare costs in the BTH region was drawn, as shown in Figure 8.

Table 6. Healthcare costs in BTH from 2018 to 2021 (CNY 100 million).

Year	City	$PM_{2.5}$				O_3				The Total Health-care Cost	Proportion of GDP (%)
		Long-Term Healthcare Cost	Short-Term Healthcare Cost	Total	Proportion of GDP (%)	Long-Term Healthcare Cost	Short-Term Healthcare Cost	Total	Proportion of GDP (%)		
2018	Beijing	1.53.665	8.043	161.708	0.488	30.342	10.174	40.516	0.122	202.225	0.611
	Tianjin	78.513	5.514	84.026	0.629	11.896	5.359	17.255	0.129	101.281	0.758
	Handan	67.704	5.947	73.615	2.260	6.380	2.920	9.300	0.285	82.950	2.545
	Xingtai	37.231	3.650	40.882	2.099	5.214	2.672	7.886	0.405	48.768	2.504
	Hengshui	9.229	0.975	10.204	0.738	3.442	1.809	5.251	0.380	15.456	1.119
	Zhangjiakou	-	-	-	-	2.269	1.092	3.361	0.235	3.361	0.235
	Chengde	-	-	-	-	1.235	0.675	1.911	0.139	1.911	0.139
	Tangshan	57.250	3.875	61.115	0.970	6.122	2.487	8.609	0.137	69.724	1.107
	Qinhuangdao	3.758	0.328	4.087	0.271	1.390	0.629	2.019	0.134	6.106	0.405
	Langfang	22.642	1.697	24.339	0.802	3.213	1.260	4.473	0.147	28.812	0.950
	Cangzhou	33.563	2.953	36.516	1.118	4.913	2.305	7.218	0.221	43.734	1.339
	Baoding	51.661	5.080	56.742	1.609	5.734	2.830	8.564	0.243	65.306	1.852
	Shijiazhuang	82.542	6.652	89.194	1.659	8.494	3.528	12.023	0.224	101.217	1.883
	total	597.749	44.715	642.464	0.815	90.643	37.740	128.384	0.163	770.848	0.977
2019	Beijing	58.501	2.957	61.458	0.174	29.369	9.785	39.155	0.111	100.613	0.284
	Tianjin	74.858	5.052	79.911	0.569	12.930	4.791	17.721	0.126	97.632	0.695
	Handan	62.900	5.345	68.246	1.958	6.598	2.989	9.588	0.275	77.833	2.233
	Xingtai	36.419	3.478	39.898	1.882	4.202	2.105	6.307	0.298	46.205	2.179
	Hengshui	15.171	1.489	16.660	1.107	2.225	1.148	3.372	0.224	20.032	1.331
	Zhangjiakou	-	-	-	-	2.010	0.925	2.962	0.191	2.962	0.191
	Chengde	-	-	-	-	1.146	0.614	1.760	0.120	1.760	0.120
	Tangshan	31.857	2.134	33.991	0.493	7.483	3.040	10.523	0.153	44.514	0.646
	Qinhuangdao	4.215	0.339	4.554	0.283	1.633	0.733	2.366	0.147	6.920	0.429
	Langfang	16.221	1.372	17.593	0.550	3.237	1.254	4.491	0.141	22.084	0.691
	Cangzhou	20.655	1.950	22.604	0.630	4.106	1.927	6.033	0.168	28.638	0.798
	Baoding	51.401	4.470	55.871	1.481	5.960	2.838	8.798	0.233	64.668	1.714
	Shijiazhuang	66.395	5.467	71.863	1.237	7.936	3.282	11.217	0.193	83.080	1.430
	total	431.778	34.055	465.833	0.552	88.835	35.457	124.293	0.147	590.125	0.699
2020	Beijing	12.219	0.722	12.941	0.036	21.579	8.328	29.907	0.083	42.849	0.119
	Tianjin	57.773	3.947	61.720	0.043	11.014	4.862	15.877	0.113	77.597	0.551
	Handan	56.699	3.313	60.012	1.650	7.363	3.597	10.959	0.301	70.971	1.952
	Xingtai	22.572	2.309	24.881	1.131	3.433	1.854	5.287	0.240	30.168	1.371
	Hengshui	6.971	0.721	7.692	0.493	2.639	1.467	4.106	0.263	11.789	0.756
	Zhangjiakou	-	-	-	-	1.139	0.585	1.724	0.108	1.724	0.108
	Chengde	-	-	-	-	1.000	0.581	1.581	0.102	1.581	0.102
	Tangshan	30.199	2.130	32.329	0.448	5.000	2.216	7.216	0.100	39.545	0.548
	Qinhuangdao	0.000	0.000	0.000	0.000	1.929	0.936	2.866	0.170	2.866	0.170
	Langfang	14.994	1.029	16.022	0.485	3.473	1.425	4.898	0.148	20.920	0.634
	Cangzhou	8.032	0.764	8.796	0.238	5.098	2.590	7.688	0.208	16.484	0.446
	Baoding	36.566	3.505	40.071	1.013	4.579	2.360	6.939	0.175	47.010	1.189
	Shijiazhuang	56.433	4.582	61.025	1.028	5.924	2.634	8.559	0.144	69.583	1.172
	total	302.467	23.022	325.489	0.376	74.172	33.435	107.607	0.124	433.096	0.501
2021	Beijing	0.000	0.000	0.000	0.000	16.044	5.921	21.966	0.055	21.966	0.055
	Tianjin	38.008	2.483	40.491	0.258	7.961	3.343	11.303	0.072	51.794	0.330
	Handan	32.980	2.404	35.333	0.860	4.762	2.216	6.978	0.170	42.361	1.029
	Xingtai	16.293	1.330	17.623	0.726	3.289	1.679	4.986	0.205	22.609	0.932
	Hengshui	1.947	0.239	2.186	0.128	2.239	1.167	3.407	0.200	5.592	0.328
	Zhangjiakou	-	-	-	-	1.147	0.556	1.703	0.099	1.703	0.099
	Chengde	-	-	-	-	0.855	0.464	1.319	0.078	1.319	0.078
	Tangshan	4.027	0.253	4.281	0.052	3.264	1.410	4.675	0.057	8.955	0.109
	Qinhuangdao	0.000	0.000	0.000	0.000	1.693	0.785	2.478	0.134	2.478	0.134
	Langfang	7.443	0.572	8.015	0.226	3.285	1.274	4.559	0.128	12.573	0.354
	Cangzhou	4.986	0.372	5.358	0.129	4.182	2.034	6.216	0.149	11.574	0.278
	Baoding	15.551	1.173	16.724	0.409	4.764	2.302	7.067	0.173	23.791	0.582
	Shijiazhuang	29.000	1.892	30.891	0.476	6.263	2.653	8.917	0.137	39.808	0.613
	total	150.234	10.717	160.951	0.168	59.750	25.823	85.573	0.089	246.524	0.257

From the regional distribution of total healthcare costs, the central and southern parts of the BTH region (Beijing, Tianjin, Baoding, Shijiazhuang, Xingtai, and Handan) have the highest healthcare costs, whereas the northern parts (Zhangjiakou, Chengde, and Qinhuangdao) have the lowest healthcare costs. Beijing was the city with the highest healthcare costs in 2018–2019, mainly due to the high costs of medical treatment and VSL. In 2020–2021, the healthcare costs in Beijing dropped sharply because of the obvious effect of pollutant control, the concentrations of $PM_{2.5}$ and O_3 decreased, and the number of people affected by negative health effects decreased.

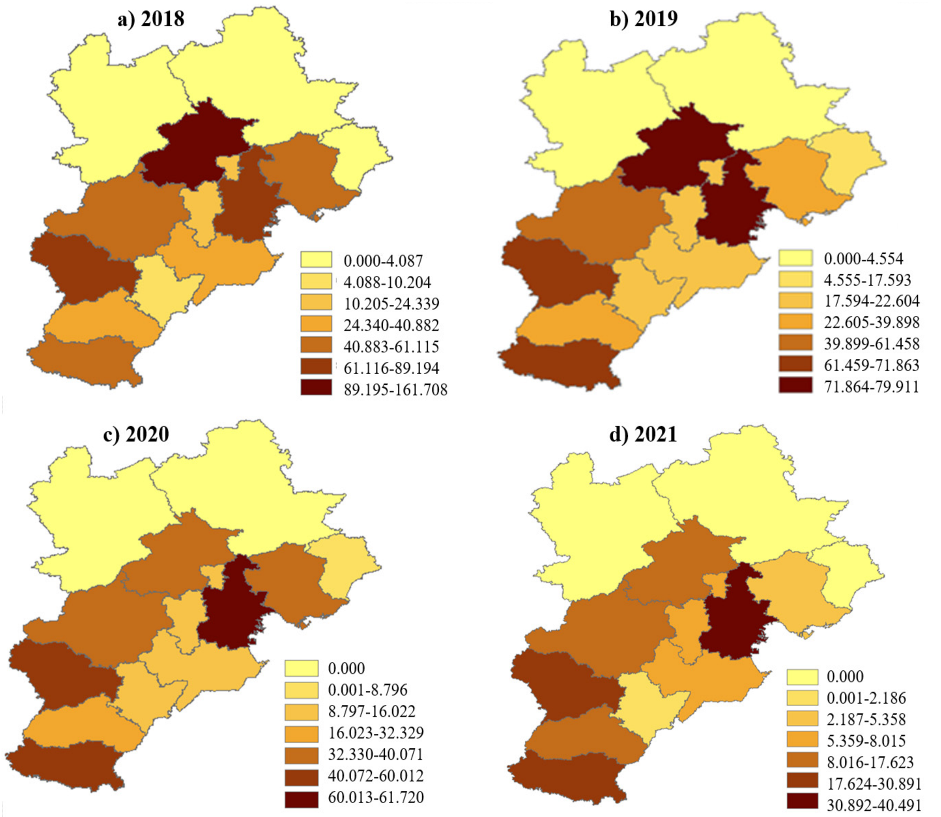

Figure 8. Healthcare costs in the BTH region from 2018 to 2021 (CNY 100 million).

4. Conclusions and Policy Implications

Based on the domestic epidemiological research results, this study used BenMAP as the core method to assess the healthcare costs of residents caused by $PM_{2.5}$ and O_3 pollution in the BTH region from 2018 to 2021. The main conclusions are as follows:

(1) From the results of the health impact assessment, the long-term exposure to $PM_{2.5}$ in the BTH region led to an increase in the incidence of chronic bronchitis, while short-term exposure mainly affected the respiratory system. Moreover, O_3 can easily cause people to suffer from respiratory diseases in the short term. However, looking at the results, O_3 exposure led to higher mortality rates from cardiovascular diseases in the long term.

(2) The calculation results of the healthcare costs showed that the healthcare costs caused by $PM_{2.5}$ and O_3 in the BTH region were CNY 77.1 billion in 2018, accounting for about 1% of the regional GDP in that year. With the improvement in pollution control, this proportion decreased annually and was 0.7%, 0.5%, and 0.3% in 2019–2021, respectively.

(3) According to the types of pollutants, the healthcare costs caused by $PM_{2.5}$ and O_3 decreased each year. The healthcare costs of $PM_{2.5}$ decreased from CNY 64.25 billion to CNY 16.1 billion, which is a decrease of 75%. The healthcare costs caused by O_3 decreased from CNY 59 billion to CNY 24.7 billion, which is a decrease of 58%, being slightly lower than that of $PM_{2.5}$.

Based on the above research conclusions and the governance status of the BTH region, this study proposes the following policy suggestions:

(1) The fundamental solution to lower the healthcare costs of $PM_{2.5}$ and O_3 is to control them, including collaborative governance among three regional governments at the

horizontal level; multi-party collaborative governance with joint participation of government, enterprises, and the public at the vertical level; and by basing the latter on the former. In addition, the ecological compensation mechanism should be further improved. Owing to its geographical proximity and the same atmospheric environment, BTH formed a cross-polluted area of $PM_{2.5}$ and O_3. To control the cross-border pollution of $PM_{2.5}$ and O_3, an ecological compensation mechanism should be established in which the Hebei Province would receive compensation, and Beijing and Tianjin should be the compensation parties. Beijing and Tianjin assisted Hebei through capital and technology for cleaner production, technological transformation, energy conservation, and consumption reduction to reduce the concentrations of $PM_{2.5}$ and O_3, seek out pollution sources, and prevent and control them from their root causes.

(2) Improve ozone control measures. The BTH region should make full use of the regional advantages around the capital, make use of the rich scientific research resources in the region to carry out new technological research and development, establish a pollution source emission list, and optimise the statistical calculation method of precursor emissions. At the same time, it is necessary to further promote the application and popularization of new energy vehicles to reduce the emissions of $PM_{2.5}$ and O_3 in the transportation sector.

(3) Improve pollution control laws and regulations. The Chinese municipal government should further improve the laws and regulations on ecological compensation in the BTH region to ensure smooth policy implementation. In the legislative process, the government should establish the relevant subjects for collaborative legislation. The local subject was the forerunner, the central subjects comprised overall planning and the governor, and the public were the subject of feedback evaluation.

This study evaluated the health effects of $PM_{2.5}$ and O_3 in the BTH region and quantified the health losses related to $PM_{2.5}$ and O_3, which are practically significant with regard to contributing to the atmospheric governance and health protection in the BTH region in China, and even the whole country. However, this study also has its limitations. First, when estimating the health effects of $PM_{2.5}$ and O_3, the same exposure–response coefficient was used for the same health terminal in the BTH region. However, due to the various reasons for the generation of various pollutants, the sensitivity of residents to pollutants was also different, so the coefficient likely varied from city to city. Therefore, determining how to develop an exposure–response coefficient that conforms to the local characteristics more accurately is an aim that needs to be focused on in future research. Secondly, due to the COVID-19 pandemic, the data in this paper that were related to inpatient and outpatient costs and days of hospitalization in 2020 and 2021 may be inflated in comparison to pandemic-free conditions. Establishing how to eliminate the effects of the COVID-19 pandemic will be our future research direction.

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Conflicts of Interest: Author Zhujun Zhu was employed by the company Shanxi Gemeng US-China Clean Energy R&D Center Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Short-term health effects of $PM_{2.5}$ in the BTH region from 2018 to 2021.

City	2018 Asthma	2018 Respiratory Diseases Hospitalizations	2018 Cardiovascular Disease Hospitalizations	2018 Outpatient Services	2018 Total	2019 Asthma	2019 Respiratory Diseases Hospitalizations	2019 Cardiovascular Disease Hospitalizations	2019 Outpatient Services	2019 Total
Beijing	10,470	18,119	3318	430,382	462,289	3801	6548	1187	153,914	165,450
Tianjin	8555	14,832	2728	353,907	380,021	7895	13,680	2512	353,907	377,994
Handan	11,694	20,461	3839	498,840	534,834	10,298	17,979	3356	498,840	530,473
Xingtai	7349	12,815	2386	309,829	332,379	6846	11,925	2215	309,829	330,815
Hengshui	1967	3402	622	80,690	86,682	2918	5063	932	80,690	89,603
Zhangjiakou	-	-	-	-	-	-	-	-	-	-
Chengde	-	-	-	-	-	-	-	-	-	-
Tangshan	6957	12,109	2245	291,540	312,852	3767	6518	1193	291,540	303,017
Qinhuangdao	641	1104	200	25,980	27,925	646	1114	202	25,980	27,943
Langfang	3173	5505	1013	131,513	141,204	2516	4356	798	131,513	139,184
Cangzhou	5753	9996	1846	239,662	257,258	3724	6445	1180	239,662	251,011
Baoding	9949	17,364	3240	420,835	451,388	8675	15,085	2792	420,835	447,387
Shijiazhuang	12,666	22,138	4143	538,329	577,276	10,212	17,788	3304	538,329	569,633
total	79,174	137,846	25,581	3,321,507	3,564,107	61,300	102,554	18,966	3,006,793	3,189,614

City	2020 Asthma	2020 Respiratory diseases hospitalizations	2020 Cardiovascular disease hospitalizations	2020 Outpatient services	2020 Total	2021 Asthma	2021 Respiratory diseases hospitalizations	2021 Cardiovascular disease hospitalizations	2021 Outpatient services	2021 Total
Beijing	854	1468	265	34,359	36,946	-	-	-	-	-
Tianjin	5747	9934	1815	235,396	252,892	3567	6153	1119	145,047	155,886
Handan	6062	10,514	1935	251,099	269,610	4324	7480	1369	177,537	190,710
Xingtai	4298	7451	1370	177,705	190,824	2442	4218	769	99,710	107,140
Hengshui	1333	2302	419	54,361	58,415	435	750	136	17,578	18,899
Zhangjiakou	-	-	-	-	-	-	-	-	-	-
Chengde	-	-	-	-	-	-	-	-	-	-
Tangshan	3513	6076	1112	144,174	154,874	411	707	128	16,554	17,800
Qinhuangdao	-	-	-	-	-	-	-	-	-	-
Langfang	1812	3128	570	73,918	79,429	993	1710	310	40,205	43,217
Cangzhou	1379	2376	431	55,871	60,056	658	1132	205	26,529	28,523
Baoding	6484	11,233	2062	267,503	287,282	2130	3672	667	86,481	92,949
Shijiazhuang	8125	14,108	2603	337,847	362,683	3320	5730	1043	135,247	145,341
total	39,606	68,591	12,582	1,621,501	1,742,280	18,280	31,552	5745	744,889	800,466

Note: the concentrations of pollutants in cities without data in the table are lower than the first-class standard, and it is considered that the pollutants have no health effects on residents, that is, the number of people with adverse health effects is 0, and there are no healthcare costs (the same is applicable to the tables below).

Table A2. Short-term health effects of O_3 in the BTH region from 2018 to 2021.

City	2018			Total	2019			Total
	Respiratory System Hospitalizations	**Cardiovascular System Hospitalizations**	**Respiratory System Outpatients**		**Respiratory System Hospitalizations**	**Cardiovascular System Hospitalizations**	**Respiratory System Outpatients**	
Beijing	18,066	3958	892,623	914,648	16,758	3670	827,596	848,024
Tianjin	12,651	2773	625,409	640,834	11,782	2581	582,180	596,544
Handan	10,301	2260	509,819	522,381	10,035	2201	496,514	508,750
Xingtai	9690	2129	480,314	492,133	7261	1592	359,120	367,973
Hengshui	6450	1419	320,002	327,871	3895	853	192,475	197,223
Zhangjiakou	3885	851	191,989	196,725	3217	704	158,843	162,764
Chengde	2351	514	115,994	118,859	2033	445	100,276	102,754
Tangshan	7546	1654	373,137	382,337	8725	1915	431,839	442,478
Qinhuangdao	2118	464	104,555	107,137	2347	514	115,867	118,727
Langfang	4034	884	199,315	204,233	3838	841	189,568	194,247
Cangzhou	7882	1729	389,966	399,577	6242	1367	308,383	315,993
Baoding	9862	2164	487,968	499,994	9685	2123	478,749	490,557
Shijiazhuang	11,814	2592	584,659	599,065	10,445	2290	516,476	529,211
total	106,649	23,392	5,275,751	5,405,792	96,263	21,097	4,757,884	4,875,244
City	2020			Total	2021			Total
	Respiratory system hospitalizations	Cardiovascular system hospitalizations	Respiratory system outpatients		Respiratory system hospitalizations	Cardiovascular system hospitalizations	Respiratory system outpatients	
Beijing	12,789	2797	630,807	646,393	8752	1912	431,119	441,782
Tianjin	10,324	2260	509,749	522,333	6859	1499	338,109	346,467
Handan	11,206	2461	555,033	568,701	6637	1453	327,643	335,733
Xingtai	5932	1300	293,078	300,310	5238	1147	258,626	265,010
Hengshui	4599	1009	227,616	233,224	3529	773	174,361	178,663
Zhangjiakou	1828	399	90,068	92,295	1677	366	82,594	84,637
Chengde	1774	388	87,445	89,606	1362	298	67,116	68,776
Tangshan	5893	1290	291,014	298,197	3544	775	174,663	178,982
Qinhuangdao	2788	611	137,779	141,178	2248	492	110,974	113,714
Langfang	4154	910	205,150	210,214	3592	786	177,266	181,645
Cangzhou	7776	1706	384,776	394,257	5853	1282	289,140	296,275
Baoding	7474	1635	368,784	377,893	6882	1507	339,822	348,211
Shijiazhuang	7869	1722	388,445	398,037	7621	1668	376,127	385,415
total	84,405	18,489	4,169,743	4,272,637	63,794	13,957	3,147,559	3,225,310

Table A3. Short-term healthcare costs of $PM_{2.5}$ exposure in 2018–2021 (CNY 100 million).

Year	City	Asthma	Respiratory Disease Hospitalizations	Cardiovascular Disease Hospitalizations	Respiratory Outpatient Services	Cardiovascular Outpatient Services	Total	Proportion of GDP (%)
2018	Beijing	1.612	2.359	0.707	1.825	1.540	8.043	0.024
	Tianjin	1.317	1.791	0.560	1.001	0.845	5.514	0.041
	Handan	1.800	1.915	0.707	0.807	0.618	5.947	0.182
	Xingtai	1.132	1.193	0.435	0.483	0.408	3.650	0.187
	Hengshui	0.303	0.321	0.114	0.129	0.108	0.975	0.071
	Zhangjiakou	-	-	-	-	-	-	-
	Chengde	-	-	-	-	-	-	-
	Tangshan	1.071	1.315	0.438	0.570	0.481	3.875	0.062
	Qinhuangdao	0.099	0.110	0.038	0.045	0.038	0.328	0.022
	Langfang	0.489	0.571	0.194	0.241	0.203	1.679	0.056
	Cangzhou	0.886	0.979	0.344	0.404	0.341	2.953	0.090
	Baoding	1.532	1.674	0.599	0.692	0.584	5.080	0.144
	Shijiazhuang	1.950	2.208	0.778	0.930	0.785	6.652	0.124
	total	12.190	14.472	4.914	7.126	6.013	44.715	0.057
2019	Beijing	0.598	0.853	0.253	0.680	0.574	2.957	0.008
	Tianjin	1.242	1.652	0.516	0.891	0.752	5.052	0.036
	Handan	1.620	1.715	0.618	0.755	0.637	5.345	0.153
	Xingtai	1.077	1.110	0.404	0.481	0.406	3.478	0.164
	Hengshui	0.459	0.478	0.171	0.207	0.175	1.489	0.009
	Zhangjiakou	-	-	-	-	-	-	-
	Chengde	-	-	-	-	-	-	-
	Tangshan	0.593	0.708	0.233	0.326	0.275	2.134	0.031
	Qinhuangdao	0.102	0.111	0.038	0.048	0.041	0.339	0.021
	Langfang	0.396	0.452	0.153	0.202	0.170	1.372	0.043
	Cangzhou	0.586	0.631	0.220	0.278	0.234	1.950	0.054
	Baoding	1.365	1.454	0.517	0.615	0.519	4.470	0.118
	Shijiazhuang	1.607	1.774	0.620	0.795	0.671	5.467	0.094
	total	9.645	10.936	3.742	5.278	4.453	34.055	0.040
2020	Beijing	0.137	0.199	0.062	0.175	0.148	0.722	0.002
	Tianjin	0.925	1.175	0.391	0.790	0.667	3.947	0.028
	Handan	0.976	1.059	0.382	0.468	0.410	3.313	0.091
	Xingtai	0.692	0.734	0.268	0.334	0.028	2.309	0.105
	Hengshui	0.215	0.231	0.083	0.105	0.088	0.721	0.046
	Zhangjiakou	-	-	-	-	-	-	-
	Chengde	-	-	-	-	-	-	-
	Tangshan	0.565	0.705	0.237	0.338	0.285	2.130	0.030
	Qinhuangdao	0.000	0.000	0.000	-	-	-	-
	Langfang	0.292	0.334	0.116	0.155	0.131	1.029	0.031
	Cangzhou	0.222	0.247	0.087	0.113	0.096	0.764	0.021
	Baoding	1.043	1.117	0.405	0.510	0.430	3.505	0.089

Table A3. *Cont.*

Year	City	Asthma	Respiratory Disease Hospitalizations	Cardiovascular Disease Hospitalizations	Respiratory Outpatient Services	Cardiovascular Outpatient Services	Total	Proportion of GDP (%)
2020	Shijiazhuang	1.307	1.477	0.525	0.690	0.582	4.582	0.077
	total	6.374	7,278	2.554	3.698	3.119	23.022	0.027
2021	Beijing	-	-	-	-	-	-	-
	Tianjin	0.599	0.727	0.241	0.496	0.419	2.483	0.016
	Handan	0.727	0.753	0.270	0.355	0.299	2.404	0.058
	Xingtai	0.410	0.416	0.150	0.192	0.162	1.330	0.055
	Hengshui	0.073	0.075	0.027	0.035	0.029	0.239	0.014
	Zhangjiakou	-	-	-	-	-	-	-
	Chengde	-	-	-	-	-	-	-
	Tangshan	0.069	0.082	0.027	0.041	0.034	0.253	0.003
	Qinhuangdao	-	-	-	-	-	-	-
	Langfang	0.167	0.183	0.063	0.086	0.073	0.572	0.016
	Cangzhou	0.110	0.118	0.041	0.056	0.047	0.372	0.009
	Baoding	0.358	0.365	0.131	0.173	0.146	1.173	0.029
	Shijiazhuang	0.558	0.600	0.210	0.284	0.240	1.892	0.029
	total	3.071	3.319	1.161	1.717	1.449	10.717	0.011

Table A4. Short-term healthcare costs of O_3 exposure in 2018–2021 (CNY 100 million).

City	2018			Total	Proportion of GDP (%)	2019			Total	Proportion of GDP (%)
	Respiratory System Hospitalizations	Cardiovascular System Hospitalizations	Respiratory System Outpatient Services			Respiratory System Hospitalizations	Cardiovascular System Hospitalizations	Respiratory System Outpatient Services		
Beijing	2.353	0.844	6.978	10.174	0.031	2.228	0.817	6.740	9.785	0.028
Tianjin	1.527	0.569	3.262	5.359	0.040	1.324	0.531	2.935	4.791	0.034
Handan	0.982	0.416	1.521	2.920	0.090	0.977	0.425	1.586	2.989	0.086
Xingtai	0.902	0.388	1.382	2.672	0.137	0.691	0.305	1.108	2.105	0.099
Hengshui	0.609	0.260	0.940	1.809	0.131	0.376	0.165	0.607	1.148	0.076
Zhangjiakou	0.368	0.156	0.568	1.092	0.076	0.312	0.136	0.504	0.952	0.061
Chengde	0.227	0.095	0.353	0.675	0.049	0.201	0.087	0.326	0.614	0.042
Tangshan	0.820	0.323	1.344	2.487	0.039	0.972	0.393	1.676	3.040	0.044
Qinhuangdao	0.211	0.087	0.332	0.629	0.042	0.238	0.101	0.394	0.733	0.045
Langfang	0.418	0.169	0.672	1.260	0.042	0.405	0.168	0.681	1.254	0.039
Cangzhou	0.772	0.322	1.211	2.305	0.071	0.627	0.268	1.032	1.927	0.054
Baoding	0.951	0.400	1.479	2.830	0.080	0.931	0.409	1.498	2.838	0.075
Shijiazhuang	1.178	0.487	1.863	3.528	0.066	1.065	0.452	1.765	3.282	0.056
total	11.318	4.517	21.905	37.740	0.048	10.347	4.258	20.852	35.457	0.042

Table A4. *Cont.*

City	2020			Total	Proportion of GDP (%)	2021			Total	Proportion of GDP (%)
	Respiratory system hospitalizations	Cardiovascular system hospitalizations	Respiratory system outpatient services			Respiratory system hospitalizations	Cardiovascular system hospitalizations	Respiratory system outpatient services		
Beijing	1.783	0.652	5.939	8.328	0.023	1.284	0.473	4.164	5.921	0.015
Tianjin	1.221	0.487	3.155	4.862	0.035	0.869	0.341	2.133	3.343	0.021
Handan	1.128	0.486	1.982	3597	0.099	0.709	0.301	1.206	2.216	0.054
Xingtai	0.584	0.254	1.016	1.854	0.084	0.545	0.234	0.918	1.697	0.070
Hengshui	0.461	0.199	0.808	1.467	0.094	0.374	0.159	0.634	1.167	0.069
Zhangjiakou	0.184	0.079	0.322	0.585	0.037	0.178	0.076	0.302	0.556	0.032
Chengde	0.182	0.077	0.321	0.581	0.037	0.148	0.062	0.253	0.464	0.027
Tangshan	1.683	0.275	1.257	2.216	0.031	0.442	0.174	0.794	1.410	0.017
Qinhuangdao	0.292	0.123	0.521	0.936	0.056	0.250	0.104	0.431	0.785	0.043
Langfang	0.444	0.185	0.795	1.425	0.043	0.405	0.167	0.702	1.274	0.036
Cangzhou	0.809	0.343	1.438	2.590	0.070	0.647	0.270	1.116	2.034	0.049
Baoding	0.743	0.321	1.295	2.360	0.060	0.736	0.312	1.254	2.302	0.056
Shijiazhuang	0.824	0.347	1.463	2.634	0.044	0.845	0.352	1.457	2.653	0.041
total	9.294	3.828	20.313	33.435	0.039	7.433	3.026	15.364	25.823	0.027

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