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A health-based assessment of particulate air pollution in urban areas of Beijing in 2000–2004

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Abstract

Particulate air pollution is a serious problem in Beijing. The annual concentration of particulate matter with aerodynamic diameter less than 10 μm (PM_{10}), ranging from 141 to 166 $\mu\text{g m}^{-3}$ in 2000–2004, could be very harmful to human health. In this paper, we presented the mortality and morbidity effects of PM_{10} pollution based on statistical data and the epidemiological exposure–response function. The economic costs to health during the 5 years were estimated to lie between US\$1670 and \$3655 million annually, accounting for about 6.55% of Beijing’s gross domestic product each year. The total costs were apportioned into two parts caused by: the local emissions and long-range transported pollution. The contribution from local emissions dominated the total costs, accounting on average for 3.60% of GDP. However, the contributions from transported pollution cannot be neglected, and the relative percentage to the total costs from the other regions could account for about 45%. An energy policy and effective measures should be proposed to reduce particulate matter, especially $\text{PM}_{2.5}$ pollution in Beijing to protect public health. The Beijing government also needs to cooperate with the other local governments to reduce high background level of particulate air pollution.

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1. Introduction

It is well known that air pollution can harm human health. Worldwide, there are more than 2.7 million deaths due to air pollution (World Health Organization (WHO), 2003). Among air pollutants, particulate matter (PM) has been found to be the most damaging to human health (USA-EPA, 1997, 1999). Many epidemiological studies in the past 20 years have revealed that the PM pollution, especially the fine particles ($\text{PM}_{2.5}$, particulate matter with an aerodynamic diameter less than 2.5 μm)

are associated with higher rates of mortality and morbidity under long- or short-term exposure (Morgan et al., 2003; Pope et al., 1995a,b, 2002, 2004; Schwartz et al., 1996; Xu et al., 1995a,b).

The rapid urbanization experienced in China since the 1980s has been accompanied by increasingly poor air quality. According to the World Bank, 16 of the world’s 20 most polluted cities are in China (Economist, 2004). Urban air pollution has become a barrier to sustainable development. Beijing, as a megacity (with a population of ≥ 10 million; Gurjar and Lelieveld, 2005) and the capital of China, has a very serious air pollution problem. The concentration of particles with aerodynamic diameters less than 10 μm (PM_{10}) monitored by the Beijing Environmental Protection Bureau (BJEPB)

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from 2000 to 2004 indicated that particulate matter was a major problem in Beijing (BJEPB, 2000–2004). During these years, the annual PM_{10} concentrations ranged between 141 and 166 $\mu\text{g m}^{-3}$ and were nearly three times the Grade 1 national standard, i.e., 50 $\mu\text{g m}^{-3}$. Epidemiological research using time series methods has shown the relationship between ambient PM concentrations and human health in Beijing (Dong et al., 1995; Chang et al., 2003a,b) and has quantified the daily mortality and morbidity relative to PM concentrations. With the 2008 Olympic Games approaching, the air quality in Beijing must be improved to project a positive image of the city to the world.

While toxicological studies can determine how PM impacts the human respiratory system, economic assessments are also required for the public and the policy makers. Relevant research has been carried out in some cities and countries around the world (Beirut, Lebanon: El-Fadel and Massoud, 2000; Singapore: Quah and Boon, 2003; Shanghai, China: Kan and Chen, 2004), indicating that the total economic cost of PM accounted for 4.31% and 1.03% of the gross domestic product (GDP) of Singapore and Shanghai, respectively. The present study evaluated the health impacts of PM_{10} pollution in Beijing from 2000 to 2004 and estimated the economic costs. The results should provide a useful reference for pollution control policies.

2. Methods

2.1. PM_{10} concentration, mortality, and morbidity data

Monitoring stations often measure several air pollutants, e.g. PM_{10} , SO_2 , NO_2 , CO, O_3 . The variation in ambient concentrations of these pollutants may be dominated by atmospheric diffusion, so that levels of the different pollutants are correlated. To avoid overestimating health effects, Künzli et al. (2000) derived estimates from a single indicator pollutant. Although fine particle ($PM_{2.5}$) pollution has a stronger association with adverse human health effects, it has not been measured in China. Researchers (Quah and Boon, 2003; Kan and Chen, 2004) therefore used PM_{10} as an indicator. The annual PM_{10} concentrations for 2000–

2004 in Beijing were reported in the BJEPB annual reports (Table 1), the data were averaged over seven urban substations. Consequently, the domain of the health effects being studied in the present study is the urban areas of Beijing. The high annual concentrations could have originated from several emission sources. The population of Beijing, both total and urban, continues to increase (Table 1; BMBS, 2005). Coal remains a major energy source in Beijing; in 2003 nearly 27 million tons of coal provided more than 50% of the total energy consumption (BJEPB, 2003). The Capital Steel Corporation, located west of urban Beijing, has the capacity to produce 6 million tons of steel each year. Sand storms frequently affect Beijing in the spring. Road dust is resuspended by shearing force as well as by the turbulent wakes of vehicles (Song et al., 2006).

The health effects of PM_{10} include mortality, especially from cardiovascular and respiratory problems, and morbidity, e.g., acute and chronic bronchitis and asthma attacks, accompanied by outpatient visits to internal medicine and pediatrics and hospital admission (Pope et al., 1995a).

Data were obtained from the yearbooks of the Beijing Municipal Bureau of Public Health (BMBPH) for 2000–2004; incidence rates are listed in Table 2. The health endpoints were excluded if they were not available or difficult to assess, e.g., lung function changes or restricted activity days.

2.2. Exposure–response function

Exposure–response functions are used in epidemiologic studies to link air pollution and its adverse health effects. Such exposure–response functions often include various forms, such as exponential form (Kan and Chen, 2004) and linear form (Quah and Boon, 2003; Seethaler et al., 2003; Wang and Mauzerall, 2006). The Cox's proportional hazard model was often selected to determine the effect of air pollution on morbidity and mortality rates after adjusting for other factors such as cigarette smoking, education level, body mass index, occupational exposure to dust or fumes, as well as age and sex of the subjects. However, some study showed the increase of adverse health effects in the lower range

Table 1
Annual PM_{10} concentration ($\mu\text{g m}^{-3}$), population (in millions), and GDP (in million US\$) for Beijing, 2000–2004

Year	2000	2001	2002	2003	2004
PM_{10} concentration	162	165	166	141	149
Urban population	8.036	8.689	9.448	9.246	9.431
Total population	12.779	13.648	14.232	14.564	14.927
GDP	29,943.6	34,381.9	38,813.5	44,256.4	51,752.7

Table 2

The incidence rates (per thousand persons) of health endpoints in Beijing, 2000–2004

Health endpoints	Frequency					References
	2000	2001	2002	2003	2004	
Mortality for individuals 30 years and older	10.13	10.13	10.13	10.13	10.13	Wang and Mauzerall (2006)
Chronic bronchitis	13.90	13.90	13.90	13.90	13.90	CMH (1998)
Respiratory hospital admission	6.3	6.3	5.8	4.8	5.8	BMBPH (2001–2004)
Cardiovascular hospital admission	11.9	11.8	10.3	9.5	10.9	BMBPH (2001–2004)
Outpatient visits to internal medicine	757.9	761.8	717.7	886.9	745.8	BMBPH (2001–2004)
Outpatient visits—pediatrics	220.5	223.9	210.0	206.2	215.2	BMBPH (2001–2004)
Acute bronchitis	37.2	37.2	37.2	37.2	37.2	Wang et al. (1994)
Asthma attacks						
(children <15 years)	69.3	69.3	69.3	69.3	69.3	Chen et al. (2002)
(adults ≥15 years)	56.1	56.1	56.1	56.1	56.1	Chen et al. (2002)

Note: Except data from BMBPH, other data cited from epidemiological papers were same in the 5 years, because we could not find precise research data annually.

of air pollution was rapid than that in the higher range of air pollution (e.g., Xu et al., 1995a). They were at variance with exponential exposure–response function. Thus, the linear function is selected in this study. The adverse health effects of air pollution were calculated as:

$$\Delta E = E - E_0 = E_0\beta(C - C_0) \quad (1)$$

where β is the exposure–response coefficient, C and C_0 are the ambient and threshold pollutant concentrations and E and E_0 are the health effects at C and C_0 , respectively. The ΔE or the health damage caused by increased pollution can be calculated if β , C , C_0 , and E are known.

The β values for short-time mortality and morbidity in this study are listed in Table 3, they were selected as follows: data from epidemiologic studies in Beijing were compared with data from the studies in China in general; if the data from these two groups of studies differed, the meta-analysis results were used. Aunan and Pan (2004) provided exposure–response coefficients for China according to a meta-analysis, based on the review of the exposure–response function for health effects and PM pollution. The results were very close to those used in Kan and Chen (2004), as both cited literatures were almost same. For long-time mortality, we acknowledge that the cohort studies were absent in China and the PM pollution level is much higher than that in Western countries. The meta-analysis results from short-time studies in Asia (almost from China and Korea) for PM₁₀ pollution on all-case mortality were similar with the studies in American and Europe (see Table 20 in HEI, 2004). The relative risks could be transferred. Aunan and Pan (2004) also suggested that the estimates from

US cohort studies may be used in China and the results be likely to be on the high side. Therefore, the results for long-time mortality from cohort studies from Dockery et al. (1993) and Pope et al. (1995b) were used in this study.

The threshold concentration, C_0 , considered the “reference concentration”, is an important and sensitive parameter in the determination of the health effects of pollution. WHO’s guideline on environmental impact assessment (WHO, 2000) recommended such values could be an ambient concentration of zero, some non-zero “clean” concentration, or a concentration mandated by an air quality standard. Ezzati et al. (2002) used a background value, 15 $\mu\text{g m}^{-3}$. Quah and Boon (2003)

Table 3

Exposure–response coefficients of PM₁₀ (per 10 $\mu\text{g m}^{-3}$) and references

Health endpoints	Mean (95% CI)	References
Mortality for individuals 30 years and older	0.0430 (0.0260, 0.0610)	Dockery et al. (1993), Pope et al. (1995b)
Chronic bronchitis	0.0577 (0.0193, 0.0961)	Jing et al. (2000)
Respiratory hospital admission	0.0120 (0.0080, 0.0160)	Wong et al. (2002), Aunan and Pan (2004)
Cardiovascular hospital admission	0.0070 (0.0030, 0.0110)	Wong et al. (2002), Aunan and Pan (2004)
Outpatient visits—internal medicine	0.0034 (0.0019, 0.0049)	Xu et al. (1995a)
Outpatient visits—pediatrics	0.0039 (0.0014, 0.0064)	Xu et al. (1995a)
Acute bronchitis	0.0550 (0.0189, 0.0911)	Jing et al. (2000)
Asthma attack		
(children <15 years)	0.0695	Wei et al. (2000)
(adults ≥15 years)	0.0390 (0.0190, 0.0590)	Künzli et al. (2000)

used the minimum monthly PM_{10} concentration, $24.7 \mu\text{g m}^{-3}$. Kan and Chen (2004) used an average value from a background site, $73.2 \mu\text{g m}^{-3}$ for Shanghai research. However, Morgan et al. (2003) showed that even the levels of particulate air pollution in Sydney were relatively low, e.g., the PM_{10} concentrations ranged only in $16\text{--}26 \mu\text{g m}^{-3}$, it was still found the PM pollution were consistently associated with both daily mortality and hospital admissions, which indicated no threshold concentrations for health effects were present. WHO has concluded that there is no zero-effect threshold for particulates and the health risks are present at any level of exposure (WHO, 1999). Therefore, we selected zero as the threshold concentration.

2.3. Determining the economic costs of health effects

Although there are ethical arguments against placing a value on human life, the value of a statistical life (VOSL) concept was adopted to assess the health effects of PM pollution. VOSL is the value of a small change in the risk associated with the dying of an unnamed member of a large group. It represents an individual's willingness to pay (WTP) for a marginal reduction in the risk of dying. For the valuation of reduced morbidity, besides WTP, the cost of illness (COI) approach could also be used. COI measures the total cost of illness that is imposed on a society (Quah and Boon, 2003). Because a survey of the economic cost of mortality and morbidity from air pollution was not available for China, the benefit transfer approach (BTA) was required. It uses the values of environmental loss of a project to estimate the values of a similar project, assuming that the latter project will have a similar impact (Quah and Boon, 2003; Kan and Chen, 2004).

Most VOSL estimates are for the United States, but results have also been reported for Lebanon and Mexico (El-Fadel and Massoud, 2000; Lopez et al., 2005). In their Shanghai research, Kan and Chen (2004) used WTP results for mortality in Chongqing, China, and USAEPA morbidity results. We used data from a contingent valuation study (CVM) conducted in Chongqing (Wang et al., 2001), where the VOSL of a local resident was about US\$34,750 and could increase by US\$14,550 with an annual income increase of US\$145.8. Based on the Chongqing resident income data from 1998 and 2000 (Chongqing Municipal Bureau of Statistics, 1999, 2001), we computed the VOSL in Chongqing in 2000 to be about \$44309. The adjustment considered the difference between the annual income in Chongqing and Beijing, while the estimation of VOSL in Beijing was transferred on the marginal WTP and income. Referencing the

Chongqing research, the VOSL in Beijing could be calculated as follows:

$$VOSL_{BJ} = VOSL_{CQ} \times (I_{BJ}/I_{CQ})^e \quad (2)$$

where $VOSL_{BJ}$ and $VOSL_{CQ}$ are the VOSL of Beijing and Chongqing, respectively, I_{BJ} and I_{CQ} are the personal income of Beijing and Chongqing, respectively, and e is the elastic coefficient of WTP and is assumed to be 1.0.

The Shanghai study results and the income difference between Beijing and Shanghai were consulted to get health endpoint values for bronchitis and asthma in Beijing. For respiratory and cardiovascular hospital admissions and outpatient visits to internal medicine and pediatrics, the COI was used for estimates. The health impact value was equal to the sum of hospital admission costs, fees for service, and lost wages during days spent in hospital. Because of a lack of hospital admissions expense data for Beijing, we used data from the China Statistical Yearbook of Public Health (China Ministry of Health, 2003–2005) and considered the average expense for the same kind of disease as the expenses of respiratory and cardiovascular hospital admissions.

The uncertainties were considered both in exposure–response functions and the economic valuation. The Monte Carlo method was used to estimate the uncertainties (mean and 95% CI). The calculations were performed by the Fortran programme.

3. Results and discussion

3.1. Health effects

Even though the problem was serious every year, PM pollution levels can be divided into two categories. The first 3 years, from 2000 to 2002, were more polluted, with concentrations of $162\text{--}166 \mu\text{g m}^{-3}$. The next 2 years, 2003–2004, were a little better with concentrations of 141 and $149 \mu\text{g m}^{-3}$ respectively. We should acknowledge that chronic effects of long-term exposure that take years to develop cannot be fully quantified in such studies. There is no evidence that all health effects, for example, pollution exposure in 2003, will be experienced in the same year. However if this were the case, the estimated health effects, e.g., the annual numbers of mortality and morbidity due to PM_{10} pollution in the urban areas are listed in Table 4.

Briefly, the status of PM pollution could be divided into two stages, even though the problem was serious each year. The first 3 years, from 2000 to 2002, were more polluted, with concentrations of $162\text{--}166 \mu\text{g m}^{-3}$. The next 2 years, 2003–2004, were a little better with

Table 4

Estimated number of cases (and 95% CI) attributable to particulate air pollution in urban areas of Beijing

Health endpoints	Attributable number of cases (95% CI)				
	2000	2001	2002	2003	2004
Mortality for individuals	19,188	20,970	25,146	22,885	23,733
30 years and older	(13,943, 23,304)	(15,271, 25,430)	(18,325, 30,479)	(16,363, 28,105)	(17,078, 29,019)
Chronic bronchitis	52,370	57,158	62,342	55,990	58,834
	(27,178, 68,013)	(29,797, 74,067)	(32,547, 80,725)	(28,103, 73,947)	(29,921, 77,186)
Respiratory hospital admission	8211	9015	9070	6402	8270
	(5827, 10,420)	(6403, 10,059)	(6444, 11,499)	(4513, 8168)	(5844, 10,529)
Cardiovascular hospital admission	9676	10,545	10,064	7846	9650
	(4497, 14,464)	(4907, 15,751)	(4684, 15,026)	(3618, 11,794)	(4464, 14,476)
Outpatient visits to internal medicine	317,368	350,956	361,579	374,562	338,584
	(18,2851, 447,845)	(202,294, 495,067)	(208,449, 509,993)	(215,116, 529,868)	(194,690, 478,517)
Outpatient visits to pediatrics	104,841	117,100	120,100	99,014	111,025
	(40,143, 166,457)	(44,872, 185,819)	(46,033, 190,546)	(37,704, 157,805)	(42,367, 176,689)
Acute bronchitis	136,829	149,371	162,929	146,053	153,869
	(71,499, 178,196)	(78,394, 194,101)	(85,632, 211,566)	(73,892, 193,393)	(78,688, 202,011)
Asthma attacks	188,481	204,224	221,525	195,594	205,354
	(132,353, 230,465)	(142,226, 250,442)	(153,278, 272,345)	(132,223, 244,199)	(138,759, 255,932)

concentrations of 141 and 149 $\mu\text{g m}^{-3}$, respectively. The health impacts of PM pollution in 2002 may have been worse than in the other years because the PM concentration (166 $\mu\text{g m}^{-3}$) and the population figures were highest at that time. Although the PM concentrations in 2000 and 2001 were close to those in 2002, generally, the health effects were less extreme than in 2002, because the population increased by about 759,000 people that year.

In 2003, both the PM_{10} concentration (141 $\mu\text{g m}^{-3}$) and the attributable number of cases were relatively lower among the 5 years, with the exception that the number of outpatient visits to internal medicine was somewhat high (374562) because of the outbreak of Severe Acute Respiratory Syndrome (SARS) in spring of 2003. The concentration in 2004 (149 $\mu\text{g m}^{-3}$) was close to that in 2003, but the estimated number of deaths due to PM pollution was higher (23,733) because of increased population (9.431 million) in the area.

3.2. Economic valuation of health impacts

Table 5 gives the unit values for various health endpoints in Beijing. According to only one survey study of Chong Qing in China, the VOSL values in our study are much lower than the US values. The valuation parameters differ by year due to different economic development level, income level, law system etc.

Using the estimated data in Tables 4 and 5, the economic cost of health impacts of PM pollution in Beijing from 2000 to 2004 was obtained (Table 6); the annual figures for 2000–2004 were about 1669.7,

2122.5, 2797.3, 2977.0, and US\$3655.5 million, respectively. GDP is a common indicator that reflects the overall economic situation, the economic burden of disease that the public have to endure cannot be expressed in the macroeconomic method (Wan et al., 2005). However, in order to let the public have impression on the quantitative assessment of their public welfare loss, we still compare the economic valuations with Beijing's annual GDP. The economic valuations accounted for 5.58, 6.17, 7.21, 6.73, and 7.06% of the annual Beijing GDP for the 5 years from 2000 to 2004, and were comparable to results for Shijiazhuang (4.3%; Peng et al., 2002) and Singapore (4.31%; Quah and Boon, 2003), and higher than the Shanghai valuation (1.03%; Kan and Chen, 2004). In the Shanghai study, a background site annual average was treated as the reference concentration, as high as 73.2 $\mu\text{g m}^{-3}$, which could contain pollution transported from the urban area of Shanghai and the other districts, such as Jiangsu Province. Hence, the estimated cost due to air pollution was lower than that in this study.

While Beijing's GDP maintained fast growth at 14.0, 14.8, 12.9, 14.0, and 16.9% from 2000 to 2004, respectively, the economic cost of air pollution could not be neglected. The air pollution costs as a percentage of GDP were lowest in 2000 and highest in 2002.

Among all the health impact endpoints, premature death played a dominant role in total costs. Chronic bronchitis also made an important contribution. Moreover, the cost of cardiovascular hospital admission was correspondingly high, while asthma attack contributed the least.

Table 5
Estimated cost (per case) of pollution-related health effects (and 95% CI)

Health endpoints	Cost per case (US\$)					Method	Data sources
	2000	2001	2002	2003	2004		
Mortality	73,066 (67,764, 78,368)	85,585 (79,654, 91,516)	96,284 (89,899, 102,669)	113,612 (106,500, 120,724)	135,397 (127,386, 143,408)	WTP	CMH (2003–2005), CMBS (1999, 2001)
Chronic bronchitis	4832 (620, 16143)	5406 (694, 18,059)	5819 (747, 19,440)	6482 (832, 21,654)	7302 (938, 24,392)	WTP	Kan and Chen (2004), CMH (2003–2005)
Respiratory hospital admission	603	576	592	717	803	COI	CMH (2003–2005)
Cardiovascular hospital admission	1217	1403	1428	2023	1626	COI	CMH (2003–2005)
Outpatient visits to internal medicine	17	23	20	26	28	COI	CMH (2003–2005)
Outpatient visits to pediatrics	17	23	20	26	28	COI	CMH (2003–2005)
Acute bronchitis	6 (2.3, 9.8)	6 (1.9, 10.2)	7 (2.5, 11.5)	7 (2.0, 12.1)	8 (2.4, 13.7)	WTP	Kan and Chen (2004), CMH (2003–2005)
Asthma attacks	4 (1.6, 6.4)	4 (1.3, 6.7)	5 (2.1, 7.9)	5 (1.8, 8.2)	6 (2.4, 9.6)	WTP	Kan and Chen (2004), CMH (2003–2005)

Note: For admission and outpatient visit, the available data did not provide the distribution of the values.

As mentioned above, the annual PM₁₀ concentrations include two parts: one is caused by local emission in Beijing, and one is long-range transported from other cities. The annual background PM₁₀ concentration in Beijing was found at 70 $\mu\text{g m}^{-3}$ (Ministry of Science and Technology, 2002), it is calculated by deducting the effects of the downtown from the measurements in a background site, Ming Tombs, where fewer people live and far away from the city center. Such background concentration could be treated as that principally caused

by the human activity from other distant cities. In other words, the annual PM₁₀ concentration contributed by the local emissions in Beijing was 92, 95, 96, 71 and 79 $\mu\text{g m}^{-3}$ in 2000–2004. The total costs due to air pollution are apportioned into such two parts: local pollution and long-range transported pollution. They were listed in Table 7. The cost contributions from local emission were dominant in the total costs in the 5 years. However, the contributions from the other regions cannot be neglected, as the background concentration

Table 6
Economic cost of health effects of particulate air pollution in urban areas of Beijing in 2000–2004 (in million US\$)

Health endpoints	Estimated economic cost (95% CI)				
	2000	2001	2002	2003	2004
Mortality for individuals	1391.23 (1019.50, 1727.65)	1781.11 (1308.63, 2206.60)	2402.93 (1767.76, 2972.94)	2579.29 (1864.77, 3232.01)	3188.50 (2320.20, 3974.15)
30 years and older					
Chronic bronchitis	253.05 (81.90, 587.02)	309.00 (100.38, 716.31)	362.77 (117.98, 840.83)	362.93 (114.37, 845.87)	429.61 (136.83, 999.35)
Respiratory hospital admission	4.95 (3.51, 6.28)	5.19 (3.69, 5.79)	5.37 (3.81, 6.81)	4.59 (3.23, 5.86)	6.64 (4.69, 8.45)
Cardiovascular hospital admission	11.78 (5.47, 17.60)	14.79 (6.88, 22.10)	14.37 (6.69, 21.46)	15.87 (7.32, 23.86)	15.69 (7.26, 23.54)
Outpatient visits to internal medicine	5.40 (3.11, 7.61)	8.07 (4.69, 11.39)	7.23 (4.17, 10.20)	9.74 (5.59, 13.78)	9.48 (5.45, 13.40)
Outpatient visits to pediatrics	1.78 (0.68, 2.83)	2.69 (1.03, 4.27)	2.40 (0.92, 3.81)	2.57 (0.98, 4.10)	3.11 (1.19, 4.95)
Acute bronchitis	0.81 (0.26, 1.45)	0.89 (0.26, 1.64)	1.12 (0.35, 2.02)	1.01 (0.27, 1.91)	1.21 (0.34, 2.27)
Asthma attacks	0.74 (0.28, 1.26)	0.80 (0.26, 1.42)	1.09 (0.42, 1.84)	0.96 (0.32, 1.69)	1.21 (0.45, 2.08)
Total	1669.74 (1114.71, 2351.70)	2122.54 (1427.01, 2969.52)	2797.28 (1902.64, 3859.91)	2976.96 (1999.27, 4129.08)	3655.45 (2478.63, 5028.19)
Percentage of Beijing's GDP (%)	5.58	6.17	7.21	6.73	7.06

Table 7

Total, internal and external economic costs (in million US\$) and percentage of GDP (%) (mean)

	Economic cost (percentage of GDP)				
	2000	2001	2002	2003	2004
Total	1669.74 (5.58)	2122.54 (6.17)	2797.28 (7.21)	2976.96 (6.73)	3655.45 (7.06)
Local emission	948.25 (3.17)	1222.07 (3.55)	1617.70 (4.17)	1499.04 (3.39)	1938.12 (3.74)
Transported	721.49 (2.41)	900.47 (2.62)	1179.58 (3.04)	1477.92 (3.34)	1717.33 (3.32)

was still high of $70 \mu\text{g m}^{-3}$. To reduce the costs by air pollution in Beijing, both the local and distant emissions should be well controlled.

We should acknowledge that the air pollution from Beijing could be transported to other districts in China, which should lead to the increases of mortality and mobility there. Moreover, only the health endpoints that could be quantitatively valued were selected in this study. Some health endpoints, such as lung function changes, pain and suffering, and restricted activity days, which are known to be associated with PM pollution, were not included, as these data were not available or difficult to assess; in addition, while the outbreak of influenza and SARS could have been included in the raw data we collected, this would have led to the overestimation of health damages. We should also point out that the results in this study could probably be overestimated on some other important reasons. The soil dust (including the primary and resuspended dusts) could account for nearly 50% of PM_{10} concentrations in the northern cities of China (Bi et al., 2007), however, the recent studies (Ito et al., 2006; Mar et al., 2006) found that soil dusts in particulate matter were not associated with daily mortality.

4. Conclusions

Particulate air pollution is a serious health problem in Beijing. Using statistical data for Beijing from 2000 to 2004 and the exposure–response function, we quantified the health impact of PM pollution. The economic cost was high, accounting for about 6.55% of Beijing's GDP on average, while the GDP maintained a fast growth rate of about 14%. The costs from local emissions dominated the total costs, but the long-range transported pollution from the other districts also had a relative high contribution to the health costs in Beijing.

However, we should point that $\text{PM}_{2.5}$ pollution was more associated with premature mortality than PM_{10} in

the epidemiological studies. The validity in this study depends on the extrapolating the observed effects of $\text{PM}_{2.5}$ to PM_{10} . Moreover, the present measurements showed annual $\text{PM}_{2.5}$ concentration in Beijing could account for 60% of the PM_{10} concentrations in Beijing (He et al., 2001), which is much higher than that in Western countries (Dockery et al., 1993; Morgan et al., 2003). Thus, the long-time series measurements and epidemiological related $\text{PM}_{2.5}$ study should be performed in Beijing in the future.

At present, policy to reduce air pollution, especially the $\text{PM}_{2.5}$ pollution is needed urgently and effective measures should be carried out as soon as possible. The emissions from combustion sources, such as coal burning and oil burning, and the secondary products from photochemical reactions contributed mostly in $\text{PM}_{2.5}$ in Beijing (Song et al., 2006). Coal is still a dominant energy source in Beijing, especially in industry for electricity generation (EGU). It could be an effective way to use the advanced coal gasification technologies in the coal-fired EGU. Raw coal used in industrial plants could be replaced by cleaner energy sources, such as natural gas or electric power. A remarkable problem is that the number of motor vehicles is increasing rapidly from 1.5 million in 2000 to 2.4 million in 2004. Conversely, the bicycle use is declining. Beijing government should preserve or restore bicycle lanes and provide free parking facilities to encourage the bicycle use. On the other hand, both the control technologies on tailpipe emission and gasoline quality should be improved in motor vehicles. Reduction of gaseous pollutants, volatile organic compounds and nitrogen oxides from tailpipe exhaust and sulfur dioxide from coal burning could alleviate the fine particles pollution transferred through photochemical reactions. As some toxic organics, such as black carbon could be still abundant in the fine part of road dust in Beijing (Song et al., 2006), the bare soil surfaces should be grassed or wooded.

However, China is a developing country with a rapid economy increase; we acknowledge the large gap between the air pollution level in China and in Western countries. To control the high background level needs the collaboration with other local governments. It is not an easy way to catch up the level in other developed countries.

This study was based on the assumption that the entire population, across urban areas of Beijing, was exposed to the average concentration levels, as recorded at the seven urban air quality monitoring stations. This was a rough estimate. We suggest using atmospheric diffusion models (e.g. ISC3, CALPUFF, and MODEL3-CMAQ) to obtain concentrations at finer spatial

resolutions. More surveys are needed to determine the appropriate economic cost of adverse health effects from PM pollution.

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References

- Aunan K, Pan XC. Exposure–response functions for health effects of ambient air pollution applicable for China — a meta-analysis. *Sci Total Environ* 2004;329:3–16.
- Beijing Environmental Protection Bureau (BJEPB). Annual Report. 2000, 2001, 2002, 2003, 2004. <http://www.bjepb.gov.cn/> [in Chinese].
- Beijing Municipal Bureau of Public Health (BMBPH). Beijing Health Yearbook. Beijing: Beijing Science and Technology Press; 2001–2004 [in Chinese].
- Beijing Municipal Bureau of Statistics (BMBS). Beijing Statistical Yearbook. Beijing: China Statistics Press; 2005 [in Chinese].
- Bi X, Feng Y, Wu J, Wang Y, Zhu T. Source apportionment of PM₁₀ in six cities of northern China. *Atmos Environ* 2007;41(5):903–12.
- Chang G, Pan X, Xie X, Gao Y. Time-series analysis on the relationship between air pollution and daily mortality in Beijing. *J Hyg Res* 2003a;32(6):565–8 [in Chinese].
- Chang G, Wang L, Pan X. Study on the associations between ambient air pollutant and hospital outpatient visit or emergency room visit in Beijing. *Chin J Sch Dr* 2003b;17:295–7 [in Chinese].
- Chen C, Chen B, Green C, Wu C. Benefits of expanded use of natural gas for pollutant reduction and health improvement in Shanghai. *Sinosphere J* 2002;5(2):58–64.
- China Ministry of Health (CMH). Report of the Second National Health Service Survey. Beijing; 1998 [in Chinese].
- China Ministry of Health (CMH). China Statistical Yearbook of Public Health. Beijing: Peking Union Medical College; 2003–2005 [in Chinese].
- Chongqing Municipal Bureau of Statistics (CMBS). Chongqing Statistical Yearbook. Beijing: China Statistics Press, 1999, 2001 [in Chinese].
- Dockery DW, Pope III CA, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six US cities. *New Engl J Med* 1993;329:1753–9.
- Dong J, Xu X, Chen Y, Dockery DW, Jiang J. A study of relationship between air pollution and residents' daily mortality of urban area in Beijing in 1990–1991. *J Hyg Res* 1995;24(4):212–4 [in Chinese].
- Economist. China's environment: a great wall of waste. http://www.economist.com/displaystory.cfm?story_id=3104453, 2004 accessed 25 August 2005.
- El-Fadel M, Massoud M. Particulate matter in urban areas: health-based economic assessment. *Sci Total Environ* 2000;257:133–46.
- Ezzati M, Lopez AD, Rodgers A, Vander Hoorn S, Murray CJ. Comparative Risk Assessment Collaborating Group. Selected major risk factors and global and regional burden of disease. *Lancet* 2002;360(9343):1347–60.
- Gurjar BR, Lelieveld J. New directions: megacities and global change. *Atmos Environ* 2005;39:391–3.
- He K, Yang F, Ma Y, Zhang Q, Yao X, Chan CK, et al. The characteristics of PM_{2.5} in Beijing, China. *Atmos Environ* 2001;38:4959–70.
- HEI. Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review, Health Effects Institute. Special Report, vol. 15. ; 2004. Available at: <http://www.healtheffects.org/Pubs/SpecialReport15.pdf>.
- Ito K, Christensen WF, Eatough DJ, Henry RC, Kim E, Laden F, et al. PM source apportionment and health effects: 2. An investigation of intermethod variability in associations between source-apportioned fine particle mass and daily mortality in Washington, DC. *J Expo Anal Environ Epidemiol* 2006;300–10.
- Jing L, Qin Y, Xu Z. Relationship between air pollution and acute and chronic respiratory disease in Benxi. *J Environ Health* 2000;17(5):268–70 [in Chinese].
- Kan H, Chen B. Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. *Sci Total Environ* 2004;322:71–9.
- Künzli N, Kaiser R, Medina S, Studnicka M, Chanel O, Filliger P, et al. Public health impact of outdoor and traffic related air pollution: a European assessment. *Lancet* 2000;356:795–801.
- Lopez MT, Zuk M, Garibay V, Tzintzun G, Iniestra R, Fernandez A. Health impacts from power plant emissions in Mexico. *Atmos Environ* 2005;39(7):1199–209.
- Mar TF, Ito K, Koenig JQ, Larson TV, Eatough DJ, Henry RC, et al. PM source apportionment and health effects. 3. Investigation of inter-method variations in associations between estimated source contributions of PM_{2.5} and daily mortality in Phoenix, AZ. *J Expo Anal Environ Epidemiol* 2006;311–20.
- Ministry of Science and Technology. Reports of Control Measures on Air Pollution in Beijing. Ministry of Science and Technology of China; 2002.
- Morgan G, Lincoln D, Sheppard V, Jalaludn B, Beard JF, Simpson R, et al. The effects of low level air pollution on daily mortality and hospital admissions in Sydney, Australia, 1994 to 2000. *Epidemiology* 2003;14(5):S111–2 [Supplement].
- Peng C, Wu X, Liu G, Johnson T, Shah J, Guttikunda S. Urban air quality and health in China. *Urban Stud* 2002;39(12):2283–99.
- Pope III CA, Bates DV, Raizenne ME. Health effects of particulate air pollution: time for reassessment? *Environ Health Perspect* 1995a;103:472–80.
- Pope III CA, Thun MJ, Namboodiri MM, Dockery DW, Evans JS, Speizer FE, et al. Particulate air pollution as a predictor of mortality in a prospective study of US adults. *Am J Respir Crit Care Med* 1995b;151:669–74.
- Pope III CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J Am Med Assoc* 2002;287:1132–41.
- Pope III CA, Burnett RT, Thurston GD, Thun MJ, Calle EE, Krewski D, et al. Cardiovascular mortality and long-term exposure to particulate air pollution, epidemiological evidence of general pathophysiological pathways of disease. *Circulation* 2004;13: 71–8.
- Quah E, Boon TL. The economic cost of particulate air pollution on health in Singapore. *J Asian Econ* 2003;14:73–90.
- Schwartz J, Dockery D, Neas L. Is daily mortality associated specifically with fine particles? *J Air Waste Manage Assoc* 1996;46:927–39.
- Seethaler RK, Künzli N, Sommer H, Chanel O, Masson M, Vernaud JC, et al. Economic costs of air pollution related health impacts — an impact assessment project of Austria, France and Switzerland. *Clean Air Environ Qual* 2003;37:35–43.

- Song Y, Zhang Y, Xie S, Zeng L, Zheng M, Salmon LG, et al. Source apportionment of PM_{2.5} in Beijing by positive matrix factorization. *Atmos Environ* 2006;40:1526–37.
- United States Environmental Protection Agency (USA-EPA). The final report to Congress on benefits and costs of the Clean Air Act, 1970 to 1990, EPA 410-R-97-002. The final report to Congress on benefits and costs of the Clean Air Act, 1990 to 2010, EPA 410-R-99-001. Office of Air and Radiation, 1997.
- United States Environmental Protection Agency (USA-EPA). The final report to Congress on benefits and costs of the Clean Air Act, 1970 to 1990, EPA 410-R-97-002. The final report to Congress on benefits and costs of the Clean Air Act, 1990 to 2010, EPA 410-R-99-001. Office of Air and Radiation, 1999.
- Wan Y, Yang HW, Masui T. Considerations in applying the general equilibrium approach to environmental health assessment. *Biomed Environ Sci* 2005;18(5):356–61.
- Wang H, Mullahy J, Chen D, Wang L, Peng R. Willingness to pay for reducing the risk of death by improving air quality: A contingent valuation study in Chongqing, China, Presented at the Third International Health Economic Association Conference in York, UK; 2001.
- Wang J, Wang Q, Bi Z. A survey on acute respiratory disease. *Chin J Epidemiol* 1994;15(3):141–4 [in Chinese].
- Wang X, Mauzerall DL. Evaluating impacts of air pollution in China on public health: implications for future air pollution and energy policies. *Atmos Environ* 2006;40(9):1706–21.
- Wei F, Hu W, Teng E, Wu G, Zhang Jim, Chapman RS. Relation analysis of air pollution and children's respiratory system disease prevalence. *China Environ Sci* 2000;20(3):220–4 [in Chinese].
- Wong CM, Atkinson RW, Anderson HR, Hedley AJ, Ma S, Chau PYK, et al. A tale of two cities: effects of air pollution on hospital admissions in Hong Kong and London compared. *Environ Health Perspect* 2002;110:67–77.
- World Health Organization (WHO). Air Quality Guidelines. Geneva: World Health Organization; 1999.
- World Health Organization (WHO). Quantification of the health effects of exposure to air pollution, Report of a WHO Working Group, Bilthoven, Netherlands; 2000. 20–22 November.
- World Health Organization (WHO). WHO guidelines for air quality. Fact Sheet No. 187. <http://www.who.int/inffs/en/fact187.html>, 2003.
- Xu X, Dockery DW, Christiani DC, Li B, Huang H. Association of air pollution with hospital outpatient visits in Beijing. *Arch. Environ. Health* 1995a;50(3):214–20.
- Xu X, Li B, Huang H. Air pollution and unscheduled hospital outpatient and emergency room visits. *Environ Health Perspect* 1995b;103:286–9.