Valuing the health risks of particulate air pollution in the Pearl River Delta, China

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ARTICLE INFO

Keywords:
- Economic loss
- Particulate matter
- Health effect
- Valuation
- Pearl River Delta

ABSTRACT

The Pearl River Delta (PRD) in Southern China is a region where the manufacturing industry is rapidly developing, accounting for about 10% of the gross domestic product (GDP) with 4% of China’s population. The economic development in this region is accompanied by severe air pollution that poses harm to people’s health and causes economic loss. This paper estimates the adverse health effects of particulate matter pollution in the PRD by using a log-linear exposure–response function, and monetizes the morbidity effect by using the cost of illness (COI) method and the mortality effects by using both the amended human capital (AHC) method and the results of contingent valuation (CV) study. The results show that in 2006 the total economic loss of the health effects from PM$_{10}$ pollution in PRD is 29.21 billion Chinese yuan by using CV results and COI method, which is equivalent to 1.35% of the regional GDP, and is 15.51 billion Chinese yuan by using AHC and COI methods, which is equivalent to 0.72% of the regional GDP. The economic loss due to premature death and chronic respiratory disease accounts for more than 95% of the total loss. Despite the uncertainties, the results clearly show the severity of the health effects and economic loss incurred by particulate matter pollution in PRD; the results further point to the need for developing environmentally friendly industry, and provide a benchmark for comparing alternative options to reduce air pollution.

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1. Introduction

The Pearl River Delta (PRD) Economic Zone consists of nine prefecture-level cities (Fig. 1), located in Guangdong, a southern coastal Chinese province adjacent to Hong Kong. The PRD is well-known as a manufacturing center supplying a wide variety goods ranging from toys, home appliances to electronics and communication equipments to all over the world (Enright and Scott, 2005). As the forerunner of China’s economic reform, this region has made tremendous economic progress since the reform and opening policy was adopted about 30 years ago. From 1978 to 2007, PRD’s gross domestic product (GDP) has been increasing at an average annual rate of 21.2%. In 2006, PRD produced 10.16% of the total national GDP in an area 0.43% of the total land (Statistics Bureau of Guangdong Province, 2007; National Bureau of Statistics of China, 2007). These achievements were accomplished by developing high energy- and resource-intensive industries. As an unwanted by-product, the air quality in the PRD cities deteriorated and the PRD has been suffering from acid rain, ozone pollution and particulate matter pollution. Especially, severe haze pollution has descended routinely into the PRD in recent years, greatly impairing the health of the population and the visibility throughout the region (Wu et al., 2007b; Huang et al., 2008; Deng et al., 2008; Xie et al., 2011). The
Fig. 1 – The Pearl River Delta and its nine cities which are Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, Huizhou and Zhaoqing, as well as the locations of air quality monitoring stations (the picture is revised from the report by Guangdong Provincial Environmental Protection Monitoring Centre and Environmental Protection Department, Hongkong (2006)).

primary culprit of haze is particulate matter (PM) (Huang et al., 2008; Wu et al., 2007a; Zhang et al., 2008). PM is comprised mostly of metals, dust, organic chemicals, sulfates and nitrates, is a mixture of small solid particles and liquid droplets, which is either directly emitted from fossil fuel combustion, industrial processes, construction activities, and various transportation sources or formed secondarily via various chemical and physical processes in the atmosphere. In the PRD, the major sources of PM are wind-blow dust and industrial activities followed by coal-fired power plants and vehicular emissions; in the individual PRD cities, these are the major PM emission sources as well, but the contributions of these sources in the different cities are somewhat different reflecting the different development strategies of them.

The associations of exposure to PM pollution and increases in premature mortality and the various morbidity effects have been well-documented (Dockery et al., 1993; Pope et al., 1995; Brunekeef and Holgate, 2002; Li et al., 2003; Jia et al., 2004). The major concerns on human health include mortality, bronchitis, asthma, respiratory and cardiovascular hospital admissions, and outpatient visits. The economic loss from health effects incurred by PM at sectoral levels and at different geographical locations has been estimated in China. Ho and Jorgenson (2007) estimated the total national health damage due to PM pollution to be 117 billion Chinese yuan, or 1.6% of GDP in 1997. Particularly, this study estimated the health damage incurred by PM contributed from the different sectors. The World Bank (2007) estimated the health cost of urban PM pollution in China in 2003 which was 157 billion Chinese yuan by using amended human capital (AHC) method and 520 billion Chinese yuan by using the value of statistical life (VSL), equivalent to 1.2% and 3.8% of the 2003 national GDP, respectively. Yu et al. (2007) estimated that the health cost of PM10 pollution over 659 Chinese cities was 170.3 billion Chinese yuan by using AHC method, which was equivalent to 1.02% of the 2004 national GDP. Zhang et al. (2007) estimated that the health cost of PM10 in Beijing from 2000 to 2004 ranges from 1.67 to 3.66 billion Chinese yuan by using adjusted VSL from previous studies, which was equivalent to 5.58–7.06% of Beijing’s GDP. Despite the inherent uncertainties in estimating and monetizing health damage, these numbers approximate the magnitude of health cost incurred by PM pollution; to date, no studies on estimating the economic cost of health effect incurred by PM pollution in PRD, the main manufacturing center in China, have been conducted yet.

About 4% of China’s population resides in the PRD, where the PM pollution is among the most severe anywhere in China (Zhang et al., 2008). As the living standards improve and people’s environmental awareness grows, the demand for cleaner air increases in PRD as indicated by the large number of complaints about air pollution in recent years (SEPA, 2008). In this research, we monetize the health effects of PM pollution in PRD for two reasons: (1) to justify the proposal and implementation of more stringent air pollution abatement strategies, and (2) to provide a benchmark for selecting alternative control options to reduce air pollution. Although PM2.5 is reported to be the part most strongly associated with the health effects (Kan et al., 2007; Pope et al., 2002; Schwartz et al., 1996; Xie et al., 2009), we select PM10 with PM2.5 being part of it as the target pollutant given PM10 instead of PM2.5 is monitored in the current routine monitoring practice. We select 2006 as the study year mainly because PM10 data is
available for the PRD cities and the PM pollution in this area has not been significantly changed since then (Wan et al., 2011).

The following sections introduce the methods that are used to estimate and monetize the health effects of PM pollution in PRD, describe the data and parameters that are chosen, discuss the results and uncertainties, and finally, conclusions drawn.

2. Methods

Following the general approach used for health damage assessment (Tietenberg, 2005), we identify the health outcomes associated with the exposure to PM_{10} pollution and the exposed population, estimate the adverse health effects by using appropriate exposure–response functions, and monetize the estimated health effects with various valuation methods.

2.1. Estimating the health effects

According to epidemiological study results, exposure to PM_{10} may cause a wide range of respiratory, systemic and cardiovascular effects. In this paper, we only select those health outcomes that can be quantitatively estimated and monetized, including chronic and acute mortality, chronic bronchitis, acute bronchitis, asthma, outpatient visits (pediatricians and internal medicine) and respiratory and cardiovascular hospital admissions. Neglected are the health outcomes that are hard to assess such as decreased lung function, pain and suffering, restricted activity days and other sub-clinical symptoms. It is understood that omitting these health outcomes may lead to the underestimation of the health cost to some extent.

Selecting the exposure–response function is the core part because it greatly affects the magnitude of the eventual valuation results (Zou and Zhang, 2010). The incidence of morbidity or mortality among the population can be regarded as random events, and follows a Poisson distribution. Most epidemiologic studies linking air pollution with health effects use a relative risk model based on Poisson regression (Kan and Chen, 2004; Kan et al., 2004). Though most of them showed statistically significant and relatively linear associations between PM concentrations and health end-points, a log-linear function is more plausible and recommended for use to estimate the health effects for cities with high PM concentrations (WHO, 2006). Given the PM_{10} concentrations in the PRD cities are high, we therefore chose a log-linear exposure–response function according to the studies of Kan and Chen (2004), Kan et al. (2004) and Yu et al. (2007) to estimate the health effects in this paper.

The incidence of each health outcome under the actual PM_{10} pollution condition can be expressed as:

$$I = I_0 \times \exp(\beta \times (C - C_0))$$  \hspace{1cm} (1)

where C is the actual PM_{10} concentration, I is the incidence rate of the population exposed in the actual situation, C_0 is the baseline PM_{10} concentration, I_0 is the incidence rate of the population exposed in the baseline scenario, and \(\beta\) is the exposure–response coefficient. There are many factors affecting the health of the population, just name a few, nutrition status, accessibility to health service, exposure to polluted air, and smoking history. The health effects due to all the factors other than exposing to PM_{10} is the health effects when PM_{10} concentration is equal to C_0.

Then, the incremental incidence rate attributed to the actual PM_{10} pollution can be estimated by using the following equation:

$$\Delta I = I - I_0 = I \times \left(1 - \frac{1}{\exp(\beta \times (C - C_0))}\right)$$  \hspace{1cm} (2)

The number of cases (E) with the specified health outcome attributed to PM_{10} pollution among the exposed population can be estimated by using the following equation:

$$E = P \times I \times \left(1 - \frac{1}{\exp(\beta \times (C - C_0))}\right)$$  \hspace{1cm} (3)

2.2. Monetizing the health effects

Welfare economics assumes that life (or health) has values like other goods and the values can be compared. Specifically, it assumes that individuals are rational and the various choices they make in their daily life involve the trade-offs between the changes in health risk and money or other economic goods that can be measured by money.

The economic loss due to the health damage attributed to PM_{10} pollution, denoted as L, can be estimated by using the following equation:

$$L = \sum_{i=1}^{M} L_i = \sum_{i=1}^{M} E_i \times L_p$$  \hspace{1cm} (4)

where i is the index of health outcomes (e.g., bronchitis, asthma) attributed to PM_{10} pollution, M is the total number of types of health outcomes attributed to PM_{10} pollution, \(L_i\) is the economic loss of health outcome i across the population in the studied region, \(E_i\) is the estimated number of people with health outcome i due to PM_{10} pollution, and \(L_p\) the economic loss associated with one case of health outcome i.

The key is to determine the economic loss associated with one case of a certain health outcome, i.e., the value of health or life. Given that health and life are irreplaceable and have no market price, indirect approaches such as contingent valuation (CV) approach, human capital (HC) or amended human capital (AHC) approach, and the cost of illness (COI) approach are used for health valuation. Different valuation methods are used for the different health outcomes attributed to PM_{10} exposure. We use CV and AHC method to evaluate the economic loss of premature death and chronic bronchitis, and COI method to estimate the economic loss of other health outcomes, including acute bronchitis, asthma, outpatients and inpatients.

2.2.1. Contingent valuation (CV) method

CV method is a nonmarket valuation method that is widely used in environmental impact assessment and cost-benefit analysis (Venkatachalam, 2004). It can effectively measure the money that individuals are willing to pay for improving their own and others’ safety or health. There are many studies conducted using CV method to estimate the value of life in...
general. However, there are only a few such studies conducted in a Chinese setting (Hammitt and Zhou, 2006; Wang and Mullahy, 2006) and none of them were conducted in the PRD, our study region. The valuation results obtained in other countries are not suitable for our estimation given the differences in economic and social development and people’s perceptions about environmental problems across nations. As an alternative, we use the value of statistical life (VSL) obtained with the CV study conducted in Chongqing (a southwestern Chinese city) in 1998 by Wang and Mullahy (2006), and take into account the differences in residential income between cities and years, to estimate the VSL in the PRD cities.

\[
VSL_{PRD} = VSL_{CQ} \times \left( \frac{I_{PRD}}{I_{CQ}} \right)^{e}
\]

where \(VSL_{PRD}, VSL_{CQ}, I_{PRD}, I_{CQ}\), and \(e\) represents the VSL of residents in the PRD cities in 2006, the VSL of residents in Chongqing in 1998, the yearly per capita income in the PRD cities in 2006, the yearly per capita income in Chongqing in 1998, and the income elasticity coefficient, respectively. The income elasticity coefficient is normally set to be 1.

2.2.2. Human capital (HC) and amended human capital (AHC) method

In the HC approach, individuals are considered as the basic unit of human capital providing products and services. This approach measures the loss of life and health according to a general standard for assessing physical capital, usually represented as wage or labor capital. The HC approach merely takes the expected income loss as the loss from premature death. So there is an implicit assumption that value of life of individuals with different incomes is different, which often raises ethical concerns. To fix this, the amended human capital (AHC) approach was put forward, which use per capita GDP to measure the value of a statistical year of life (Eq. (6)). It estimates human capital from the perspective of the entire society, neglecting individual differences. AHC approach has advantages in data collection, and is currently widely used in life valuation. The estimated results by using HC or AHC are more conservative than those obtained with the CV method.

\[
HCL = \sum_{k=1}^{\tau} GDP_t^k = GDP_0 \times \sum_{k=1}^{\tau} [(1 + \alpha)/(1 + r)]^k
\]

where \(HCL\) represents the human capital or life value of individuals based on per capita GDP, \(t\) is the per capita loss of life years, \(GDP_t^k\) is the per capita GDP in year \(k\), \(GDP_0\) represents per capita GDP in the baseline year, \(\alpha\) is the growth rate of per capita GDP, and \(r\) is the social discount rate.

2.2.3. Cost of illness (COI) method

COI method directly estimates the minimum value of health damage by calculating various disease related costs, including pharmaceutical, diagnostic, treatment and hospitalization costs, and the loss of income or social loss of GDP due to illness. Cost of illness (COI) method is widely used to measure the cost of different diseases in various regions with different levels of economic and social development. We use the COI method to estimate the cost of acute bronchitis, asthma, outpatients and inpatients. The basic formula is as follows:

\[
C_i = (C_{pi} + GDP_p \times T_i) \times \Delta_i
\]

where \(C_i\) is the aggregated cost of health outcome \(i\), \(C_{pi}\) is the cost per case of medical treatment for health outcome \(i\), \(GDP_p\) is the per capita GDP, \(T_i\) is the working time loss due to disease \(i\), and \(\Delta_i\) represents the increased number of cases of health outcome \(i\) attributed to PM10 pollution.

3. Results

In using the equations in Section 2 to estimate the health effects associated with exposure to PM10 pollution in the PRD cities in 2006 and monetize the health effects, we need the information on ambient PM10 concentration, baseline PM10 concentration, exposed population, exposure–response coefficients, and the economic loss per case of a certain health outcome. The inputs and results are detailed below.

3.1. Inputs

3.1.1. PM10 concentration

The hourly and annual average ambient PM10 concentrations in the nine PRD cities from January 1, 2006 to December 31, 2006 are provided by Guangdong Provincial Environmental Monitoring Center (data are available upon request); they operate 13 air quality monitoring stations across the PRD (Fig. 1). The distributions of PM concentrations across the PRD cities are shown in Fig. 2. It can be seen that PM concentrations in cities located at central and northeast PRD (e.g., Foshan, Dongguan and Huizhou), where manufacturing industry is dynamic, are higher than the PM concentrations in cities located at southeast PRD (e.g., Zhuhai), where tourism industry is booming.

The baseline PM10 concentration is set at zero. Generally, a threshold, derived from the lowest concentration at which individual’s adverse health effects can be observed or the highest concentration at which individual’s adverse health effects cannot be observed, is taken as the baseline concentration. However, a large number of studies show that there seem to be no health effect threshold concentration for ambient PM (Morgan et al., 2003; Pope, 2000). Thus, we set the baseline PM10 concentration at zero.

3.1.2. Exposure–response coefficients

The exposure–response coefficients are derived from the meta-analysis results of Kan and Chen (2002) and Xie et al. (2009), as shown in Table 1. Exposure–response coefficients obtained from cohort study in the study region are ideal for estimating the health effects due to PM pollution. No cohort studies in a Chinese setting have been reported yet. The results from the two American cohort studies, which are the Harvard Six Cities study (Dockery et al., 1993) and the American Cancer Society cohort study (Pope et al., 2002), are not applicable to the PRD, given that these studies were conducted in USA cities where the PM concentration were significantly lower than that in the PRD cities. Previous studies show that the relative risk curve gets flatter as PM
concentration increases and becomes horizontal as the PM$_{10}$ concentration exceeds 100 μg/m$^3$. The PM$_{10}$ concentration in PRD ranges from below 10 μg/m$^3$ to 300 μg/m$^3$ and above, directly applying the coefficients of Pope’s or Dockery’s study is inappropriate. Therefore, we adopted the results of meta-analysis of well-selected studies in Chinese settings.

There are three studies using meta-analysis to integrate the epidemiological studies on the relationship between exposure to PM pollution and health effects in China: Kan and Chen (2002), Aunan and Pan (2004) and Xie et al. (2009). The health outcomes from Aunan and Pan (2004) do not match the health outcomes that we selected for health effect valuation. Therefore, based on the selected health outcomes that we want to assess, the exposure–response coefficients derived from two meta analysis, i.e. Kan and Chen (2002) and Xie et al. (2009), are selected for their corresponding health outcomes and applied to our estimation.

3.1.3. Health information
The mortality and the morbidity of each disease in the PRD cities are mainly estimated by using the data in the Health Statistical Yearbook of Guangdong Province 2007 (Department of Health of Guangdong Province, 2007) and the results of the 2000 population census of Guangdong province (Population Census Office of Guangdong Province, 2002). When the information for disease incidence rate in a city is not available, the average health information of Guangdong Province is used. The basic health information is listed in Table 1.

3.1.4. Exposed population
The exposed population is obtained from Guangdong Statistical Yearbook 2006 (Statistics Bureau of Guangdong Province, 2006). We include both the registered residents and non-registered residents, taking into consideration the large size of the migrating population in the PRD. The population is divided into two categories, children and adults, as shown in Table 2.

3.1.5. Economic loss per case of a certain health outcome
The economic loss per case of a certain health outcome as estimated by using the different valuation methods is shown in Table 3.

The economic loss per case of premature death is estimated by using CV and AHC methods. In using CV results, the VSL in the different PRD cities is derived from the VSL obtained with Chongqing subjects according to Eq. (5), which

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**Table 1 – Exposure–response coefficients (refer to Eq. (1)) and the incidence rate of each health outcome under the actual PM$_{10}$ pollution condition.**

<table>
<thead>
<tr>
<th>Health outcome</th>
<th>Coefficients β (95% CI)</th>
<th>Reference</th>
<th>Incidence rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic effect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All cause mortality</td>
<td>0.00148 (0.00038, 0.00252)</td>
<td>Kan and Chen (2002)</td>
<td>-a</td>
</tr>
<tr>
<td>Chronic bronchitis</td>
<td>0.00505 (0.00183, 0.0078)</td>
<td></td>
<td>0.00148</td>
</tr>
<tr>
<td>Acute effect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All cause mortality</td>
<td>0.00046 (0.00013, 0.00079)</td>
<td>Kan and Chen (2002)</td>
<td>-a</td>
</tr>
<tr>
<td>Acute bronchitis</td>
<td>0.00505 (0.00192, 0.00904)</td>
<td></td>
<td>0.0372</td>
</tr>
<tr>
<td>Asthma</td>
<td>0.0019 (0.00145, 0.00235)</td>
<td>Xie et al. (2009)</td>
<td>0.0094</td>
</tr>
<tr>
<td>Hospital admissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory disease</td>
<td>0.00124 (0.00086, 0.00162)</td>
<td>Xie et al. (2009)</td>
<td>0.00797</td>
</tr>
<tr>
<td>Cardiovascular disease</td>
<td>0.00066 (0.00036, 0.00095)</td>
<td></td>
<td>0.00325</td>
</tr>
<tr>
<td>Outpatient visits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal medicine</td>
<td>0.000042 (0.000025, 0.000061)</td>
<td>Kan and Chen (2002)</td>
<td>0.14856</td>
</tr>
<tr>
<td>Pediatrics</td>
<td>0.000047 (0.000017, 0.000077)</td>
<td></td>
<td>0.54261</td>
</tr>
</tbody>
</table>

*a All cause mortality rate for chronic and acute effect refers to the non-accident mortality as shown in Table 2.
was US$34,458 in 1998. In using the AHC method, the human capital (the value of individuals’ life) is estimated according to Eq. (6) by setting the loss of years of life for an individual, the growth rate of per capita GDP and the social discount rate to be 14 years, 10.89%, and 8%, respectively, following Han et al. (2006) and the Health Statistics Yearbook of China and Guangdong Province.

The economic loss per case of asthma and acute bronchitis is assumed to be equal to the cost of medical treatment per case of asthma and acute bronchitis, respectively. Tang et al. (2000) surveyed 71,867 asthmatics in Guangdong Province where the PRD is located in 1999 and found that the average medical cost per case of asthma was 634.2 Chinese yuan. The average medical cost per case of asthma in 2006 in the PRD cities is derived from this 1999 value, adjusted by using disposable per capita incomes in the different years. The economic loss per case of acute bronchitis in 2006 in the PRD cities is derived from the medical cost per case of acute bronchitis in Shanghai (52.56 Chinese yuan) by Kan and Chen (2004), taking into consideration the difference in disposable income in these cities.

For chronic bronchitis, it is difficult to estimate its health cost by using the COI method since we do not know how often one needs to visit doctors. Viscusi et al. (1991) suggested an alternative approach to derive the revealed utility of living with a disease, and found that the utility of living with chronic bronchitis was about 0.68 of the utility of living in good health (Viscusi et al., 1991). That means if good health is scaled to equal 1 and death is scaled to equal 0, living a life with chronic bronchitis is equal to losing 32% of life. Thus, this number can be converted to the value of a statistical case of chronic bronchitis by multiplying the VSL by 0.32.

In estimating the cost per case of outpatient and inpatient care in the PRD cities, the cost per case of medical treatment for health outcome is obtained by using the average cost for outpatient and hospital admission and the average duration of stay from Guangdong Health Statistical Yearbook 2007. The work time loss for outpatient is assumed to be 0.5 days; the work time loss for inpatient is set to be 9.5 days for respiratory disease and 11.5 days for cardiovascular disease.

### 3.2. Results

#### 3.2.1. Health effects of PM$_{10}$ pollution

Table 4 shows the various health effects attributed to PM$_{10}$ pollution in the PRD cities in 2006. It can be seen that about 12,800 premature deaths, 21,600 cases of chronic bronchitis, 496,900 cases of acute bronchitis, 55,000 cases of asthma, 292,200 outpatient visits and 38,500 hospital admissions in 2006 can be attributed to PM$_{10}$ pollution in the PRD. The number of premature deaths due to long-term exposure is more than 3 times that due to short-term exposure, which is consistent with the implication of Kan et al. (2005). The number of cases of acute bronchitis is overwhelmingly larger than that of the chronic bronchitis. Further analysis shows that although the absolute number of adult outpatient visits is significantly greater than that of the children outpatient visits, children are about 1.5 times more likely to be impacted by air pollution taking into consideration the population sizes of children and adults respectively. The number of hospital

<table>
<thead>
<tr>
<th>City</th>
<th>Population (persons)</th>
<th>Child (%) (&lt;15 years old)</th>
<th>Adult (%) (≥15 years old)</th>
<th>Population density (persons/km²)</th>
<th>Non-accident mortality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guangzhou</td>
<td>9,496,800</td>
<td>14.91</td>
<td>85.09</td>
<td>1277</td>
<td>3.5734</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>8,277,500</td>
<td>9.21</td>
<td>90.79</td>
<td>4299</td>
<td>0.0734</td>
</tr>
<tr>
<td>Zuhai</td>
<td>1,415,700</td>
<td>16.39</td>
<td>83.61</td>
<td>839</td>
<td>1.2734</td>
</tr>
<tr>
<td>Foshan</td>
<td>5,800,300</td>
<td>14.19</td>
<td>85.81</td>
<td>1507</td>
<td>3.3834</td>
</tr>
<tr>
<td>Jiangmen</td>
<td>4,102,900</td>
<td>18.38</td>
<td>81.62</td>
<td>430</td>
<td>3.5834</td>
</tr>
<tr>
<td>Dongguan</td>
<td>6,560,700</td>
<td>7.65</td>
<td>92.35</td>
<td>2662</td>
<td>1.9534</td>
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<tr>
<td>Zhongshan</td>
<td>2,434,600</td>
<td>13.65</td>
<td>86.35</td>
<td>1352</td>
<td>2.7634</td>
</tr>
<tr>
<td>Huizhou</td>
<td>3,706,900</td>
<td>19.90</td>
<td>80.10</td>
<td>332</td>
<td>2.3634</td>
</tr>
<tr>
<td>Zhaoqing</td>
<td>3,676,000</td>
<td>26.55</td>
<td>73.45</td>
<td>247</td>
<td>3.5434</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>City</th>
<th>Premature death (million)</th>
<th>Chronic bronchitis (million)</th>
<th>Acute bronchitis</th>
<th>Asthma</th>
<th>Outpatient</th>
<th>Inpatient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guangzhou</td>
<td>VSL 1.54</td>
<td>AHC 1.08</td>
<td>VSL 0.49</td>
<td>AHC 0.35</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>VSL 1.75</td>
<td>AHC 1.19</td>
<td>VSL 0.56</td>
<td>AHC 0.38</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Zuhai</td>
<td>VSL 1.37</td>
<td>AHC 0.90</td>
<td>VSL 0.44</td>
<td>AHC 0.29</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Foshan</td>
<td>VSL 1.51</td>
<td>AHC 0.86</td>
<td>VSL 0.48</td>
<td>AHC 0.28</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Jiangmen</td>
<td>VSL 1.24</td>
<td>AHC 0.39</td>
<td>VSL 0.40</td>
<td>AHC 0.13</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Dongguan</td>
<td>VSL 1.87</td>
<td>AHC 0.68</td>
<td>VSL 0.60</td>
<td>AHC 0.22</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Zhongshan</td>
<td>VSL 1.47</td>
<td>AHC 0.72</td>
<td>VSL 0.47</td>
<td>AHC 0.23</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Huizhou</td>
<td>VSL 1.08</td>
<td>AHC 0.43</td>
<td>VSL 0.34</td>
<td>AHC 0.14</td>
<td>1512</td>
<td>1113</td>
</tr>
<tr>
<td>Zhaoqing</td>
<td>VSL 0.90</td>
<td>AHC 0.24</td>
<td>VSL 0.29</td>
<td>AHC 0.35</td>
<td>1512</td>
<td>1113</td>
</tr>
</tbody>
</table>
admissions due to respiratory disease is more than 4 times that due to cardiovascular disease, implying that reducing PM$_{10}$ concentration would gain significant benefit from avoiding respiratory disease in the PRD region.

By analyzing the health effects due to PM pollution in the individual PRD cities, it can be found that (1) the attributable number of premature deaths (due to both acute and chronic exposure) in Guangzhou and Foshan are the largest and are significantly greater than that in other cities, and (2) the attributable number of cases of all diseases in Guangzhou, Foshan, Shenzhen and Dongguan are greater than that in Zhuhai and Zhongshan. The size of the population, the age structure, the PM$_{10}$ concentration, and all the other factors affecting people’s health (e.g. accessibility to health service, nutrition status, etc.) all contribute to these differences.

### 3.3 Economic loss of health effects

Table 5 shows the economic loss of each health outcome as estimated by using CV, AHC and COI methods. The total economic loss of health effects of PM$_{10}$ pollution in nine PRD cities in 2006 is 29.214 (9.552, 45.013) billion Chinese yuan by using CV and COI, equivalent to 1.35% (0.44%, 2.08%) of the total regional GDP, and is 15.508 (5.153, 23.846) billion Chinese yuan by using AHC and COI, equivalent to 0.72% (0.24%, 1.10%) of the regional GDP. Among all the health effects, the economic loss of premature death and chronic bronchitis accounts for more than 95% of the total loss. Though our estimation is lower than other similar studies conducted in China in terms of the proportion of economic loss incurred by PM pollution to local GDP, such as Kan and Chen (2004), Kan et al. (2004), Yu et al. (2007), World Bank (2007) and Zhang et al. (2007), our results show that ambient particulate matter pollution in the PRD is severe and causes significant economic loss.

Comparing the economic loss from health effect due to exposing to PM$_{10}$ pollution in the nine different cities, it can be found that Guangzhou, Foshan and Dongguan suffer the greatest loss from PM$_{10}$ pollution in 2006, while Zhuhai and Zhongshan suffer the least, which is similar to the results of the physical health effects. Besides the factors affecting the number of cases of the various health effects due to exposing to PM$_{10}$ pollution, the economic development status (as indicated by the per capita GDP) and medical expenses in the different cities all contribute the differences in the aggregated economic loss due to PM$_{10}$ pollution.

The economic loss of the same health outcome estimated by using the CV method is greater than that estimated by using the AHC method. This is reasonable as the CV method is based on investigation of individual willingness to pay for reducing the risk of death or diseases and reflects all the loss of individual welfare caused by death or diseases (including time cost and income loss, medical expenses, pain suffered), while the AHC method is based on per capita GDP which only considers the loss of individual contribution to the productivity of the society.

### 4. Discussion and conclusions

Uncertainty arises in estimating both the health effects and monetary valuation. In estimating the health effects, the incomplete health outcomes, choice of the exposure–response functions and coefficients, selection of baseline PM$_{10}$ concentration, and assumption in the exposure of the population all result in uncertainties. In estimating the monetary value of the health effects, uncertainties are inevitable in using VSL derived from survey and the benefit transfer method.

The health effects of PM are not completely understood yet, and there are many uncertainties in using epidemiological or
Table 5 – Economic loss of health effects attributed to PM\textsubscript{10} pollution in the PRD cities in 2006, mean value (95% CI) (in million Chinese yuan).

<table>
<thead>
<tr>
<th>City</th>
<th>Premature death\textsuperscript{a}</th>
<th>Premature death\textsuperscript{b}</th>
<th>Chronic bronchitis</th>
<th>Acute bronchitis</th>
<th>Asthma</th>
<th>Outpatient visits</th>
<th>Hospital admissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CV AHC</td>
<td>CV AHC</td>
<td>CV AHC</td>
<td>CV AHC</td>
<td>COI</td>
<td>COI</td>
<td>COI</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>5474 (1467,8972)</td>
<td>3849 (1032,6310)</td>
<td>1740 (519,2971)</td>
<td>1223 (365,2090)</td>
<td>2176</td>
<td>1531 (70,247)</td>
<td>161 (10,16)</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>90 (24,149)</td>
<td>61 (16,101)</td>
<td>26 (8,45)</td>
<td>18 (5,31)</td>
<td>1791</td>
<td>1219 (46,168)</td>
<td>39 (7,10)</td>
</tr>
<tr>
<td>Zhuhai</td>
<td>144 (38,241)</td>
<td>94 (25,157)</td>
<td>43 (13,74)</td>
<td>28 (8,48)</td>
<td>170</td>
<td>111 (46,168)</td>
<td>14 (7,10)</td>
</tr>
<tr>
<td>Foshan</td>
<td>4782 (1312,7673)</td>
<td>2728 (748,4377)</td>
<td>1506 (454,2548)</td>
<td>859 (259,1454)</td>
<td>1872</td>
<td>1068 (63,193)</td>
<td>135 (27,71)</td>
</tr>
<tr>
<td>Jiangmen</td>
<td>1790 (478,2941)</td>
<td>568 (152,933)</td>
<td>564 (168,963)</td>
<td>179 (53,305)</td>
<td>716</td>
<td>227 (28,1012)</td>
<td>65 (28,100)</td>
</tr>
<tr>
<td>Dongguan</td>
<td>3113 (843,5055)</td>
<td>1129 (306,1832)</td>
<td>912 (274,1548)</td>
<td>330 (99,561)</td>
<td>2194</td>
<td>796 (920,3018)</td>
<td>119 (82,100)</td>
</tr>
<tr>
<td>Zhongshan</td>
<td>582 (153,970)</td>
<td>287 (75,478)</td>
<td>171 (51,294)</td>
<td>84 (25,145)</td>
<td>317</td>
<td>156 (920,3018)</td>
<td>23 (55,174)</td>
</tr>
<tr>
<td>Huizhou</td>
<td>1052 (283,1720)</td>
<td>420 (113,687)</td>
<td>333 (100,569)</td>
<td>133 (40,227)</td>
<td>627</td>
<td>250 (257,876)</td>
<td>66 (20,16)</td>
</tr>
<tr>
<td>Zhaoqing</td>
<td>1280 (344,2094)</td>
<td>343 (92,561)</td>
<td>395 (118,673)</td>
<td>106 (32,180)</td>
<td>510</td>
<td>137 (209,714)</td>
<td>61 (27,92)</td>
</tr>
<tr>
<td>Total</td>
<td>18,307 (4941,29816)</td>
<td>9479 (2559,15437)</td>
<td>5690 (1705,9686)</td>
<td>2961 (887,5041)</td>
<td>10,373</td>
<td>5494 (4278,14463)</td>
<td>751 (333,1135)</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Premature deaths attributed to the chronic impact with long-term exposure.

\textsuperscript{b} Premature deaths attributed to the acute impact with short-term exposure.
toxicological studies to derive exposure–response functions and coefficients. No cohort studies, which are considered to be the basis of estimating the health effect on long-term exposure to PM, are reported in a China setting. We use meta-analysis results of cross-sectional study in China instead. The results of the meta-analysis on the health effects due to PM exposure in other places may not be appropriate for PRD, given the population structure and the activity-time pattern of the population from different places could be quite different.

The threshold concentration of particulate matter is still inconclusive; WHO (2000) has proposed several feasible thresholds for environment impact assessment: zero, non-zero “clean” concentration, and background concentration of a site. Based on the meta-analysis on worldwide epidemiological studies, WHO (2006) carefully made an air quality guideline for ambient particulate matter for human health and safety, which indicated that the annual average PM$_{10}$ concentration should not exceed 20 $\mu$g/m$^3$ and the 24-h average PM$_{10}$ concentration should not exceed 50 $\mu$g/m$^3$. The choice of different baseline PM$_{10}$ concentration is expected affect the results of health effect estimation and monetary valuation. If the baseline concentration is set at 20 $\mu$g/m$^3$ (annual average PM$_{10}$ concentration) and 50 $\mu$g/m$^3$ (24-h average PM$_{10}$ concentration), the total economic loss of the health effects attributed to PM$_{10}$ pollution in the PRD cities in 2006 becomes 22,374 (7143, 34,939) million Chinese yuan by using CV and COI methods and 11,753 (3788, 18,334) million Chinese yuan by using AHC and COI methods. The corresponding values when zero is set to be the baseline concentration are 29,214 (9552, 45,013) million Chinese yuan and 15,508 (5153, 23,846) million Chinese yuan, respectively.

In conclusion, we estimate the adverse health effects of particulate matter pollution in PRD by using a log-linear exposure–response function, and monetize the morbidity effect by using the cost of illness (COI) method and the mortality effects by using both the amended human capital (ACH) method and the results of contingent valuation (CV) study. The results show that total economic loss of the health effects from PM$_{10}$ pollution in PRD is 29.21 billion Chinese yuan by using CV and COI methods, which is equivalent to 1.35% of the regional GDP, and is 15.51 billion Chinese yuan by using AHC and COI methods, which is equivalent to 0.72% of the regional GDP. The economic loss due to premature death and chronic respiratory disease accounts for more than 95% of the total loss. Despite the uncertainties, the results imply the severity of the health effects incurred by PM$_{10}$ pollution in the PRD. Aggressive actions are needed to alleviate the PM pollution problem and these research results provide a benchmark for choosing alternative air pollution abatement options.

Acknowledgements

The authors would like to thank the members of Environmental Economics and Policy Study Group, Peking University, including Zou Wenbo, Chen Xiaolan, Wu Dan, Xie Xuxuan, Wan Wei, Yu Jialing, Mu Quan, Yi Ru, Ma Xunzhou and Zhang Xiuli, for the simulating discussion and insightful suggestion. Special thanks are given to Dr. Leong Eugene for his effort in editing the paper. The research is supported by the Research Fund of National High Technology Research and Development Projects (“863” Projects, Grant No. 2006AA06A309): Synthesized Prevention Techniques for Air Pollution Complex and Integrated Demonstration in Key City-Cluster Region (3C-STAR).

References


