# An Economic Evaluation of the Health Effects of Reducing Fine Particulate Pollution in Chinese Cities

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Fine particulate pollution ($PM_{2.5}$) is a leading mortality risk factor in the People's Republic of China (PRC) and many Asian countries. Current studies of $PM_{2.5}$ mortality have been conducted at the national and provincial levels, or at the grid-based micro level, and report only the exposure index or attributable premature deaths. Little is known about the welfare implications of $PM_{2.5}$ mortality for urban areas. In this study, we estimate the total cost of $PM_{2.5}$ mortality, the benefit of its reduction achieved through meeting various air quality targets, and the benefit of mortality reduction achieved through a uniform 10 micrograms per cubic meter decrease in $PM_{2.5}$ concentration in the urban areas of 300 major cities in the PRC. Significant heterogeneity exists in welfare indicators across rich versus poor and clean versus dirty cities. The results indicate that cities in the PRC should accelerate the fine particulate pollution control process and implement more stringent air quality targets to achieve much greater mortality reduction benefits.

*Keywords:* benefit valuation, integrated exposure-response model, mortality risks, People's Republic of China, $PM_{2.5}$
*JEL codes:* D61, I18, Q51, Q53

## I. Introduction

Air pollution, especially the ambient fine particulate matter known as $PM_{2.5}$, which are particulates with aerodynamic diameter $\leq 2.5$ micrometers ($\mu$m), is a risk to human health (Dockery et al. 1993, Pope et al. 2002). The benefit of reduction in premature mortality risk attributable to lowering $PM_{2.5}$ comprises the vast majority of the overall benefit of air pollution control policies, and has been used to inform

policy efficiency in various regulatory contexts (United States Environmental Protection Agency 2006, 2011). For example, the cost–benefit analysis of the Clean Air Act in the United States (US) suggests that in 2020 the total annual benefit will reach $2 trillion (in 2006 prices), more than 30 times the total compliance costs; of the total benefit, 85% is due to reductions in mortality attributable to ambient $PM_{2.5}$ (hereafter $PM_{2.5}$ mortality) (United States Environmental Protection Agency 2011).

Rapid economic growth powered by surges in fossil fuel consumption and urbanization in many developing countries in Asia, such as the People's Republic of China (PRC) and India, have led to increases in air pollution and adverse health outcomes that are much more severe than in developed countries. Of the 1.37 billion people living in the PRC, 83% live in areas where the $PM_{2.5}$ concentration exceeds the PRC's ambient air quality standard (AQS) of 35 micrograms per cubic meter ($\mu g/m^3$) (Liu et al. 2016a). The northern, eastern, and central regions of the PRC have been exposed to annual $PM_{2.5}$ concentrations ranging from 40 $\mu g/m^3$ to 100 $\mu g/m^3$. Meanwhile, fine particulate pollution was associated with 4 million premature deaths worldwide in 2015, including 1 million in the PRC and 1 million in India (Global Burden of Disease Study 2015).

Recently, fine particulate pollution and its impacts have become national concerns and are now among the top political priorities in the PRC (Young et al. 2015; Jin, Andersson, and Zhang 2016). Stringent policies have been implemented on a national scale. Yet, the economic benefit of $PM_{2.5}$ control is unclear, and the effectiveness and efficiency of current policies is still being debated (detailed information is provided in section II). The targets of $PM_{2.5}$ concentration reduction, the prioritization of local interventions across sites and sectors, and the pace of the fine particulate pollution control process have been frequently questioned (Liu 2015; Jin, Andersson, and Zhang 2016, 2017). A sound economic analysis of the benefit of fine particulate pollution control is urgently needed to inform efficient policy design and implementation in the PRC.

In this study, we measure the benefit of fine particulate pollution control by quantifying $PM_{2.5}$ mortality and its welfare implications for the census-registered population in the urban areas of 300 cities at the prefecture level and above (hereafter major cities) in the PRC.[1] We develop an analytical framework that only requires publicly available data on $PM_{2.5}$ concentration and official statistics. We focus on analyzing three monetized benefits of $PM_{2.5}$ mortality reduction: (i) the theoretical maximum benefit, achieved by reducing $PM_{2.5}$ concentration from

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[1]Cities in the PRC cover both urban and rural areas. There are 653 cities, including 292 cities at the prefecture level and above, and 361 county-level cities. These two types of cities have used different statistical indicator systems since 1997, and some of these indicators are not comparable. Therefore, the data for the two types of cities are presented separately in the statistical yearbooks. Cities at the prefecture level and above provide statistical information for the total city and for urban areas (districts in the city), whereas county-level cities only have information for the total city. In this study, we focus on the urban areas of the 292 cities at the prefecture level and above.

the current level to zero, which is identical to the total cost of $PM_{2.5}$ mortality;[2] (ii) the total benefit of mortality reduction achieved by meeting the World Health Organization's (WHO) Air Quality Guidelines (AQG) ($TB_{AQG}$) and three interim targets for fine particulate pollution ($TB_{IT-1}$, $TB_{IT-2}$, and $TB_{IT-3}$);[3] and (iii) the benefit of mortality reduction achieved by a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration ($UB_{10}$).

Three main considerations motivate our research design. First, we focus on clearly defined city-level jurisdictions across the PRC rather than on provinces or grid-based maps with square cells. Most provinces in the PRC are vast territories, and the distributions of income, population, and pollution are highly uneven within each province. Therefore, the estimates aggregated at the national or provincial levels used in prior studies (see, for example, World Bank 2007, 2016; Xie et al. 2016a) may mask heterogeneity in $PM_{2.5}$ mortality. Furthermore, because it is the municipal governments that implement policies at the local level, it is more useful to provide estimates at the level of these micro jurisdictions. One may naturally think that the recent grid-based studies mapping $PM_{2.5}$ mortality distribution (see, for example, Lelieveld et al. 2015, Liu et al. 2016a, Xie et al. 2016b) are suitable for this purpose, but it is often burdensome to match the estimates of multiple cells with the borders of cities and districts.[4] Therefore, in this study we directly estimate outcomes at the level of city jurisdictions.

Second, we focus on the urban areas of major cities.[5] The greatest benefit of a reduction in $PM_{2.5}$ mortality will occur in urban areas because they have larger populations, more fine particulate pollution, and higher income levels, which are associated with a greater willingness to pay to reduce mortality risks. Further, in developing countries like the PRC, databases of monitored $PM_{2.5}$ concentrations and official statistics on socioeconomic status, which are essential for the validity of welfare estimates, are much more comprehensive for urban areas than rural areas. For simplicity, in the rest of this paper, we use "cities" to refer to the urban areas of major cities, unless indicated otherwise.

Third, in addition to considering the total cost and total benefit, we analyze the benefit of mortality reduction achieved by a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration in cities across the PRC. The distribution of $UB_{10}$ across cities is of both polity and research relevance. Most cities in the PRC are exposed to fine

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[2]The total cost of mortality attributable to $PM_{2.5}$ is only one important part of the total cost of fine particulate pollution; the latter also includes many other elements such as morbidity costs, citizens' defensive and adaptive expenditures, productivity losses, decrease in visibility, and damage to materials and crops.

[3]IT-1, IT-2, and IT-3 refer to WHO targets of $PM_{2.5}$ concentration meeting 35 $\mu g/m^3$, 25 $\mu g/m3$, and 15 $\mu g/m^3$, respectively.

[4]As a result, these papers invariably aggregate the cells at the provincial level and then use provincial average socioeconomic data to discuss the likely socioeconomic factors.

[5]In our analysis, urban areas meet the definition of *shi xia qu*, a statistical indicator in the PRC, which refer to city-governed districts, city-controlled districts, or municipal districts that are subdivisions of prefecture-level or larger cities.

particulate pollution levels far above WHO's first interim target (35 $\mu g/m^3$), and it may take decades of effort to meet this standard. Therefore, the economic benefit of a unit of pollution reduction, for example, a 10 $\mu g/m^3$ $PM_{2.5}$ concentration reduction, is policy relevant. Efficient fine particulate pollution control requires that the cost of reducing $PM_{2.5}$ pollution by one unit should be lower than the estimated $UB_{10}$ for that unit change. However, the estimation of $UB_{10}$ is complicated by two issues. Recent evidence shows that the concentration response (CR) function between fine particulate pollution and mortality risks may be nonlinear (concave), especially at high $PM_{2.5}$ concentrations (Burnett et al. 2014, Pope et al. 2011). The concave CR function indicates that in cites with the same population density, the same reduction in $PM_{2.5}$ concentration will lead to less mortality risk reduction in cities with higher concentrations than in cleaner cities, which is counterintuitive and has raised environmental equity concerns (Pope et al. 2015). However, citizens in dirtier cities can sometimes have higher incomes and may therefore be more willing to pay to reduce health risks. These contradictory effects make the real distribution of $UB_{10}$ among different types of cities a complicated empirical question.

This study contributes to the growing literature on the economic analysis of the health impacts of air pollution in developing countries. In particular, our estimation framework uses only publicly available data; is based on clearly defined jurisdictional urban areas; and considers the total cost of $PM_{2.5}$ mortality, the benefit of meeting different air quality standards, and the benefit outcomes of a uniform reduction in $PM_{2.5}$ concentrations. Our study focuses on the outcomes of annual $PM_{2.5}$ exposure in 2016, but the same approach can be applied to other years and countries. This framework enables us to not only evaluate the environmental benefits of pollution control, but also to provide stakeholders with an easy-to-use tool for generating inputs for policy impact analyses.

Our analysis suggests that ambient $PM_{2.5}$ in the urban areas of major cities in the PRC caused 0.67 million premature deaths in 2016. The percentage of deaths attributable to fine particulate pollution in urban areas is twice the national average, indicating that urban residents face considerably higher mortality risks than the general population. For 2016, the aggregated total cost of $PM_{2.5}$ mortality in major PRC cities was about CNY1,172 billion.[6] The average per capita cost of $PM_{2.5}$ mortality is CNY2,255. The aggregated benefit of mortality reduction from a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentrations in these cities was about CNY141 billion in 2016, which is equal to a per capita $UB_{10}$ of CNY321. Our results show significant heterogeneity across cities with different characteristics. Cities with medium to high $PM_{2.5}$ concentrations, high per capita income, and large populations have the highest total cost. Cities with lower $PM_{2.5}$ concentrations, high per capita income, and large populations can realize the most benefit from a uniform

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[6]$1 = CNY6.64 at the 2016 average exchange rate.

10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentrations. Meeting the PRC's current AQS of 35 $\mu$g/m$^3$ will realize a very limited reduction in PM$_{2.5}$ mortality; therefore, all cities in the PRC should aim at reducing fine particulate pollution to levels below the stringent WHO third interim target and AQG.

The rest of the paper is organized as follows. Section II describes the available data and the challenges of fine particulate pollution in the PRC. Section III develops an analytical framework to quantify the premature deaths from fine particulate pollution and the welfare measures of total cost, total benefit, and the benefit of a uniform 10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentration. Section IV presents the results and section V discusses the implications for the literature and policy makers. Section VI concludes the paper. The list of technical terms used in this paper is found in the Appendix.

## II.  Background and Data

We collect three sets of publicly available data to form a city-level, cross-sectional data set for all the major cities in the PRC in 2016. They include the following data: (i) city-specific annual average PM$_{2.5}$ concentration, (ii) urban census registered population sizes, and (iii) urban per capita disposable income.[7] The fine particulate pollution data are available from the Qingyue Open Environmental Data Center.[8] The urban population and income data are collected from provincial statistical yearbooks.[9] With this data set, we can assess PM$_{2.5}$ mortality, the various welfare indicators, and their heterogeneity across cities with different characteristics. Before presenting our formal estimation, we provide an overview of the PRC's ambient fine particulate pollution, recent policies, and how current pollution levels compare to various air quality targets.

The PRC's economy has been growing rapidly for decades; uneven regional development has concentrated most of the population, fossil fuel consumption, and vehicles in city clusters in the eastern and central PRC. As a result, citizens in these areas enjoy much of the benefit of economic development but have more severe environmental problems such as air pollution. Cities in the northern PRC are exposed to more severe air pollution than the national average, mainly because of the coal consumed by heavy industries and by urban central heating during the winter in these areas. Furthermore, rural households in the northern PRC use coal and biomass for winter space heating. Due to incomplete combustion, these fuels make substantial contributions to ambient fine particulate pollution throughout the

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[7]In cities in the PRC there are both citizens with urban *hukou* (household registration) and unregistered rural–urban migrants who live in cities without an urban *hukou*. In this paper, we focus on the urban-registered population. Examining the environmental health impacts of the rural–urban migrants are of importance and a city-level analysis would rely on nonpublicly available data sources, which we direct to future studies.

[8]See https://data.epmap.org.

[9]See, for example, Beijing Municipal Bureau of Statistics (2017) and Jiangsu Bureau of Statistics (2017).
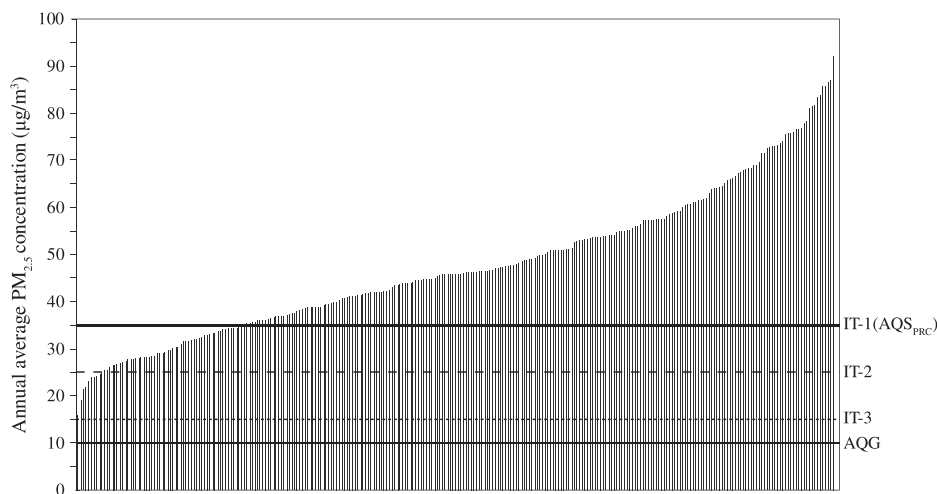
region (Liu et al. 2016b). In addition to coal, vehicle emissions are important contributors to pollution in all cities in the PRC (Shao et al. 2006, Tsinghua University 2006). In megacities such as Beijing and Shanghai, vehicles make the greatest contribution to local fine particulate pollution, exceeding other sources such as coal combustion, road and construction site dust, and industry processes (Beijing MEPB 2014, Shanghai MEPB 2015). Finally, regional-scale transported $PM_{2.5}$ also affects cities in the plains (Xu, Wang, and Zhang 2013), whereas for the basin cities in the central PRC such as Chengdu and Chongqing, meteorological conditions that are unfavorable to pollutant diffusion worsen local pollution (Liang et al. 2016).

In January–February 2013, a winter-long haze caused by extremely high $PM_{2.5}$ concentrations enveloped the whole northern and eastern PRC. Fine particulate pollution and its impacts on health became, for the first time, a nationwide concern (Chris and Elizabeth 2016). The strong political will to control $PM_{2.5}$ pollution was seen in the quick and stringent response from the Government of the PRC. The China State Council (2013) issued the Air Pollution Prevention and Control Action Plan, 2013–2017 (hereafter the Action Plan), which contains compulsory regional air quality improvement goals and 10 key tasks. The goals were largely uniform within each region but varied between regions: the Action Plan required the Beijing–Tianjin–Hebei, Yangtze River Delta, and Pearl River Delta regions to reduce their annual average $PM_{2.5}$ concentration by 25%, 20%, and 15%, respectively, between 2013 and 2017, whereas the rest of the PRC was assigned the more relaxed goal of reducing particulates with aerodynamic diameter ≤10 micrometers ($PM_{10}$) by 10% over the same period. Faced with these mandatory air quality improvement goals, local authorities implemented a variety of regulations. Although improvements were observed at the end of the 5-year policy window, it was difficult for the northern region of Beijing–Tianjin–Hebei, which has much higher $PM_{2.5}$ levels (Tsinghua University and Clean Air Alliance of China 2014), to reach the policy goals even though regulations with very high compliance costs had been implemented (Jin, Andersson, and Zhang 2017; Wang 2017). However, the cleaner region of the Pearl River Delta reached its goals easily (China Environmental Protection Association 2016).

In the long term, the PRC's cities must meet the challenge of more stringent air quality targets. WHO AQG for annual average $PM_{2.5}$ concentration is 10 $\mu g/m^3$.[10] WHO also defines three interim targets (IT-3, IT-2, and IT-1) to gauge different countries' progress in reducing fine particulate pollution. In 2012, the PRC updated the AQS and set 35 $\mu g/m^3$ as the annual average $PM_{2.5}$ standard, equaling WHO's first interim target level of 35 $\mu g/m^3$. Figure 1 shows that the

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[10] Although adverse health effects are still observable below this concentration (Di et al. 2017), the 10 $\mu g/m^3$ level is recommended as the long-term guideline value as it is only slightly higher than the environmental background $PM_{2.5}$ and has been shown to be achievable in large urban areas in highly developed countries (WHO 2005).

Figure 1. **Annual Average Fine Particulate Pollution Concentration in Chinese Cities at the Prefecture Level and Above, 2016**



AQG = World Health Organization's Air Quality Guidelines, AQS = ambient air quality standard, IT = World Health Organization's Air Quality Interim Target, $PM_{2.5}$ = particulates with aerodynamic diameter $\leq 2.5$ $\mu$m, PRC = People's Republic of China.
Source: 2016 Annual Average $PM_{2.5}$ Concentration from Qingyue Open Environmental Data Center. https://data.epmap.org.

$PM_{2.5}$ concentration of all major cities in the PRC in 2016 exceeded the AQG target. Two-thirds did not meet WHO's first interim and the PRC's AQS.

In sum, reducing $PM_{2.5}$ concentration in the PRC's cities will inevitably be a difficult and long-term process. This is evident from the severe and complex nature of the pollution itself, the policy dynamics of the Action Plan, and the large gap between current pollution levels and WHO's interim targets. We examine the economic value of various $PM_{2.5}$ concentration or reduction scenarios to provide a welfare perspective on this long-term $PM_{2.5}$ control process. As defined earlier, we define the values as the total cost, total benefit of WHO's AQG ($TB_{AQG}$) and three interim targets ($TB_{IT-1}$, $TB_{IT-2}$, and $TB_{IT-3}$), and the benefit of a uniform 10 $\mu$g/m$^3$ decrease in fine particulate pollution concentration ($UB_{10}$). As discussed in the next sections, total cost, together with the physical estimates of premature deaths, can represent a major part of the welfare loss attributable to fine particulate pollution across cities. The results of $UB_{10}$ answer important questions such as how significant is the benefit of near-term achievable $PM_{2.5}$ control, and why relatively clean cities should further reduce their fine particulate pollution. The relative sizes of the total cost, total benefit, and the benefit of a uniform 10 $\mu$g/m$^3$ decrease in fine particulate pollution concentration have implications for setting targets and choosing appropriate speeds for $PM_{2.5}$ pollution reduction across cities.

### III. Methodology

In this section, we build an estimation framework using an integrated exposure-response (IER) model and parameters suitable for the PRC context. We first note that, regardless of the estimation scales used, the economic value of the mortality (or mortality changes) attributable to $PM_{2.5}$ will eventually be composed of the following four sets of information: (i) the exposed population; (ii) the baseline mortality rate; (iii) the CR relationship, which is a monotonic increasing function of $PM_{2.5}$ concentration with its slope usually called the CR coefficient; and (iv) the value of a statistical life (VSL), which represents the willingness to pay for mortality risk reduction aggregated over the affected population. As discussed below, holding other factors unchanged, the economic estimate will grow with an increase in any of the four factors.

### A. Premature Deaths Attributable to 1 Year of Exposure to Fine Particulate Pollution

In epidemiological studies of the health effects of ambient air pollution, the relationship between $PM_{2.5}$ exposure and mortality is characterized by the CR function. The conventional view is that the CR function is a linear function of $PM_{2.5}$ concentration, $c_i$, with a slope defined as the CR coefficient (Dockery et al. 1993, Pope et al. 2002). Pooled estimates from meta analyses, such as the one by Hoek et al. (2013), suggest the CR coefficient is a 6% (95% confidence interval from 4% to 8%) increase in all-cause mortality per 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration. The constant CR coefficient assumption has been applied in many developed countries where $PM_{2.5}$ concentration generally ranges below 30 $\mu g/m^3$. Accordingly, the relative risk (RR) for premature death at $PM_{2.5}$ concentration $c_i$ can be written as

$$RR(c_i) = 1 + CR\ coefficient * (c_i - c_0) \qquad (1)$$

where $c_0$ is the threshold concentration that causes health impacts.

Recent evidence suggests that the CR function is nonlinear (concave), and the CR coefficient is lower when the $PM_{2.5}$ concentration is higher (Pope et al. 2011, Burnett et al. 2014). This implies that using the constant CR coefficient derived from studies of cleaner developed countries may overestimate the health impacts from fine particulate pollution in places with very high $PM_{2.5}$ concentrations. To better describe the concave characteristics of the CR function, an IER model was developed by Burnett et al. (2014) and Smith et al. (2014). It has been applied in the Global Burden of Disease project (Lim et al. 2013) and recently in PRC-specific studies (Liu et al. 2016a, Xie et al. 2016a, Xie et al. 2016b, and Mu and Zhang 2015). The IER simulates a set of disease-specific RR curves that cover the whole range of $PM_{2.5}$ exposure by integrating available evidence for the health impacts of

ambient air pollution, indoor air pollution from household solid fuel use, second-hand smoking, and active smoking. It therefore can be used to estimate the $PM_{2.5}$ mortality risks for cities in the PRC with high concentrations.

The IER describes the RR for several diseases, $k$, associated with $PM_{2.5}$ pollution.

$$RR_k(c_i) = \begin{cases} 1 + \alpha_k & \left(1 - e^{-\gamma_k(c_i - c_0)\delta_k}\right), & if \, c_i > c_0 \\ & 1, & else \end{cases} \qquad (2)$$

where $k$ is one of the four major adult diseases associated with $PM_{2.5}$: ischemic heart disease, chronic obstructive pulmonary disease, stroke, and lung cancer. $\alpha_k$, $\gamma_k$, and $\delta_k$ are the parameters characterizing the shapes of the $RR_k$ curve.

The Global Burden of Disease Study (2013) provides the exact $RR_k(c_i)$ value and its 95% confidence interval for disease $k$ at each integer's concentration level for the IER model. Therefore, given city $j$'s 2016 annual average $PM_{2.5}$ concentration ($c_i$), we know the corresponding $RR_k(c_i)$.

The attribution fraction of the mortality risks of disease $k$ from $PM_{2.5}$, $AF_k$ can be written as

$$AF_k = \frac{RR_k(c_i) - 1}{RR_k(c_i)} \qquad (3)$$

The disease-specific premature deaths due to the annual exposure to ambient $PM_{2.5}$ in city $i$, ($D_{ki}$), is

$$D_{ki} = I_{ki} * P_i * AF_k \qquad (4)$$

where $I_{ki}$ is the mortality rate for disease $k$ in city $i$. Currently, there is no publicly available city-level mortality information for cities in the PRC. We apply the provincial disease-specific mortality estimated by Liu et al. (2016a) to all the cities in the same province. $P_i$ is the population of city $i$.

## B. Total Cost of Mortality Attributable to 1 Year of Exposure to Fine Particulate Pollution

The premature deaths from $PM_{2.5}$ are monetized using the VSL estimates for the PRC. VSL is the marginal rate of substitution between income and micro mortality risk reduction (Hammitt 2000) and is nonconstant across income groups and risk contexts (Cameron and DeShazo 2013). It is obtained by aggregating individuals' willingness to pay for mortality risk reductions over the affected population. Therefore, the higher the income level of the affected population, the higher their willingness to pay and VSL. Meta analyses of VSL empirical estimates show that it increases with the income of the sampled population and decreases with the level of mortality risk reduction in the research (Viscusi and Aldy 2003,

Lindhjem et al. 2011). As a result, Cameron (2010), among others, advocates not using a one-size-fits-all VSL for populations across sites and regulatory contexts, and proposes adjusting it to fit the population's income level and a study's risk settings.

Empirical VSL estimates for the PRC are limited, and the data are more than 10 years out-of-date. Reviews of these studies are available in Huang, Andersson, and Zhang (2017); and Jin (2017). Due to the large differences in income and health risks between developed countries and the PRC, and the changes over the last decade, applying VSL values from United States-based or old PRC studies to current PRC data sets using benefit transfer methods would incur large uncertainties. Motivated by this gap, Jin (2017) designed a state-of-the-art discrete choice experiment (DCE) that incorporated the newest IER evidence on the health impacts of air pollution and constructed risk reduction scenarios that are realistic in the PRC setting. Based on online DCE surveys implemented in September 2016 on a representative sample of over 1,000 Beijing citizens, Jin reported the VSL for air pollution mortality impacts in Beijing to be CNY3 million (95% confidence interval from CNY2.2 million to CNY5 million, in 2016 prices).[11] More detailed information of this DCE survey, econometric analysis, and results are available in Jin (2017).[12] This VSL estimate of Beijing's air pollution fits this study's research objective, as it is up-to-date and the risk contexts in the two studies are the same.

As Jin (2017) did not find significant differences in the VSLs of the major adult diseases associated with $PM_{2.5}$, we use her base estimate of CNY3 million as the $VSL_{Beijing,\ air\ pollution}$ to monetize the premature deaths $D_{ki}$. We then adjust the $VSL_{Beijing,\ air\ pollution}$ to every city $i$ as follows:

$$VSL_i = VSL_{Beijing,\ air\ pollution} * \left( \frac{Y_{Beijing}}{Y_i} \right)^e \tag{5}$$

where $Y_{Beijing}$ and $Y_i$ are, respectively, urban per capita disposable income in Beijing and in city $i$, and $e$ is the income elasticity of VSL, which in this study is assumed to be 1.[13]

The total cost of the premature deaths for city $i$ ($TC_i$) can be written as

$$TC_i(c_i) = VSL_i * \sum_k D_{ki} \tag{6}$$

Finally, combining equation (6) with equation (1) to equation (5), the total cost of premature deaths in city $i$ from 1 year of exposure to the average annual $PM_{2.5}$ concentration $c_i$ is

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[11] As the VSL enters estimation in this study as a multiplier, its absolute size only "shifts" the welfare indicators to higher or lower levels. Our conclusions remain.

[12] The full survey questionnaire (in English) is available at yanajin.weebly.com.

[13] Most studies use per capita GDP to adjust the VSL across sites (e.g., Huang, Xu, and Zhang 2012; and Mu and Zhang 2013). We improve this by using per capita disposable income (Hammitt 2000).

$$TC_i(c_i) = VSL_{Beijing,\,air\,pollution} * \left(\frac{Y_{Beijing}}{Y_i}\right)^e * P_i \sum_k \left\{ I_{ki} * \frac{RR_k(c_i) - 1}{RR_k(c_i)} \right\} \qquad (7)$$

## C. Benefit of Mortality Reduction from a Uniform 10 $\mu g/m^3$ Decrease in $PM_{2.5}$ Concentration and from Meeting WHO AQG and Interim Targets

In this study, the benefit of mortality reduction from a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration in city $i$ is defined as the $TC_i(c_i)$ in equation (7) minus $TC_i(c_i - 10)$, i.e., the total cost in the same year with a counterfactual 10 $\mu g/m^3$ reduction in $PM_{2.5}$ concentration. The interpretation is as follows: if city $i$ realizes a 10 $\mu g/m^3$ reduction in annual average $PM_{2.5}$ concentration, and everything else stays at the 2016 level, then the benefit of prevented premature deaths caused by this specific reduction in $PM_{2.5}$ concentration equals the following:

$$UB_{10,i}(c_i) = TC_i(c_i) - TC_i(c_i - 10) \qquad (8)$$

We define $UB_{10}$ as based on a 10 $\mu g/m^3$ decrease, rather than on a 1 $\mu g/m^3$ decrease of $c_i$ because a 10 $\mu g/m^3$ change is more policy relevant. A stable and significant reduction in the $PM_{2.5}$ concentration of 10 $\mu g/m^3$ could in most cases only be achieved through policy, whereas a 1 $\mu g/m^3$ change may occur due to natural factors such as meteorological fluctuations. Furthermore, the PRC's Action Plan sets air quality improvement goals based on percentage changes that, if transformed into concentration changes, are on a 10 $\mu g/m^3$ order of magnitude. Therefore, using a 10 $\mu g/m^3$ change in our estimations provides ready-to-use references for local policy economic evaluations.

Likewise, the benefit of reductions in $PM_{2.5}$ mortality achieved by meeting different air quality targets, $TB_{AQG}$, $TB_{IT-1}$, $TB_{IT-2}$, and $TB_{IT-3}$, are defined as

$$TB_{t,i}(c_i) = \begin{cases} TC_i(c_i) - TC_i(c_t), & if\ c_i > c_t \\ 0, & else \end{cases} \qquad (9)$$

where $t$ is one of the four air quality targets and $c_t$ is each target's corresponding concentration level, which are WHO's AQG (10 $\mu g/m^3$) and interim targets, IT-3 (15 $\mu g/m^3$), IT-2 (25 $\mu g/m^3$), and IT-1 (35 $\mu g/m^3$).

## IV. Results

### A. Estimated Premature Deaths

Our first set of results is for the estimated premature deaths attributable to 1 year of exposure to ambient $PM_{2.5}$ in 2016 in the major cities in the PRC. Table 1 reports the estimated total reductions and disease-specific reductions. It also compares our results with those of the newest estimates given in the Global

Table 1.   **Premature Deaths Attributable to Ambient PM$_{2.5}$—Comparison of National and Urban Estimates**

| Estimates and Calculations | GBD 2015 (a) | This Study (b) | Urban/National Ratio (b/a) |
|---|---|---|---|
| Research areas in the People's Republic of China | nationwide | urban areas | — |
| Population affected (million) [A] | 1,370 | 446 | 0.3 |
| Total deaths except from injuries (million) [B] | 8.6 | 2.7 | 0.3 |
| Premature deaths due to PM$_{2.5}$ (million) [C] | 1.1 | 0.7 | 0.6 |
| Rate of disease-related death (per 100,000) [B]/[A] | 630 | 620 | 0.9 |
| Percent attributable to PM$_{2.5}$ [C]/[B] | 12.8% | 25.0% | 1.9 |

| Premature Deaths Due to PM$_{2.5}$ by Disease | GBD 2015 | Liu et al. 2016 | This Study |
|---|---|---|---|
| Stroke | 322,228 | 688,000 | 349,139 |
| Ischemic heart disease | 291,764 | 381,900 | 185,860 |
| Lung cancer | 145,985 | 129,400 | 58,343 |
| Chronic obstructive pulmonary disease | 281,703 | 168,100 | 76,084 |

GBD = Global Burden of Disease Study, PM$_{2.5}$ = particulates with aerodynamic diameter $\leq$2.5 $\mu$m.
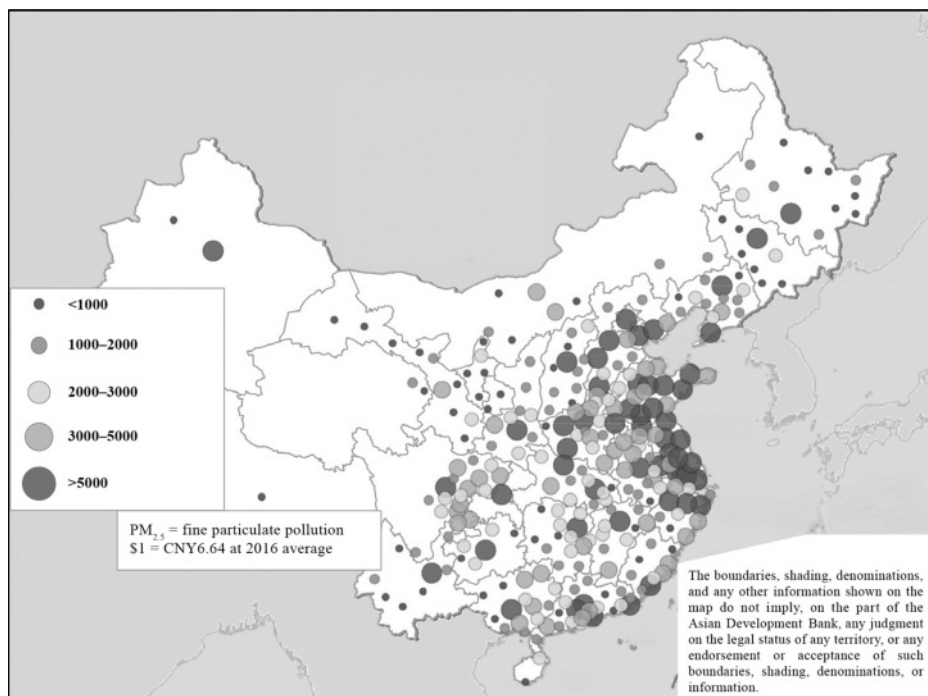Source: Authors' calculations.

Burden of Disease Study (2015) and in Liu et al. (2016a). In the latter's analysis, the premature deaths are also calculated based on the IER model, but for the entire population of the PRC.

Our results, as shown in Table 1, suggest that 0.67 million premature deaths are attributable to ambient PM$_{2.5}$ in the urban areas of major cities in the PRC cities in the 2016 data set. Although the urban-registered population in our study area is 0.45 billion, which is only 33% of the 1.37 billion people living in the PRC, the premature deaths due to ambient fine particulate pollution account for 60% of the deaths nationally. The rate of disease-related death for urban residents is almost the same as that of the whole population, suggesting that although there is no difference between the baseline mortality risks of urban residents and the national average, the percentage of deaths attributable to ambient PM$_{2.5}$ in urban areas is almost twice the national average. These results indicate that urban residents face considerably higher mortality risks associated with ambient fine particulate pollution than the general population.

The lower part of Table 1 compares disease-specific premature deaths. Stroke accounts for the majority of premature deaths, followed by ischemic heart disease; chronic obstructive pulmonary disease and lung cancer are less common. This is consistent with the fact that the baseline mortality risks for stroke and ischemic heart disease are higher. The relative magnitude of the four types of disease-specific PM$_{2.5}$ mortalities in our study are similar to the patterns in nationwide estimates.

Cities with higher estimates of premature deaths are those with larger populations and higher PM$_{2.5}$ concentrations. The magnitudes and distribution of our results are in accordance with recent grid-based studies such as Liu et al. (2016a) and Xie et al. (2016a).

Figure 2.   **Total Cost of Mortality Attributable to 1 Year of Exposure to PM$_{2.5}$, 2016**
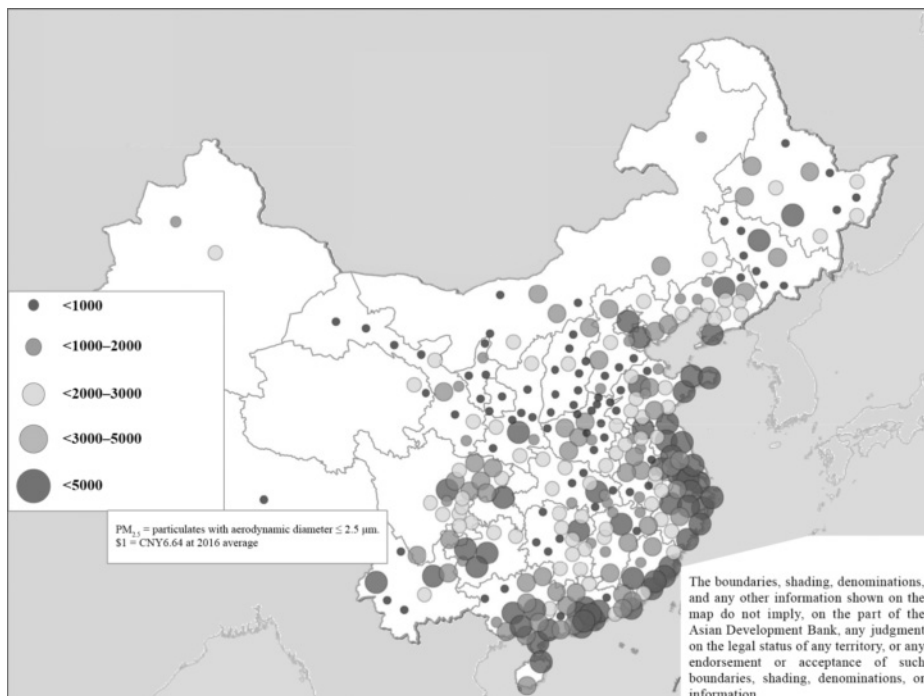(CNY million)



CNY = yuan.
Source: Authors' calculations.

## B.   Total Cost of PM$_{2.5}$ Mortality, Benefit of a Uniform 10 $\mu$g/m$^3$ Decrease in PM$_{2.5}$ Concentration, and Benefit of Meeting WHO AQG and Interim Targets

In the second set of results, we determine welfare outcomes by analyzing the monetary terms of different PM$_{2.5}$ mortality impacts. We begin with the total cost estimates; that is, the total cost of PM$_{2.5}$ mortality. It represents a majority of the annual social welfare loss if ambient fine particulate pollution remains unchanged. In other words, total cost is the theoretical maximum benefit that could result from reducing the current PM$_{2.5}$ concentration to zero. In major cities in the PRC in 2016, it aggregated to about CNY1,172 billion. The spatial distribution of total cost is shown in Figure 2. Megacities in the Beijing–Tianjin–Hebei and Yangtze River Delta regions, as well as Chengdu and Chongqing in the central PRC, have the highest total cost. Income, population, and PM$_{2.5}$ concentration are all high in these cities, pulling up their total cost estimates. In the highly developed Pearl River

Figure 3.   **The Benefits of Mortality Reduction from a Uniform 10 $\mu$g/m$^3$ Decrease in PM$_{2.5}$ Concentration Reduction** (CNY million)
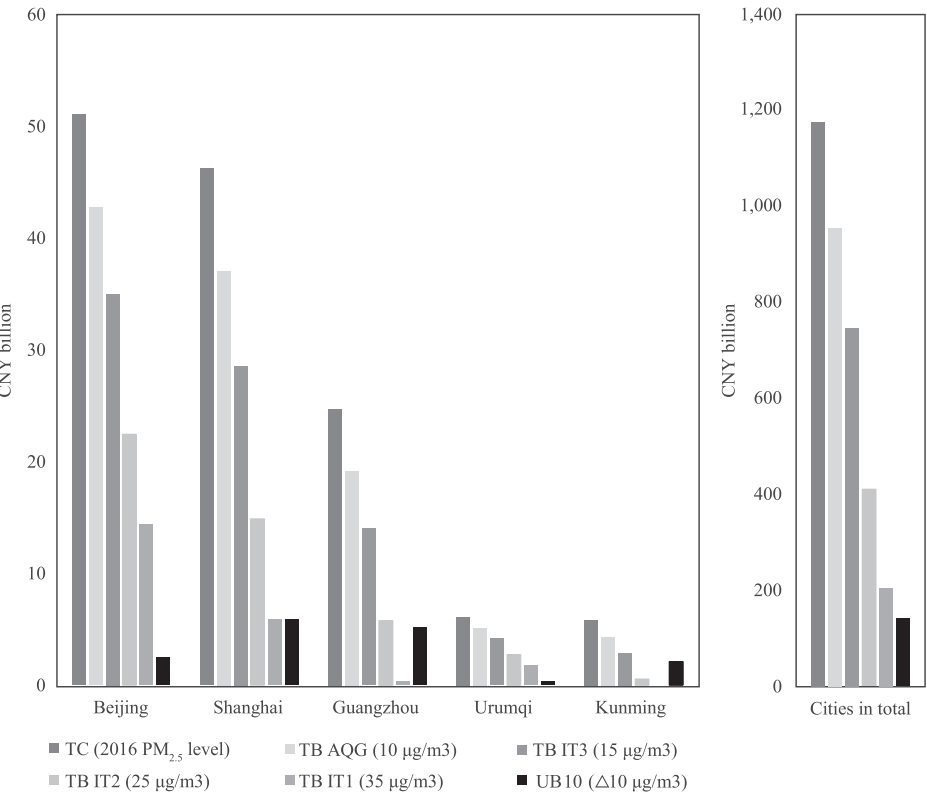


CNY = yuan.
Source: Authors' calculations.

Delta region, although PM$_{2.5}$ concentration is relatively low, populated cities such as Guangzhou and Shenzhen have very high total cost.

We then consider UB$_{10}$, that is, the benefit of mortality reduction from a uniform 10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentration in 2016 in each city. It should be noted that for most of the PRC's cities with currently high PM$_{2.5}$ concentration levels, UB$_{10}$ measures the near-term and achievable benefits of implementing effective fine particulate pollution control measures. In contrast, for cities with a very low PM$_{2.5}$ concentration, a further decline of 10 $\mu$g/m$^3$ is a big reduction and may be difficult to achieve. The total UB$_{10}$ of all cities in 2016 was about CNY141 billion. Importantly, the spatial distribution of the UB$_{10}$, shown in Figure 3, is very different from that of the total cost, shown in Figure 2. Beijing, Tianjin, Chongqing, and provincial capitals with high PM$_{2.5}$ concentrations such as Chengdu and Shenyang have high UB$_{10}$ values. However, cities with medium and low PM$_{2.5}$ concentrations, high incomes, and high populations, such as those along the eastern and southern coastline, also have very high UB$_{10}$.

Figure 4. **Total Cost of PM$_{2.5}$ Mortality, Total Benefits of Meeting Different Air Quality Standards, and Benefits of a Uniform 10 $\mu$g/m$^3$ Decrease in PM$_{2.5}$ Concentration**



AQG = World Health Organization's Air Quality Guidelines, CNY = yuan, IT = World Health Organization's Air Quality Interim Target, PM$_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m, TB = benefit of mortality reduction achieved by meeting certain air quality targets, TC = total cost of PM$_{2.5}$ mortality, UB$_{10}$ = benefit of a uniform 10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentration.
Notes: The scales are different in the vertical axes of the left and right panels. $1 = CNY6.64 (2016 average prices).
Source: Authors' calculations.

Next, we compare the values for total cost with total benefit, which include the benefit of a reduction of mortality achieved by meeting different air quality targets and a uniform 10 $\mu$g/m$^3$ decrease in fine particulate pollution concentration for five representative cities and for all cities (Figure 4). Intuitively, it seems that more stringent air quality targets will have greater benefits. However, a disproportionately increasing trend can be seen from TB$_{IT-1}$ to TB$_{IT-3}$ and finally TB$_{AQG}$. This is due to the concavity of the CR relationship between PM$_{2.5}$ concentration and mortality. The current PRC's AQS of 35 $\mu$g/m$^3$, which is equal to WHO's first interim target, represents a huge reduction in PM$_{2.5}$ concentration for some cities, but the associated benefit (TB$_{IT-1}$) is very small (less than one-third of the total cost). Cities will achieve a much higher total benefit (TB$_{IT-3}$) (more than

Table 2.   Top 20 Cities for Attributable Premature Deaths, TC, $TB_{IT-3}$ (15 $\mu g/m^3$), and $UB_{10}$

| Attributable Premature Deaths | | Total Cost | | Total Benefit $_{IT-3}$ (15 $\mu g/m^3$) | | $UB_{10}$ | |
|---|---|---|---|---|---|---|---|
| Top 20 Cities | Deaths | Top 20 Cities | CNY billion | Top 20 Cities | CNY billion | Top 20 Cities | CNY million |
| Chongqing | 36,113 | Chongqing | 56.0 | Chongqing | 36.7 | Shanghai | 5,837 |
| Tianjin | 17,032 | Beijing | 51.1 | Beijing | 35.0 | Guangzhou | 5,190 |
| Beijing | 17,030 | Shanghai | 46.2 | Shanghai | 28.6 | Chongqing | 4,858 |
| Shanghai | 15,302 | Tianjin | 33.1 | Tianjin | 22.5 | Nanjing | 3,494 |
| Chengdu | 12,692 | Nanjing | 29.3 | Nanjing | 18.6 | Shenzhen | 3,051 |
| Nanjing | 11,190 | Guangzhou | 24.7 | Chengdu | 16.1 | Beijing | 2,452 |
| Xi'an | 10,803 | Chengdu | 23.9 | Guangzhou | 14.0 | Hangzhou | 2,192 |
| Guangzhou | 9,256 | Xi'an | 20.2 | Xi'an | 13.8 | Shantou | 2,123 |
| Shijiazhuang | 9,021 | Hangzhou | 19.2 | Hangzhou | 12.2 | Kunming | 2,076 |
| Zhengzhou | 8,417 | Wuhan | 17.0 | Wuhan | 11.2 | Suzhou | 2,057 |
| Wuhan | 8,149 | Suzhou | 16.5 | Jinan | 10.6 | Xiamen | 1,912 |
| Shenyang | 7,468 | Shenyang | 15.3 | Suzhou | 10.4 | Tianjin | 1,776 |
| Harbin | 7,406 | Jinan | 15.2 | Shijiazhuang | 10.2 | Foshan | 1,768 |
| Hangzhou | 7,006 | Zhengzhou | 14.6 | Zhengzhou | 10.2 | Qingdao | 1,711 |
| Tangshan | 6,802 | Shijiazhuang | 14.4 | Shenyang | 9.9 | Chengdu | 1,634 |
| Jinan | 6,752 | Qingdao | 13.0 | Changsha | 8.4 | Fuzhou | 1,561 |
| Xuzhou | 6,266 | Changsha | 12.9 | Harbin | 8.3 | Nanning | 1,429 |
| Baoding | 6,107 | Harbin | 12.9 | Tangshan | 8.3 | Shenyang | 1,371 |
| Suzhou | 5,780 | Changzhou | 12.5 | Qingdao | 8.2 | Putian | 1,336 |
| Qingdao | 5,711 | Tangshan | 12.0 | Changzhou | 8.1 | Wuhan | 1,326 |

CNY = yuan, IT = World Health Organization's Air Quality Interim Target, $PM_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m, $UB_{10}$ = benefit of a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration.
Notes: Total benefit (TB) refers to the benefit of mortality reduction achieved by meeting certain air quality targets. Total cost refers to the total cost (TC) of $PM_{2.5}$ mortality. \$1 = CNY6.64 (2016 average prices).
Source: Authors' calculations.

one-half of the total cost) if the annual $PM_{2.5}$ concentration is lower than WHO's third interim target level of 15 $\mu g/m^3$. When cities meet WHO's AQG, the $TB_{AQG}$ is about 80% of the total cost. Figure 4 illustrates the welfare implications of the uniform 10 $\mu g/m^3$ decrease in fine particulate pollution concentration for different cities. For dirty cities such as Beijing and Urumqi, $UB_{10}$ is much lower than the total benefit, whereas for clean cities such as Guangzhou and Kunming, it corresponds to a significant pollution reduction and is therefore comparable to the total cost.

In Table 2, we list the 20 cities with the highest estimates of attributable premature deaths along with their corresponding total cost, total benefit of WHO's third interim target (15 $\mu g/m^3$), and the benefit of a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration. The cities' rankings of total cost and total benefit of WHO's third interim target vary slightly from their ranking of premature deaths, but the ranking of $UB_{10}$ is totally different from the other three measures. In fact, among the cities with the most deaths, cleaner and dirtier cities swap rankings for the $UB_{10}$, and many new cities that are generally cleaner and wealthier appear on the $UB_{10}$'s top 20 list.

### C.    Comparing Cities Using per Capita Welfare Indicators

Our third set of results considers per capita welfare indicators. We use them to remove the influence of huge disparities in cities' populations on our results. Due to space limitations, we focus on per capita total cost and per capita $UB_{10}$. Per capita total cost can be interpreted as the economic cost of the annual attributable mortality risk for an average individual in city $i$ in 2016. Per capita $UB_{10}$ represents the economic benefit of this individual's mortality risk reduction from a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration. We also study how income and $PM_{2.5}$ pollution levels influence individual welfare. Ideally, we would use subsamples of populations with different socioeconomic statuses within and across cities for this purpose. However, due to data limitations, we only approximately examine this issue by looking at the difference between low- and high-income cities. We equally divide the cities into five income groups with the first group having the lowest income and the fifth group having the highest income. Then we plot the per capita total cost and per capita $UB_{10}$ for these cities against the $PM_{2.5}$ concentration, as shown in Figures 5 and 6, respectively. The areas of the circles represent the city's population.
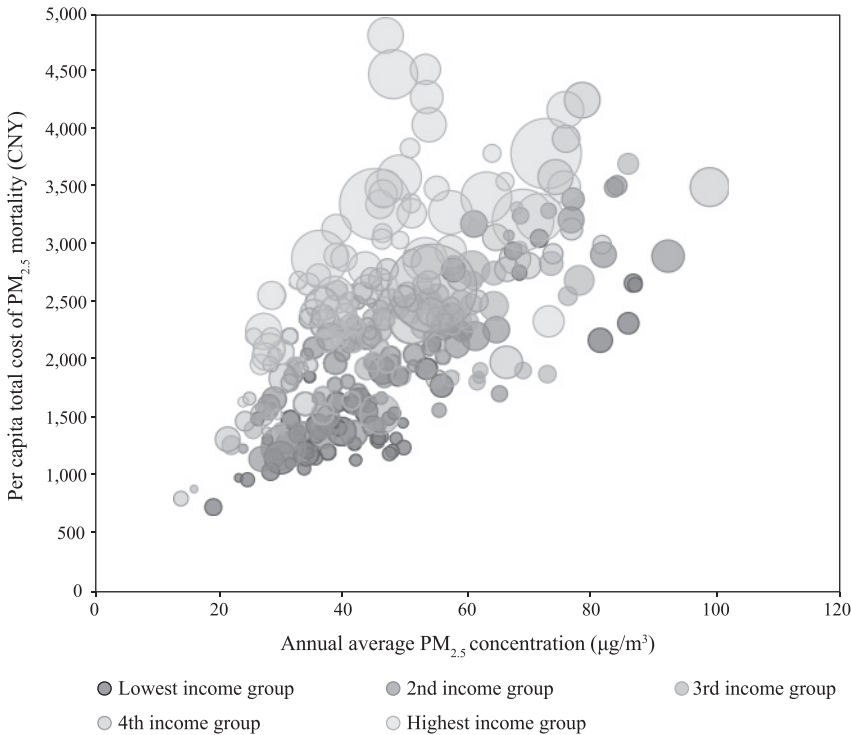
For per capita total cost in Figure 5, we see that cities with the highest per capita total cost are high-income cities with $PM_{2.5}$ concentrations between 40 $\mu g/m^3$ and 60 $\mu g/m^3$. Residents in low-income and high $PM_{2.5}$ concentration cities (see the circles for the first and second income groups with $PM_{2.5} > 60 \ \mu g/m^3$) bear a greater burden in terms of the economic costs of $PM_{2.5}$ mortality.

Figure 6 shows a clear trend of decreasing per capita $UB_{10}$ as $PM_{2.5}$ concentration increases. This is contrary to the conventional understanding that the first unit of pollution reduction has the highest benefit. As indicated in previous analyses, this is due to the concavity of the $PM_{2.5}$ CR function. In each income group, the per capita $UB_{10}$ spans a wide range, from about CNY100 to CNY900.

### D.    How Do Cities in the People's Republic of China Differ from Cities in Other Countries?

Our last exercise is to compare the results for cities in the PRC with those in other countries. We choose two megacities in developed countries, New York City (population 8.5 million; annual $PM_{2.5}$ concentration in 2016, 13.5 $\mu g/m^3$) and Seoul (population 10.3 million; annual $PM_{2.5}$ concentration in 2016, 27 $\mu g/m^3$). We also choose Monrovia (population 1.1 million; annual $PM_{2.5}$ concentration in 2016, 22 $\mu g/m^3$), the capital city of Liberia, to represent cities in least developed countries. We perform the same total cost and $UB_{10}$ estimation process on the three cities. It should be noted that it is a huge step for cities with low $PM_{2.5}$ concentrations to further reduce them by 10 $\mu g/m^3$ (e.g., for New York City, the final $PM_{2.5}$ concentration would be near zero).

Figure 5.   **Per Capita Total Cost for Cities with Different Incomes and PM$_{2.5}$ Concentrations**
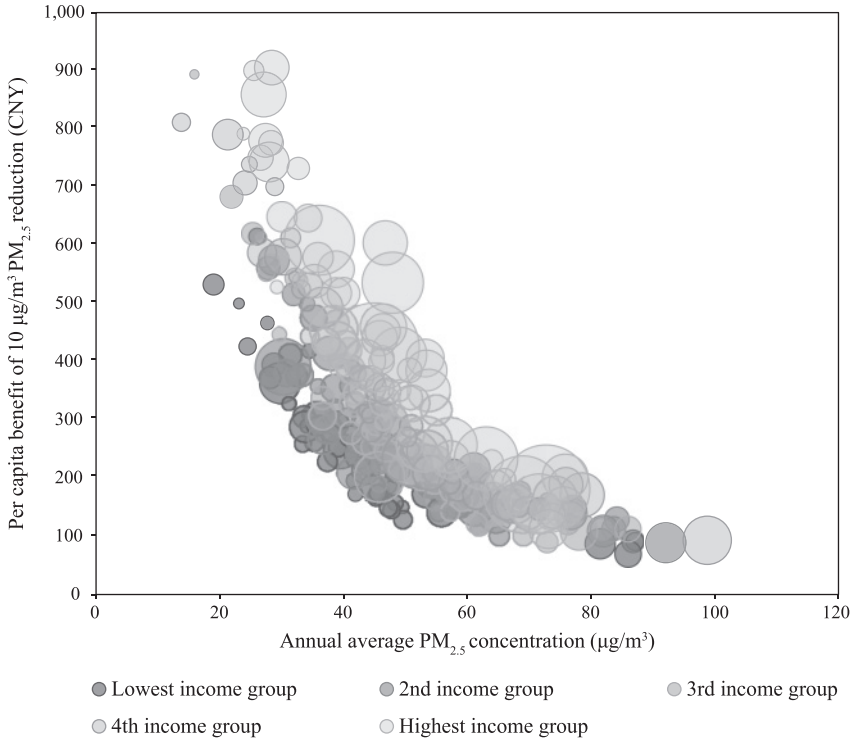


CNY = yuan, PM$_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m.
Notes: Cities are divided into five equal groups according to urban per capita disposable income, from the 1st (lowest income group) to the 5th (highest income group). Circle size represents the affected population in each city. $1 = CNY6.64 (2016 average prices).
Source: Authors' calculations.

Figure 7 shows the estimated per capita total cost for all these cities. The results for the PRC's cities are well below CNY5,000, whereas they are near CNY15,000 for New York City and CNY20,000 for Seoul. Similarly, Figure 8 indicates that the per capita UB$_{10}$ is much lower in cities in the PRC than in cities in developed countries. The huge differences are mainly due to the concavity of the CR function and the income disparity between cities in the PRC and those in developed countries.

Figure 9 further explains the difference in the benefit of a uniform 10 $\mu$g/m$^3$ decrease in fine particulate pollution concentration between cities. In the right part of Figure 9, we show several typical cities along the per capita UB$_{10}$ curve, from those with low pollution levels (Shenzhen, Sanya, and Kunming), through middle pollution levels (Guangzhou, Shanghai, and Zhangye), to high pollution levels (Chongqing, Beijing, Urumqi, and Hengshui). These cities also vary significantly

Figure 6.    **Per Capita Benefit of Reduction in Mortality from a 10 $\mu$g/m$^3$ Decrease in PM$_{2.5}$ Concentration for Cities with Different Per Capita Incomes and PM$_{2.5}$ Concentrations**



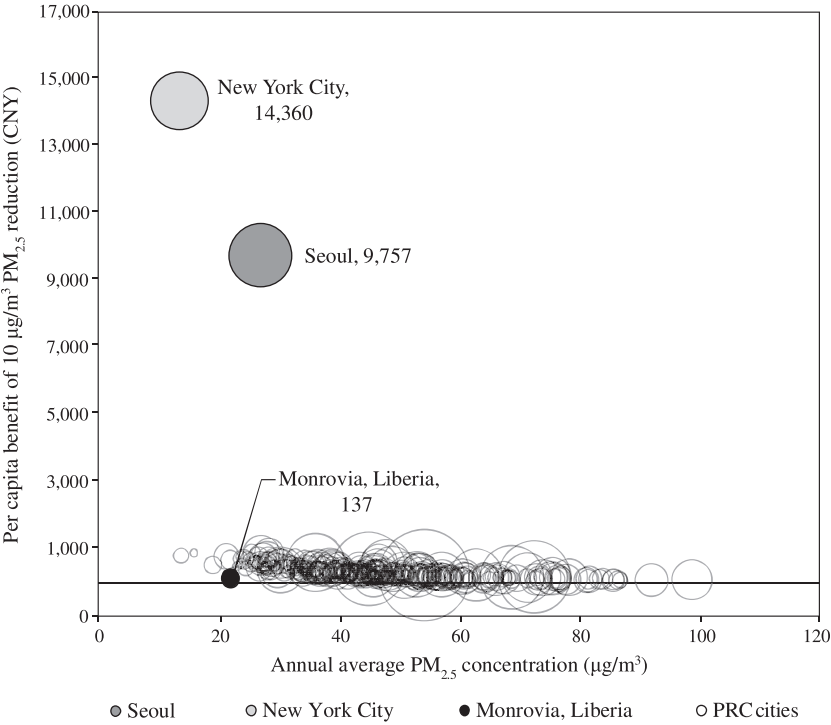CNY = yuan, PM$_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m.
Notes: Cities are divided into five equal parts according to urban per capita disposable income, from 1st (lowest income group) to 5th (highest income group). Circle size represents the affected population in each city. $1 = CNY6.64 (2016 average prices).
Source: Authors' calculations.

in per capita income and population. For example, Beijing and Urumqi have almost the same PM$_{2.5}$ concentration levels, but Beijing has a higher per capita income than Urumqi; therefore, the per capita UB$_{10}$ in Beijing is higher. On the left panel of Figure 9, we multiply per capita UB$_{10}$ by each city's population and get squares representing the size of the UB$_{10}$. In this figure, the difference in the populations of Beijing and Urumqi results in more widely differing UB$_{10}$. Similarly, all cities with high PM$_{2.5}$ concentrations have relatively lower UB$_{10}$, and cities with middle to high pollution levels, relatively small populations, and low per capita income have the lowest (e.g., Hengshui, Urumqi, and Zhangye). Figure 9 also suggests that when dirty cities reduce their fine particulate pollution enough to enter the lower PM$_{2.5}$ concentration ranges, the UB$_{10}$ of a further reduction significantly increases. For example, if Beijing's concentration decreases to the level of Shanghai's, they

Figure 7.   **Per Capita Total Cost for Cities in the PRC versus Monrovia, New York City, and Seoul**
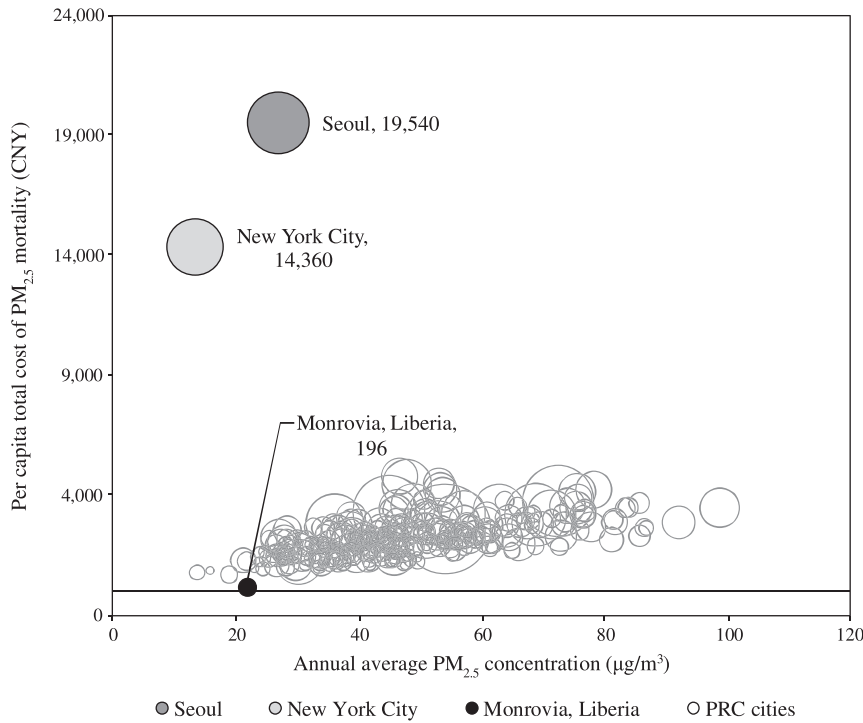


CNY = yuan, $PM_{2.5}$ = particulates with aerodynamic diameter $\leq 2.5$ $\mu$m, PRC = People's Republic of China.
Notes: \$1 = CNY6.64 (2016 average prices). Circle size represents the affected population in each city.
Source: Authors' calculations.

would have similar $UB_{10}$ values, and if they both become as clean as Shenzhen, they would have very large values.

## V.  Policy Implications

The first and foremost implication of our results is that when $PM_{2.5}$ pollution is high, the benefit of controlling it is relatively low. Thus, the PRC and other emerging economies with high levels of fine particulate pollution should accelerate their pollution control processes. Although the optimal $PM_{2.5}$ control pathway and speed depend on factors such as projections of changes in a country's technology, economy, and population, the implications of the relative size differences of the total benefit, and the increasing trend of $UB_{10}$ are clear: given compliance costs and assuming steady economic development, the lower the $PM_{2.5}$ concentration, the more beneficial an extra pollution control effort is to society.

Figure 8.  **Per Capita UB$_{10}$ for Cities in the PRC versus Monrovia, New York City, and Seoul**
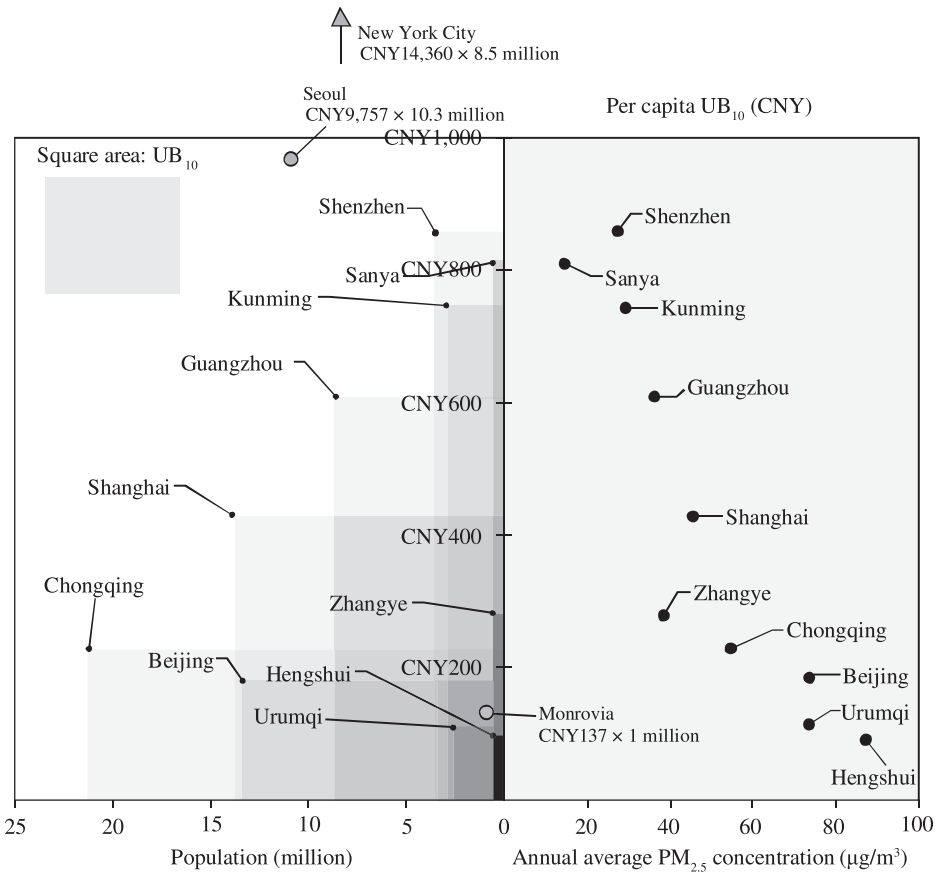


CNY = yuan, PM$_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m, PRC = People's Republic of China, UB$_{10}$ = benefit of a uniform 10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentration.
Notes: S1 = CNY6.64 (2016 average prices). Circle size represents the affected population in each city.
Source: Authors' calculations.

Second, our results highlight the importance of considering the cost effectiveness of PM$_{2.5}$ control policies. This is especially relevant for cities with high pollution levels. To reach the socially optimal pollution level, an efficient policy requires that the marginal cost of pollution reduction is smaller than the marginal benefit.[14] Thus, for cities with a UB$_{10}$ that is close to the marginal benefit of pollution reduction, policies to reduce high pollution have to be very cost effective. However, in the PRC and many developing countries, the cost of controlling PM$_{2.5}$ across sites and sectors is unclear. Sound economic analyses of the available technologies and policy instruments are urgently needed to enhance the cost effectiveness of PM$_{2.5}$ control. Furthermore, as fine particulate pollution can be transported over long distances, regional control strategies that combine the

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[14]This is not necessary in a dynamic efficiency perspective. Dynamic efficiency favors the policy that maximizes the sum of the present value of the net benefit for each period.

Figure 9.  **UB$_{10}$ for Typical Cities with Different Characteristics**



CNY = yuan, PM$_{2.5}$ = particulates with aerodynamic diameter ≤2.5 $\mu$m, UB$_{10}$ = benefit of a uniform 10 $\mu$g/m$^3$
decrease in PM$_{2.5}$ concentration.
Note: $1 = CNY6.64 (2016 average prices).
Source: Authors' calculations.

efforts of neighboring cities and provinces are essential to cost-effective reductions
in PM$_{2.5}$ concentrations (Wu, Xu, and Zhang 2015).

Third, our estimation scheme can be easily used by the general public and
the government. Our approach mainly relies on official statistics and data on PM$_{2.5}$
annual concentrations. We focus on clearly defined jurisdictional urban areas rather
than on cells in grids. As pollution control costs are usually calculated for specific
programs and projects within certain jurisdictional areas, our approach helps to
unify the cost–benefit analyses of PM$_{2.5}$ control. This helps local authorities to
understand the trade-offs between the cost and benefit for their own administrative

areas, and will help neighboring cities to coordinate their pollution control efforts through economic mechanisms (e.g., transfers).

Fourth, our results imply that current policy targets of uniform percentage reductions in regional $PM_{2.5}$ concentrations do not consider the significant heterogeneity in the welfare impacts of these reductions among cities with different characteristics. We show how income, population, and original fine particulate pollution levels can alter the welfare measures of $PM_{2.5}$ pollution reduction. More efficient pollution control policies could incorporate these factors and set differential targets for different cities. Our results also demonstrate the importance of equity considerations, which are a critical part of the policy-making process. We show that for low-income and high-pollution cities, the benefit of a uniform 10 $\mu g/m^3$ decrease in fine particulate pollution concentration is much lower than that for high-income and low-pollution cities. For the former, the sooner they enter the low $PM_{2.5}$ concentration range, the greater their benefit. However, these less advantaged cities often have more tension between economic growth and pollution control, and are therefore more likely to continue to have high pollution levels. Equity considerations would support the allocation of extra resources to these cities to accelerate the $PM_{2.5}$ control process.

## VI. Conclusions

Air pollution, especially ambient $PM_{2.5}$, is one of the most pressing challenges for the PRC and many developing countries. It results in millions of premature deaths annually. Although a growing body of literature provides increasingly precise and high-resolution information on fine particulate pollution exposure and its health impacts at the regional, national, and provincial levels, the social welfare implications of $PM_{2.5}$ mortality in urban areas have remained unclear. Multiplying the estimated premature deaths by monetary values such as VSL does not generate accurate economic results due to the nonlinear concentration response relationship between $PM_{2.5}$ and mortality, disparities in income and population, and the mismatch between the grid cells commonly seen in the literature and the more policy-relevant jurisdictional areas.

This study develops an accessible estimation scheme to provide welfare implications for $PM_{2.5}$ mortality in urban areas of the PRC. Based on the integrated exposure-response model, our approach uses publicly available $PM_{2.5}$ concentration data and city-level socioeconomic statistics to estimate the total cost of $PM_{2.5}$ mortality, the benefit of a uniform $PM_{2.5}$ concentration reduction, and the benefit of meeting WHO AQG and interim targets for the urban areas of nearly 300 major PRC cities. The results suggest that in these cities the aggregated total cost of annual $PM_{2.5}$ mortality for 2016 is about CNY1,172 billion. The average per capita total cost is CNY2,255. The aggregated benefit of mortality reduction resulting from a uniform 10 $\mu g/m^3$ decrease in $PM_{2.5}$ concentration ($UB_{10}$) in these cities is about

CNY141 billion for 2016; the per capita $UB_{10}$ is CNY321. Cities with high incomes and large populations that are located in areas with severe air pollution suffer the highest welfare losses, and the $UB_{10}$ is lower than for cleaner cities. The benefit of meeting WHO's first interim target is very low relative to the benefit of meeting more stringent air quality targets. As most of the cities in the PRC still have $PM_{2.5}$ concentrations well above WHO's first interim target of 35 $\mu$g/m$^3$, local authorities need to accelerate fine particulate pollution control in a cost-effective manner. Only in this way can greater benefits of $PM_{2.5}$ mortality reduction be achieved.

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## Appendix: List of Technical Terms

| | |
|---|---|
| AF | attribution fraction of the mortality risks of a disease |
| CR function | concentration response function |
| IT-1 | interim target of PM$_{2.5}$ concentration meeting 35 $\mu$g/m$^3$ |
| IT-2 | interim target of PM$_{2.5}$ concentration meeting 25 $\mu$g/m$^3$ |
| IT-3 | interim target of PM$_{2.5}$ concentration meeting 15 $\mu$g/m$^3$ |
| IT | air quality interim target of the World Health Organization |
| PM$_{2.5}$ | particulates with aerodynamic diameter ≤2.5 micrometers |
| PM$_{2.5}$ mortality | mortality attributable to ambient PM$_{2.5}$ |
| PM$_{10}$ | particulates with aerodynamic diameter ≤10 micrometers |
| RR | relative risk |
| TB$_{AQG}$ | the benefit of mortality reduction achieved by meeting the World Health Organization's air quality guidelines |
| TB$_{IT-1}$, TB$_{IT-2}$, and TB$_{IT-3}$ | the benefit of mortality reduction achieved by meeting the World Health Organization's interim targets 1, 2, and 3, respectively. |
| TC | total cost of PM$_{2.5}$ mortality |
| UB$_{10}$ | the benefit of mortality reduction achieved by a uniform 10 $\mu$g/m$^3$ decrease in PM$_{2.5}$ concentration |
| VSL | value of a statistical life |
| $\mu$g/m$^3$ | micrograms per cubic meter |

Source: Authors' compilation.