Air pollution in China: sector allocation of emissions and health damage

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1. Introduction

Many studies have put the damage to human health due to air pollution in China at very high levels, e.g. ECON (2000) and Feng (1999). In this report we take a disaggregated look at these total damages and estimate the portion contributed by each sector of the Chinese economy. These estimates are needed to identify the major sources of damage -- the share of total damages and the damages per unit output. Such information is used to examine the relative benefits of various pollution control policies in a companion report, "Market policies to control air pollution damages in China" (Ho and Jorgenson 2003).

In order to allocate total pollution damage to the various sources one needs to first identify the emissions from each sector, and secondly to relate how these emissions contribute to the ambient concentration of pollutants. It is probably obvious that different sectors produce different levels of emissions, both in absolute terms as well as emission per *yuan* of output. What may be less obvious is that each ton of, say, TSP emission from different sectors may cause different amount of health damage.

Health damage to an individual is believed to depend on the quantity of fine particles breathed in, and this depends on the ambient concentration of the pollutants. The relation between concentration and emissions, and hence the relation between total damages and emissions, depend on many factors. Firstly, the location of the source of emissions is key, the proximity to population centers and the meteorological conditions determines the amount of damage to a large degree. Secondly, the source characteristics like stack height, emission temperature and velocity matter, e.g. emissions from higher chimneys allow it to be blown away from population centers. Thirdly, in the case of primary particulate matter, the particle size distribution is important since the transportation rates and the health impacts are different for different particle diameters. Other factors include those that affect the rate of chemical reactions that generate secondary particles.

It is therefore important to identify the major sources of *health damage* rather than just the sources of emissions in order to develop efficient pollution control strategies. In the sections below we describe our estimates of sector emissions, how they relate to industry characteristics like output and fuel use, and how these are translated to estimates of health damages. We shall concentrate on two pollutants, TSP and SO2, for now, recognizing that other emissions such as mercury and nitrogen oxides affect human health too.

Our earlier work, Garbaccio, Ho and Jorgenson (2000) uses a very simple method to allocate the total health damages to the various sectors. Here we include another method that uses detailed sample data from emissions sources in the most polluting sectors to estimate exposures. This is also a big refinement of a similar analysis in HUCE (2002, Chapter 7).

2. Output and Emissions by Sector

The policy analysis in the companion report, Ho and Jorgenson (2003), is based on a model of the Chinese economy that is built around the 1997 input-output table, the most recent official accounts of inter-industry flows. That model divides the economy into 33 production sectors, plus one household sector. The emission and fuel use data here are constructed to be consistent with that framework.

Table 1 gives the emissions of total suspended particulates (TSP) and sulfur dioxide (SO2) for the 34 sectors in 1997. These estimates are modified from data in the *China Environmental Yearbook* and *China Energy Yearbook* (Fridley 2002) which provides estimates for 14 sectors at our level of classification. (Estimates for finer particle sizes such as PM10 are not available at the national level.) We divide these aggregate estimates into our more detailed sectors using fuel emission factors provided by Lvovsky and Hughes (1997) and the fuel use data in the input-output table. The details of the disaggregation procedures are described below.

The official emission estimates were massively revised in 1997 and 1998 to incorporate information for town and village enterprises that were previously ignored.[1] There is also a dramatic decline in the TSP estimates for the nonindustrial sectors, from 6.40 mil. tons in 1995 to 3.1 in 1997 and 2.1 in 1999. These are official estimates based on emission factors, not actual measurements of total emissions. We thus believe that the recent estimates are not mostly due to actual changes in emissions but rather more accurate estimates, and we therefore incorporated the new 1998 and 1999 information into our estimates for 1997.

The Chinese emission data are divided into two types – combustion and process. The former is due to the burning of fossil fuels and the latter from mechanical or other chemical processes. The data for the industrial sectors (mining, manufacturing, utilities) are estimated for

[1] The official time series have jumps in these years and make our current estimates based on 1997 quite different from our earlier work based on 1992 and 1995 data (Garbaccio, Ho and Jorgenson 2000 and Ho, Jorgenson and Di 2002).

20 sectors while only one total is provided for the remaining nonindustrial sectors (agriculture, construction, transportation, services, household). We allocate these official estimates to our 34 sectors using eqs. (1-3), and the estimates for the nonindustrial sectors are obviously quite rough. We should also note that the household sector is widely believed to be getting much cleaner with the replacement of coal stoves by gas ones, however, there is no systematic national data.

From Table 1 one can see that the combustion and process emissions of TSP are about equal. The major sectors contributing to the national total of 12.4 million tons of combustion TSP are electricity (4.0mt), nonmetal mineral products (2.5mt, mostly cement), chemicals (0.7mt), and households (0.7mt)[2]. For process TSP, 92% are from cement and metals smelting. One can say that the widespread use of coal for manufacturing purposes as well as for heating means that most sectors contribute significant amounts of pollution, there were only a few "clean" sectors in 1997.

Emissions of sulfur dioxide are predominantly from combustion which amounted to 17.4 million tons nationally. Again the major sources are electricity (7.8mt), nonmetal mineral products (1.5mt) and chemicals (1.2mt), the sector pattern is similar to that of combustion TSP except that nonmetal mineral products has proportionately less sulfur dioxide.

How do these emissions relate to the fuel mix and output levels of the different sectors? In table 2 we provide estimates of output (in 1997 *yuan*), coal, oil and gas inputs of each sector along with the combustion TSP from Table 1. The fuel inputs for each sector are derived from the *yuan* values in the input-output table and converted to quantities by assuming that all sectors pay a common price[3] . The price is chosen such that the quantity of national coal output, oil output and gas output is equal to the official total output.[4] Output is the sum of domestic purchases, net exports and changes in inventories.

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[2] Estimates for all sectors are taken from data for 1997 except for the following. For nonmetal mineral products the emissions from 1998 were more substantially revised and we scaled up the 1997 official emissions according to changes in cement output between 97 and 98. For non-industrial sectors the 1999 total of 2.06 mtons were used instead of the 1997 figure of 3.08 mtons.

[3] The input output data comes from the official 1997 benchmark table (NBS 1999b).

[4] This makes our estimates somewhat different from those in the China Statistical Yearbook (NBS 1999a, Table 7-4,7-5,7-9) which provides data on coal and oil use, and total energy consumption in tons of coal equivalents. The assumption of a common price corresponds to the abstraction in the economic model in the policy report Ho and Jorgenson (2003). The use of implied prices from the quantity data would mean different prices of the same input for different buyers. This complicates matters, and we chose another way to reconcile the fuel use to the emissions. This is described later.

Even a casual examination will show that there is a wide variation of emissions of TSP per ton of coal or oil combusted. We shall be more specific below but for now we note that the largest emitters are the largest users of coal – electricity, nonmetal mineral products, and metals smelting. The transportation sector is a small user of coal but the second largest user of oil, and is thus also a large emitter of TSP. At the other end, the cleanest sectors are communications, finance and apparel. Some of the non-manufacturing sectors, including households, have somewhat surprisingly high estimated emissions due to their high coal use for heating.

In table 3 we present a different angle of the output-emission relation. In addition to gross output, which is the value of the industry's goods to its customers, we also give the *value added*, which is the output minus intermediate inputs, essentially the value of labor and capital. The column marked "energy value" is the amount paid for purchases from the coal, oil (crude and refined), gas and electricity sectors, i.e. both primary and secondary energy inputs including feedstocks. Finally, the column marked "energy use" is the official estimate of the energy input in standard coal equivalents that is derived from quantity data on coal, oil, gas and electricity used, this excludes transformation to secondary energy products.[5]

The sectors with the largest energy value to output ratio are the energy transformation sectors – refining, gas production and electricity. Next are the mining and metals smelting industries. The petroleum refining and chemicals sectors transform a large portion of their purchased energy inputs into secondary products and so their energy use to output ratio is much smaller than the energy value to output ratio. This means they have a lower emission to energy purchased ratio. The other sectors have emission to energy purchased ratios that are convenient summaries of the separate information for coal, oil and gas inputs given in table 2. The highest emissions per yuan of energy purchased is nonmetal mineral products, followed by electricity and sawmills.

In terms of value added, the rankings of energy input is similar but not identical to the rankings of energy:output ratios. The sectors with the three highest energy value to output ratios also have the three highest energy value to value added ratios. However, chemicals which has the sixth highest energy:output ratio is only twelfth in terms of energy:value added. This highlights the importance of measuring energy use in terms of gross output, unlike some studies that measure it in terms of the more easily available value added.

[5] China Energy Statistical Yearbook (1997-1999), Table 5-5. Also in China Statistical Yearbook 2000, Table 7-3.

3 Pollutant emissions and emission factors

We now turn to the factors that contribute to the sector emissions given in Table 1. We gave output and the estimated use of energy -- coal, oil and gas -- in Tables 2 and 3, and now describe the relation between emissions, output and fuel use in greater detail. Recall that total emissions are made up of noncombustion (process) and combustion parts. The combustion component shall be ascribed to the burning of coal, oil and gas, ignoring minor items like wood. Let us then specify total emissions of pollutant x from sector j at time t, as :

(1) $$EM_{jxt} = EM_{jxt}^{NC} + EM_{jxt}^{C}$$
$$EM_{jxt}^{NC} = \sigma_{jx} QI_{jt}$$
$$EM_{jxt}^{C} = \sum_f \left(\psi_{jxf} AF_{jft} \right)$$

where x = TSP, SO_2 , f = coal, oil, gas , j=1,....33, H .

where EM_{jxt} is the annual emissions of pollutant x (in ktons), and the *NC* and *C* superscripts denote noncombustion and combustion respectively. QI_{jt} is the output of industry j (in billion constant 1997 *yuan*), and AF_{jft} is the quantity of fuel f combusted (billion tons of oil equivalent). σ_{jx} is the process emission rate (kton/bil. yuan) and ψ_{jxf} are the fuel emission factors (ktons/bil. toe). These coefficients are the average rates of emissions, and by the linearity assumption of equation (1), they are also the marginal rates. That is, while it is very likely that the last ton of coal used in the newest plant will have an emission rate lower than the average of all existing plants, we shall ignore this distinction for now. The j index runs over the 33 production sectors and the household sector (H).

Eqn. (1) and the following sections on emission factors, concentrations, and dose-response follow closely Lvovsky and Hughes (1997, hereafter referred to as LH). We also utilize their data as described in more detail in Appendix A.[6]

The fuel inputs in oil equivalents (bil. toe) are derived from the quantities, which in turn are derived from the purchased values:

(2) $$AF_{jft} = \theta_f FT_{fjt}$$

(3) $FT_{jft} = \lambda_{fj} \xi_f A_{fjt}$

$FT_{j,coal,t}$ and $FT_{j,oil,t}$ are the physical quantities of coal and oil (bil. tons), while $FT_{j,gas,t}$ is natural gas (bil. m^3). The θ_f coefficients translate the physical units to oil equivalents. A_{fjt} is the constant *yuan* measure from the input output matrix, and this is converted to physical units by the ξ_f coefficient. $1/\xi_f$ may be interpreted as the average price of the fuel. A_{fjt} is the total purchases of fuels, and for the refining & coking and chemical sectors part of the fuel inputs are converted to secondary products, we therefore multiply A_{fjt} by a loss ratio, λ_{fj}, to obtain only the combusted portion.

The official estimates of TSP and sulfur dioxide emissions, EM_{jxt}, are available for 13 industrial sectors, some of which are aggregates of our sectors in Table 1. The combustion component is computed using an equation similar to (1) with more detail on fuel types. Unfortunately these detailed data are not readily available. In order to make estimates for all our sectors we turn to the emission factors provided by Lvovsky and Hughes. Their coefficients for coal, oil and gas were scaled evenly so that the second term on the right side of (1) match the 1997 official combustion emissions. The details are given in Appendix A, the scaled ψ_{jxf}'s are reported in Tables A1, A2. The sectors that produce the most TSP per unit fuel combusted are the nonindustrial sectors with their small boilers and poorly filtered emissions.

For the process emissions, the σ_{jx} coefficient is derived by dividing the official emissions by the value of gross output given in the input-output table. The procedure and results are reported in Appendix Table A3. This source of pollution is essentially dominated by the nonmetal mineral products (cement) sector and the metals smelting (iron and steel) sector. The other manufacturing sectors have low estimated process emissions.

4 Emissions, Concentrations and Health damage: Method I

In this section we shall describe a method to estimate damages to human health from these emissions using the procedure in Lvovsky and Hughes (1997) and updated to the recent

[6] Lvovsky and Hughes (1997) is the basis of the World Bank report *Clear Water Blue Skies* (Chap. 3) which estimates of the benefits of pollution control policies. Gordon Hughes kindly shared his estimates with us which are used in this section.

data. In the next section we shall use the intake fraction (*iF*) method developed by the Harvard University Center for the Environment China Project.[7]

In the simple approach adopted by LH the heterogeneity in plant size, vintage, location etc. are ignored. What is taken into account is that, on average, different industries emissions enter the atmosphere at different levels due to the different stack heights used. To take simple account of this, emission sources are classified as low, medium, or high height, and each sector is assigned to one category. The electric power sector is classified as high height, the manufacturing industries are classified as medium, and the nonindustrial sectors and household as low. The exact designations by sector are given in Table 10. The emissions of pollutant x at height c, denoted E_{cxt}, is the sum of all industries in that height classification :

(4) $$E_{cxt} = \sum_{j \in c} EM_{jxt} \quad , \qquad \text{where } c = \text{low, medium, high} \quad .$$

The emissions data are in terms of total suspended particulates, TSP. However, health damage is believed to be primarily from fine particles. We choose to estimate health effects in terms of PM10 (particulate matter less than 10 microns in diameter) since the dose response coefficients are mostly estimated in terms of PM10. The emissions above are converted to PM10 assuming a factor of 0.6 as in LH.

(4b) $$E_{c,PM10,t} = 0.6 E_{c,TSP,t}$$

This is a simple assumption since we do not have much information on particle size distribution at the industry level. The lack of data also means that there is no point in specifying damages in terms of finer particles, say, PM25.

The next step is to estimate concentrations of pollutants in population centers due to these emissions of PM10 and SO2. The simple approach taken by LH is to use a linear reduced form to relate emissions at the various heights to concentrations in 11 cities. For city y, the concentration is:

(5) $$C_{xt}^{y} = \gamma_{low,x}^{y} E_{low,xt}^{y} + \gamma_{medium,x}^{y} E_{medium,xt}^{y} + \gamma_{high,x}^{y} E_{high,xt}^{y} \quad , \qquad x\text{=PM10, SO2}$$

[7] The preliminary research of that China Project was presented at a Harvard-Tsinghua "Workshop on Reconciling Economy, Energy and Environment" in Beijing on September 12, 2002. The information here incorporates revised estimates from that research project which we shall reference as HUCE (2002).

where the γ_{cx} coefficients translate emissions at height *c* to concentration of *x*. These relations were derived from air models run in other countries and calibrated to the Chinese concentration data in 1993 for various cities. Since our model is national in scope without regional detail we aggregate these city relations from LH to derive a national equation linking emissions to urban concentrations. The concentrations for these cities updated to our base year 1997 are given in Table 4.

We write the national average urban ambient concentration (in $\mu g/m^3$) as:

(6) $$C^N_{xt} = \gamma_{low,x} E^u_{low,xt} + \gamma_{medium,x} E^u_{medium,xt} + \gamma_{high,x} E^u_{high,xt}\,, \qquad x\text{=PM10, SO2}$$

where E^u_{cxt} is the urban portion of total national emissions given in eq. (4) and C^N_{xt} for 1997 is given in the last row of Table 4. The γ_{cx} coefficients are obtained as a population weighted average over the estimates of 11 cities in the LH study. To implement eq. (6) we need to first divide total emissions into urban and rural sources :

(7) $$EM_{jxt} = EM^u_{jxt} + EM^r_{jxt}$$

We do not have such data, but it is clear that the manufacturing sectors are more heavily concentrated in urban areas compared to agriculture, health, education, services and households. We make a rough allocation of the share of urban sources:

(8) $$EM^u_{jxt} = \upsilon_j EM_{jxt}$$

The estimation of these shares is described in Appendix A2.[8]

With the urban emissions, EM^u_{jxt}, the city-based emission coefficients γ^y_{cx}'s from LH, and the actual concentrations, we rescale the emission coefficients for the three heights proportionately so that the right side of eq. 6 equal the observed concentration. The resulting national coefficients, γ_{cx}, are given in Table 5. Our estimate of the national urban concentration of TSP in 1997 is 298 $\mu g/m^3$, or 178 $\mu g/m^3$ for PM10. The estimated concentration for SO2 is 93 $\mu g/m^3$. Our γ_{cx}'s are national coefficients, these are about two orders of magnitude smaller than the Lvovsky and Hughes city-based coefficients.

[8] In our earlier work, Garbaccio, Ho and Jorgenson (2000) we did not make a distinction between urban and national emissions, i.e. we assumed the urban shares were 1. That probably overstated the damage from nonindustrial sources relative to the industrial sources. The total damage estimates are not affected.

This approach ignores the distinction between primary PM and secondary PM. The measured concentration levels are for all PM, but the emissions on the right hand side of eq. 5 are primary particulate emissions only. Implicitly, what is being assumed is a constant proportion of primary to secondary particles averaged over all locations.

The next step is to estimate the damage to human health due to these levels of concentration of pollutants. As our base case we follow LH in identifying eight separate health effects for PM-10 and two for SO_2. These effects are listed in Table 6, the most important being mortality and chronic bronchitis. We shall be focused on marginal changes and like most work on this topic, we write the damage as a simple linear function of the concentration above a critical value. The number of cases of health effect *h* in urban China in period *t* is :

$$(9) \qquad HE_{ht} = \sum_x \left(DR_{hx}(C_{xt}^N - \alpha_x) POP_t^u er \right) \qquad h = \text{Mortality, RHA,...} \quad ,$$

where DR_{hx} is the dose-response relationship (number of cases per million people per $\mu g/m^3$). α_x is the World Health Organization reference concentration, POP_t^u is the urban population (in millions), and er is the exposure rate (the share of the urban population exposed to pollution of concentration C_{xt}^N).

The issues of defining and estimating appropriate dose-response coefficients are discussed in various places including HUCE (2002)[9]. This includes the issue of differential age impacts, and how to translate the relationships estimated in clean developed countries to China with very different pollution mixes, particle size distribution, threshold levels, and populations with different demographic and health characteristics. In our reference case we use the DR_{hx}'s taken from Lvovsky and Hughes (1997) and reported in Table 6. The 7.14 number of excess deaths per million people per year due to an increase in the concentration of PM-10 $\mu g/m^3$ is derived from using a 0.1% response in the acute mortality rate and the death rate in 1992. This effect is interpreted as a proxy for both PM and SO2 effects.[10] The 0.1% response rate is also the

[9] A revised Chapter 3 of HUCE (2002) contains a good summary by Levy and Greco. Aunan et. al. (2002) discuss the differences between low coefficients from China based studies and the higher ones from the rich countries. See also the discussion in Wang and Smith (1999), Appendix E.

[10] The World Bank (1997, p. 24) report discusses the effects of both PM and SO2 on mortality, and stated, "the interpretation here is that sulfur, ... is a good proxy for fine particulates, and that a portion of the fine particulates are formed from sulfur ... thus used PM10 as the key measure."

central estimate in Wang and Smith (1999b, Table 5) and ADB (1999). These studies and WHO (1999) also cite a range of estimates for acute mortality effects, 0.04% to 0.30%, based on the work by Xu et. al. (1994), Dockery and Pope (1996).

In one of the earliest work in China, Ziyang Xu (1993) estimated a response of 0.02% per $\mu g / m^3$ for both TSP and SO2. Using data from Beijing, Xiping Xu et. al. (1994) estimated a large significant coefficient for SO2 (0.12%) and an insignificant one for PM10 (0.036%). Venners et. al. (2002) study of Chongqing is another of the few studies that found no association between mortality and PM after controlling for SO2, their estimate of relative risk for SO2 was 1.04 per 100 $\mu g / m^3$. These other estimates are summarized in Table 7.

The World Bank sponsored a recent study to update earlier estimates used in World Bank (1997). This ECON (2000) report included new survey results from their recent study in Guangzhou. It discusses the inclusion of chronic effects and suggested a coefficient of 0.4% for combined acute and chronic mortality for PM10 (their Tables 3.2, 8.1). This is four times higher than the rates reported in Table 6. It stresses, however, that this is very uncertain, and gives a range of (0.00-0.6) for this coefficient. They also discuss the differing results for SO2 versus PM in the literature and suggest a procedure where both are calculated and the higher estimate used, emphasizing that they cannot be summed when taken from distinct studies.

Levy et. al. (1999) pooled estimates from 24 studies that are done in cleaner rich countries and arrive at an estimate for acute mortality from PM10 of 0.06% (95% CI: 0.02%, 0.09%) per $\mu g / m^3$, holding all other pollutants constant. For SO2, controlling for PM, the effect is 0.004% (95% CI -.0003%,0.008%). Given these ranges of estimates, we shall use the dose response used by Lvovsky and Hughes as the base case, and the Levy et. al. pooled estimates as the lower end. Given the (0.04%,0.30%) range for PM10 in WHO (1999) and the ECON (2000) recommendations, we decided to use 0.3% for PM10, and 0% for SO2 as a simple upper end. These are summarized in Table 8.

The exposure rate coefficient, *er*, should be viewed as a parameter to allow the right hand side of eqn. (9) to approximate the true exposures which is concentration at a particular location multiplied by the population in that location, and summing over all locations.

Finally, we value these health damages in order to compare with the costs of other environmental damages, and to compare the benefits of different policies. For those wishing to perform cost-benefit analysis this would be one essential ingredient. Let V_{ht} denote the value of one case of health effect h (e.g. *yuan* value per case of chronic bronchitis). The national value of damage due to all cases of h in year t is given by:

(10) $$Damage_{ht} = V_{ht} HE_{ht}$$

The value of total national health damages is simply the sum over all the health effects:

(11) $$TD_t^N = \sum_h Damage_{ht} \quad .$$

We use valuations derived from contingent valuation or compensation (willingness to pay) studies. It should be pointed out that these are the valuations of people who might suffer the health effect. This is not the same as calculating the medical costs, the cost of lost output of sick workers, the cost of parents time to take care of sick babies, etc. The personal willingness-to-pay may, or may not, include these costs, especially in a system of publicly provided medical care.

The valuation of these damages is a controversial and difficult exercise, with arguments over discounting (Heinzerling (1999)), whether the "contingent valuation" method works (Hammit and Graham (1999)), and how to aggregate the willingness to pay (Pratt and Zeckhauser (1996)). We believe the willingness to pay approach is valid[11] although one may argue about how that could be implemented. We ignore age effects and follow, as a base case, the route taken by most studies which use an estimated willingness to pay in the U.S. and scale them by the ratio of per capita incomes in China and the U.S.

The value of a statistical life (VSL) chosen by World Bank (1997) and ADB(1999) is $3.6 million in the U.S.[12] The U.S. values associated with each of the 10 health effects identified are given in Table 6 under the column marked "Valuation in US". Multiplying them by the ratio of per capita incomes in 1997 (in nominal terms) gives the *yuan* values for China (last column in Table 6). This simple scaling means that one is assuming a linear income effect. This procedure results in an estimate of 702,000 yuan for VSL. This translates to US$85,000 using the nominal exchange rate in 1997, and is a little above the World Bank (1997) figure of $60,000 for 1992, after adjusting for the increase in Chinese incomes during these years.

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[11] ECON (2000) also argues the appropriateness of using the "willingness to pay" method. It also uses a transfer calculation almost identical to the one here.

[12] This is from Chapter 2 of World Bank (1997), which also discusses the use of "willingness to pay" valuation versus "human capital" valuation, the method used by many in China. The $3.6 mil. figure is recommended in the early 1990s, we have chosen not to adjust this for the small increase in US incomes since then to be on the conservative side.

Zhou and Hammitt (2003) is one of the few contingent valuation studies conducted in China that we are aware of. The study covered Beijing and Anqing and estimated VSLs that are very different for different locations. For Beijing, the median VSL was about 130,000 *yuan* and the mean was 500,000, but in Anqing city the median is only 34,000 (see Table 7). After surveying the literature, ECON (2000) recommends a simple rule of using 100 times the GDP per capita as a conservative estimate of the VSL, this would be 610,000 *yuan* in 1997. The U.S. EPA currently uses a VSL of $7 million for their analysis, which is about 200 times US per capita GDP. Using this ratio, the figure for China in 1997 would be 1.21 million *yuan*. In a study using wages in Taiwan, Liu et.al. (1997) estimates a range for VSL of US$413-624,000. 400,000 US dollars, adjusted for the differences in per capita incomes between Taiwan and China, is 190,000 *yuan*, which is higher than the Zhou and Hammitt (2003) estimate but lower than World Bank (1997).[13]

Given the linear assumptions in our model, these alternative valuations may be applied by simply scaling our estimates. We shall use the estimates derived from World Bank (1997) as our base case for mortality valuation, and the median urban valuation in Zhou and Hammitt, 135,000 *yuan* as our lower case. For the upper case we shall use 1.2 million yuan.

i) Damage per unit output

The total national health damages are given by eqn. 9-11. These total estimates are not the focus of our study and we briefly note them just for the record. The results, using the central parameter values, are given in Table 9. The value of national health damages due to air pollution is 300 billion yuan or 4.0% of GDP in 1997. Of this premature mortality accounts for 179 billion, and respiratory symptoms 65 billion.

We now turn to the allocation of this total which is one of the main aims of our study. We begin with the calculation of marginal damages per unit output of each sector. An additional unit of urban emission increases mean national concentration by γ_{jx} as in eq. (6), where γ_j could be one of three values depending on the emission height classification of *j*. An increase in the concentration of the various pollutants by an amount γ_{jx} will produce an additional health effect

[13] The approach in Aunan et. al. (2002) is more detailed where they calculate age specific effects and estimate the value of life years lost. Such an approach requires age specific exposure-response coefficients and valuations. We have to defer such intensive work for our national estimates to future research.

h of $\sum_x DR_{hx}\gamma_{jx}POP_t^u er$ (using eq. 9). The marginal damage per unit urban emission of *x* from *j* is obtained by summing over the values of all health effects :

$$(12) \qquad MDX_{jx} = \sum_h V_{ht} DR_{hx}\gamma_{jx}POP_t^u er$$

The total urban emissions from producing output in sector *j* is given by eq. 1 and 8. As discussed above, the simple form of eqn. 1 means that the marginal emission rate (emissions per unit output) is equal to the average emission rate. This urban emission rate for pollutant *x*, in the base year *tb*, is given simply by $\frac{\upsilon_j EM_{jx,tb}}{QI_{j,tb}}$. The value of the marginal damage due to *x* from the last unit of output is

$$(13) \qquad MDX^O_{jx,tb} = MDX_{jx}\frac{\upsilon_j EM_{jx,tb}}{QI_{j,tb}}$$

where the O superscript denotes that it is the damage per unit output. The total damage due to one unit of output is obtained by summing over all pollutants :

$$(14) \qquad MD^O_{j,tb} = \sum_x MDX^O_{jx,tb}$$

The results of this calculation are given in Table 10 where both combustion and noncombustion PM are assumed to be equally harmful. As we can see from the dose response and valuation coefficients, most of the damage is due to particulate emissions and very little from SO2 emissions. The highest health damage producing sector is nonmetal mineral products (cement) with a rate of 0.248 *yuan* of damage per *yuan* of output, this sector has very large combustion and process emissions. The transportation sector has damage rate of 4.6% with its substantial low-height high-damage emissions, while health, education and other services has a rate of 4.2%. The rates for the service sectors are implausibly high since emissions are not explicitly identified and we may have attributed emissions to them that belong to other nonindustrial sectors. (However, we should also note that its value of output is low since this is a mostly non-commercial government run sector where the output is not really priced in the market but valued according to the cost of inputs).

The damage from noncombustion particulate matter may be different from that of combustion ones because of different particle sizes or chemical composition. We therefore repeat the calculations only for combustion emissions in Table 11. That is, in eq. (13) we use EM^C_{jxt}

instead of total EM_{jxt}. The biggest difference is the cement sector with its large noncombustion emissions, the marginal damage rate is now only 0.048 *yuan* per *yuan* of output, instead of 0.248. Metals smelting damage rate is only 1.4% compared to 4.1% when both emissions are included. The damage rate of the electricity sector remains at 2.7%. These rates may seem small because we assume that damages are sustained only in the urban areas but we are dividing by total national output.

(ii) Sector allocation of total damages.

If the functional form assumed in eq. 9 is correct, that is, damages are positive only for concentrations above a certain critical level, then the marginal and average damages are different. The first ton of emission is harmless while the last ton causes an amount of damage given by MDX_{jx} in eqn. 12. One has therefore to be careful about what it means to apportion total damages to the various actors in the economy. Each individual enterprise, or even a whole sector, can claim to be harmless since its emissions contribute to less than the critical level!

We shall do something a little different, and instead apportion the sum of all marginal damages, which would be larger than total damages given in eqn. 11. The marginal total damages of sector *j* will be assumed to be the damage per unit output, MD^O_{jt}, multiplied by the national output of the sector:

(15) $$MTD_{jt} = MD^O_{jt} QI_{jt} = \sum_h V_{ht} \sum_x \left(DR_{hx} \gamma_{jx} POP^u_t er \upsilon_j EM_{jx,t} \right)$$

And the national total marginal damage is the sum of these marginal sector damages:

(16) $$MTD^N_t = \sum_j MTD_{jt}$$

The share of each sector in this national total, MTD_j / MTD^N, is given in Tables 10 and 11 for the base year 1997 in the column marked "share of total". In Table 10, which assumes that noncombustion TSP is as harmful as combustion TSP, we see that the biggest source of damage by far is the nonmetal mineral products sector which accounts for 52% of total national damage. This is due to its large share of noncombustion emissions. The next three biggest contributors are metals smelting, and transportation and health-education-services with their large low-height and highly damaging emissions, accounting for about 7% each. Household emissions is the next biggest source of damage. We should note again that the service sectors are poorly estimated.

The electric power generation sector, which has been the focus of much pollution research, is not a big contributor to local pollution, accounting for less than 3%. This is due to the assumed high height of the sector's smoke stacks and the corresponding low contribution to ground level concentration. This share may be higher if the maintained assumptions about the range of the particulate matter is proved incorrect, or if the inclusion of secondary PM proves to be significant as discussed in HUCE (2002, Chapter 6).

The allocation calculation is repeated in Table 11 for combustion emissions only. In this case the nonmetal mineral products sector accounts for 19% of the national total, while health-education-services contributes 13% and transportation 11%. The other poorly measured sectors also loom large -- households accounts for 9% while social services accounts for 7%. If we ignore these nonindustrial sectors, then the biggest culprits are chemicals (5.1%), metals smelting (4.8%), and electricity (4.7%).

Are these sector allocations reasonable? The electricity sector which burns about 30% of all coal consumed contributes only 5% of combustion related damages, and the manufacturing and mining sectors, which use about 60% of all coal and 40% of refined oil, contributes only 38%. On the other hand the nonindustrial sectors which use about 10% of coal and 55% of refined oil, and produces only 17% of combustion TSP, has 58% of national damages attributed to it. These surprising allocations are driven by the high emission factors (ψ), the values of the γ_{cx} coefficients that translate emissions at height *c* to concentration, and the crude designation of emissions heights to the sectors. If one thinks that the gamma coefficient for high heights is too low relative to the one for medium heights and make a correction for that, then the damage attributed to the electric power sector would be higher. We shall comment more on this in the section below describing our *iF* based results.

iii) Damage per unit fossil fuel

We now calculate the damage due to primary fuels to provide guidance for fuel price policies. In writing eqn. 1 we are assuming that the fuel emission factors are constant. In reality, they are a function of the choice of control strategies. These choices are different for different enterprises in any given year, and they also change over time. This means that the last ton of coal burnt by the cleanest enterprise will have marginal emissions smaller than the sector average. We shall ignore this but the reader should keep this distinction in mind.

Using the same reasoning that was used to derive eq. (16), the marginal damage from a unit of fuel in sector *j* is the sum over pollutants of the marginal damage per unit of urban emissions from fuel *f* :

(17) $$MD^F_{fj} = \sum_x \left(MDX_{jx} \psi_{jxf} \theta_f \right)$$

As described in the companion report on pollution control policy (Ho and Jorgenson 2003), we shall examine a simple national tax on fuels, a tax that is proportional to the damage caused by each fuel. In appendix Table A1 we show that different sectors produce different emissions per ton of fuel burnt. We shall not try to estimate the damage done by a ton of fuel for each sector, but only to estimate the average national damage per ton of coal, oil or cubic meter of gas. This is obtained by averaging over all sectors in the base year, *tb*, remembering that we assume only urban populations suffer the damage and hence multiply total fuel use by the urban share:

(18) $$AMD_f = \frac{\sum_j MD^F_{fj} \upsilon_j FT_{jf,tb}}{\sum_j FT_{jf,tb}} \qquad f\text{=coal, oil, gas}$$

The values of the average damage are given in Table 12. The estimated damage from coal is very high, 153 *yuan* per ton in 1997, or 0.94 *yuan* of damage per *yuan* of coal[14]. The damage from oil is a lot less, only 0.028 *yuan* per *yuan* of oil, while the damage from gas is negligible. If we calculate the average marginal damage only in terms of the fuel combusted in the urban areas:

(18') $$AMD^U_f = \frac{\sum_j MD^F_{fj} \upsilon_j FT_{jf,tb}}{\sum_j \upsilon_j FT_{jf,tb}}$$

then the damage rate is much higher as shown in the column marked "urban fuel use" in Table 12. In Ho and Jorgenson (2003) we focus only on national policies without making such a location distinction and hence we shall only consider the estimates in the "national" column.

[14] The value of all coal used is taken from the input-output table. This consist of a mixture of raw and washed coal which overstates the coal value compared to just the raw coal value. On the other hand, the value is taken at the mine mouth, not the delivered price which includes trade and transportation.

5 Emissions, Concentrations and Health damage: iF Method.

Method I above is relatively easily implemented and provide a quick rough estimate of the health damages due to air pollution. To improve these estimates the research program given in HUCE (2002) developed the "intake fraction" method that uses air dispersion models to explicitly estimate the exposures due to particular sources of pollution but does so in a way that does not require the modeling of all sources. While this is an improvement, we recognize that it is still a rough approximation to the true concentration caused by the millions of chimneys and exhaust pipes. (The intake fraction concept is discussed in Bennett et. al. 2002). Another important aspect that is ignored here are the secondary particles. The dosage of sulfur dioxide is estimated but not the secondary sulfate particles. (The estimates in HUCE (2002, Chapter 6) indicates that the secondary particles of SO2 is of the same order of magnitude as the primary PM10.)

iF_{xr}, the fraction of emissions of pollutant x from source r that is breathed in by the exposed population may be expressed as:

(19) $$iF_{xr} = \frac{BR \sum_d C_{xd} POP_d}{EM_{xr}}$$

where C_{xd} is the change in concentration at location d, POP_d is the population at d, BR is the breathing rate, and EM_{xr} is the emissions from source r. The summation is over all locations where the concentration is estimated to be positive.

HUCE (2002) calculates the national average intake fraction, iF_{xj}^N, using information from a national sample of sources for each of 3 sectors, j=Iron and Steel, Cement, and Chemicals. It also estimates the national average for the electric power sector using a detailed database of the power plants[15]. For mobile sources in the Transportation sector there was no national sample, and we use the *iF* based on a limited sample. We interpret the product of iF_{xj}^N and the total national emissions from sector j as the total dosage (total amount of x breathed in by all people):

(20) $$DOSE_{xj} = iF_{xj}^N EM_{xj} = BR \sum_d C_{xd} POP_d$$

[15] In the revised HUCE (2002) Chapter 5, Table 5.10 gives the intake fractions for the three manufacturing sectors and Chapter 4 reports on the electric power sector.

where the summation here may be interpreted as the adding over all exposed population in the country.

From the health effects eqn. 9 above, and eqn. 18, we may write the marginal effect of sector *j*'s emissions as the dose response coefficient multiplied by the dosage for each pollutant and summed over all pollutants :

$$(21)\qquad HE_{hj}^{S} = \sum_{x}\left(DR_{hx}\frac{iF_{xj}^{N} EM_{xj}}{BR}\right), \qquad \text{h=mortality, RHA, …}$$

The S superscript denotes sector health effects. By "marginal effect" we mean holding the emissions of all sectors other than *j* fixed at current levels, and asking what the damages due to emissions from *j* are. This is relevant if one believes that the health effect function is non-linear, or not proportional. In eq. 9 we regard concentrations less than the critical level α to be not damaging. As discussed above this means that the marginal effect is larger than the average effect. The sum over all sectors of the marginal damages will be larger than total damage if expression 9 is the correct one, i.e. for each health effect *h* :

$$(22)\qquad \sum_{j} HE_{hj}^{S} = \sum_{j}\sum_{x}\left(DR_{hx}\frac{iF_{xj}^{N} EM_{xj}}{BR}\right) \geq \sum_{x}\left(DR_{hx}(C_{xt}^{N} - \alpha_{x})POP_{t}^{u} er\right)$$

Using this second method of estimating health effects we repeat the calculations for the damage per unit output and damage per unit fuel. The marginal total damage from all emissions from sector *j* is obtained by adding over all health effects :

$$(23)\qquad MTD_{jt} = \sum_{h} V_{ht} HE_{hj}^{S} = \sum_{h} V_{ht} \sum_{x}\left(DR_{hx}\frac{iF_{xj}^{N} EM_{xj}}{BR}\right)$$

The marginal damage per unit output is then simply:

$$(24)\qquad MD_{jt} = \frac{MTD_{jt}}{QI_{jt}}$$

The intake fractions reported in HUCE (2002) are for combustion emissions from smoke stacks. No estimates have yet been made for the noncombustion emissions which are substantial for the cement sector. We make two separate calculations for eq. 24, one for just the combustion emissions, and another for total emissions assuming that the same *iF* applies. This is probably incorrect given the different emission heights, particle size distributions, and exit temperatures and velocities, however the direction of the bias is not obvious.

The results of this *iF* method of estimating unit damages are given in Table 13. The national average intake fractions for TSP that we use are reproduced in the first column. The unit damages from combustion only and from total emissions are given in the next two columns. These MD_j's are quite different from the damages estimated using method I reported in Table 10-11. Comparing combustion only damages, for chemicals we have 0.0011 *yuan* of damages per *yuan* of output (in 1997 prices), compared to the much higher 0.0074 for method I (Table 11). For metals smelting (iron and steel) it is 0.0023 compared to 0.0137, while nonmetal mineral products it 0.0070 compared to 0.0475 from Method I. That is, the *iF* based estimates are about a sixth of the damages estimated from Method I. This gap is partly explained by the exclusion of secondary particles in the *iF* calculations. Another difference might be the more precise location of the plants in the *iF* calculations, many of them are in the rural areas and are thus less damaging. The similarity of the differences is due to the similar values of *iF* for these three manufacturing sectors which are all regarded to be in the medium height class in Method I. Again we note that the similar intake fractions for these three are due to the low stack heights in cement roughly offsetting the more rural location of cement plants. They are not a product of some common factor among these sources.

On the other hand, for electricity, the *iF* coefficient produced a damage ratio of 0.0161, similar to the 0.0267 from method I. To recall, in method I, electricity was designated as the high height sector and used a very low γ_{cx} coefficient that converts emissions to concentrations (about 16% of the coefficient for medium height sources). In HUCE (2002, Chapter 4) the electricity sector was estimated using a large sample of power plants and has an estimated *iF* that is about two thirds the *iF* for chemicals or cement. The very much lower γ_{cx} compared to the intake fraction makes the difference in the damage ratios here smaller than the differences in the three manufacturing sectors.

For transportation, HUCE (2002) has a much weaker set of estimates due to a lack of data and sample size. An *iF* was estimated for primary PM and a search of the literature produced one for secondary nitrates. These are given in Table 13. Since there are no official estimates of total national emissions for this sector other estimates from Tsinghua University are used[16] -- 140 ktons of primary PM10, and 3230 ktons of NOx. We make additional assumptions about the share of these total emissions that is in the urban areas, and about the contribution of transportation other than vehicles, on net multiplying the total emissions by 0.7. From these we estimated the total dosage of PM and made the damage calculations. The estimate for marginal damage is 0.038 *yuan/yuan*, quite similar to the 0.046 from method I. One should not read much precision into the similarity of the estimates given the lack of data for this sector. However, the relative magnitude of the damage from transportation versus the damage from the other manufacturing sectors is likely to be reasonable. We believe this adds weight to the emphasis on finding effective transportation policies, both as a good in itself and as a way to reduce air pollution damage.

The above results are based on the intake fractions derived from modeling the dispersion out to 50km. As is pointed out in HUCE (2002, Chapter 5), it is quite possible that the damage outside this range could add another 100-200% to the estimated *iF*'s. In the last column of Table 13, marked "extended", we report this augmented damage per unit output by assuming that the total *iF* is 2.0 times the modeled *iF*. This estimate of the full damage closes the large gap between the *iF* method and method I's estimates for the three manufacturing sectors. It makes the damages for electricity and transportation bigger than those estimated using Method I, instead of being a little smaller. While uncertainty in this dimension affects the estimated absolute damages, it would have only a small effect on the relative damages, i.e. the damages of one sector relative to another.

(i) Sector allocation of total damages.

In order to provide another angle for comparing our *iF* coefficients with those implied in Method I when we use the coefficients from Lvovsky and Hughes, we estimated the damages for the better measured sectors - manufacturing and transportation. We ignore agriculture, mining and services. To do this we make the following assumptions about the intake fractions of the sectors that are not studied in HUCE (2002). For manufacturing other than chemicals, nonmetal mineral products, and metals smelting, we assign *iF*'s that are the sample averages of all plants in the 5-city sample -- 7.15E-6 for TSP and 6.65E-6 for SO2 (HUCE 2002, Table 5.3).

[16] This is described in a revised Appendix D to HUCE (2002).

The results are given in Table 14. The big difference is that transportation and nonmetal mineral products change places, in Method I cement accounted for 19% of total damages while in the *iF* Method it is only 9.2%. Transportation, on the other hand moved from 10.9% to 24.9%. Electricity also has a much higher damage contribution using our intake fractions, 9.1% versus 4.7%. As explained above, the high value of *iF* for electricity compared to the low emission-concentration coefficient for high-height emissions makes the estimated damages much higher in the *iF* Method.

Similarly, for transportation, the very high estimated *iF* (high relative to the *iF* for manufacturing), gives a much higher allocation of damages to transportation than Method I. The low emission height transportation sector is given a γ_{low} value that is only 5 times higher than the γ_{medium} given to the manufacturing sectors in Method I, whereas the transportation *iF* is an order of magnitude larger than the intake fractions of the manufacturing sectors.

6 Sensitivity Analysis

All the components of damage analysis -- atmospheric dispersion, exposure calculation, dose-response, and valuations -- are based on parameters that we do not have very precise estimates of. In tables 7-8 we have tabulated the range of estimates for the dose-response coefficient and valuations. We also noted our crude proxy for estimating urban sources of the national emissions that is officially estimated. HUCE (2002, Chapter 5) describes the sensitivity of the intake fraction estimates to various modeling assumptions and gives a range of plausible values.

As a simple summary indicator of these uncertainties we calculated the damage ratios using the end points of the uncertainty range for some of these parameters. In the previous section we described the calculation of marginal damages using the intake fraction, dose-response coefficients, health end-point valuations, and estimates of sector emissions. These estimates (*yuan* value of damage per *yuan* of sector output) were given in Table 13. We repeated the calculations using the low and high valuations, and low and high dose-response given in Table 8. The results are given in Table 15.

The marginal damage, MD_j, calculated using the base values of the parameters are repeated in the first row, that is, using the "base" column in Table 8. In Table 15, this is marked by DR(mortality, PM10)=0.1% and value of statistical life (VSL) of 702000 yuan to represent the whole "base" column of values. If we use the low estimate of DR(mortality) then the MD(electricity) is 0.0091, or about 60% of the base estimate of 0.0161. This reflects how the mortality effect dominates the total value of damages. Roughly speaking, if we take the low end values for both DR and V then the marginal damage is about a third of the base estimate. And if we take the high values then it is about three times the base estimate. (There is no reason to suspect that DR and V are correlated measures and so the uncertainties may be summed). We remind the reader that our intake fractions are calculated for a 50-km domain, if we make a rough estimate of the effect using the complete domain as in the last row of Table 15, then we double the damage ratios.

Two comments are in order. The large range of uncertainty reflects the use of many parameters in this analysis, each of which are not well measured. This points to a need for more data and research. However, some of these uncertainties affect every sector in the same way, so the ranking of damages or their relative damage, are not affected by the uncertainty in DR or V. The ranking is of course a direct function of the intake fraction.

7 Conclusion

In this report we have focused on the sector contribution to human health damage from air pollution in China that have been estimated at very high levels. Here we calculated the damage done per unit output of the various sectors, and the damage done per unit of fossil fuel burnt. The first point that we wish to emphasize is that one should be focused on damages and not on energy consumption or quantity of emissions per se, the electricity sector that consumes the most coal may not be the biggest source of air pollution damage. The biggest sources, as classified in here, are transportation, cement, households and electricity.

Secondly, while the estimates for the transportation sector are weak due to the poor data base, they are very large and may be the biggest or second biggest source of damage today. (Our projections indicate that it is likely that it will be the biggest source of air pollution in the future.) This indicate that research priority should be given to this source of pollution to improve the data and estimates, and this sector be given due attention in pollution control efforts.

The uncertainty in the results may be troubling. However, the damages do not seem trivial in any case. These uncertainties show the critical importance of developing further data and intake fraction estimates for the other sectors to pin down more accurately their contribution to total health damage. Several areas should be highlighted. (a) The estimated damages from the nonindustrial sectors are very high, and may not appear to be right. A more precise estimate would require data on the stack heights in these sectors and a corresponding intake fraction estimate. (b) The inclusion of secondary pollutants is crucial to have a complete accounting of the damages. (c) The large estimate for total damages from the cement sector is due to the assumption that combustion particles and process particles are equally damaging. This is probably not correct and information on the particle size distribution would help sharpen the damage estimates.

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Table 1 Sector emissions in 1997*

	Sector	TSP (kton)			SO2 (kton)		
		Combustion	**Process**	**Total**	**Combustion**	**Process**	**Total**
1	Agriculture	160	0	160	367	0	367
2	Coal mining and processing	181	65	245	163	29	192
3	Crude petroleum mining	57	51	108	78	23	101
4	Natural Gas Mining	0	3	3	1	1	2
5	Metal ore mining	22	31	53	21	14	35
6	Non-ferrous mineral mining	44	60	104	45	27	72
7	Food products, tobacco	310	16	326	467	11	478
8	Textile goods	166	3	169	332	2	334
9	Apparel, leather	16	1	17	24	0	24
10	Sawmills and furniture	90	46	136	114	4	118
11	Paper products, printing	201	92	292	254	8	261
12	Petroleum refining & coking	72	76	148	112	51	163
13	Chemical	672	200	872	1216	214	1429
14	Nonmetal mineral products	2549	10756	13305	1525	654	2178
15	Metals smelting & pressing	632	1244	1876	739	925	1664
16	Metal products	39	84	123	26	8	34
17	Machinery and equipment	125	24	150	185	4	189
18	Transport equipment	43	16	59	65	3	67
19	Electrical machinery	28	15	43	44	3	47
20	Electronic & telecom. equip	8	13	22	13	2	16
21	Instruments	6	3	9	9	0	10
22	Other manufacturing	83	99	182	181	55	235
23	Electricity, steam, hot water	3953	72	4025	7846	49	7895
24	Gas production and supply	16	3	19	24	2	26
25	Construction	121	0	121	414	0	414
26	Transport & warehousing	361	0	361	609	0	609
27	Post & telecommunication	0	0	0	6	0	6
28	Commerce & Restaurants	118	0	118	273	0	273
29	Finance and insurance	13	0	13	28	0	28
30	Real estate	72	0	72	124	0	124
31	Social services	222	0	222	441	0	441
32	Health, Educ., other services	416	0	416	714	0	714
33	Public administration	112	0	112	216	0	216
	Households	462	0	462	778	0	778
	Total	11369	12974	24343	17452	2089	19541

Source: China Environment Yearbook and authors' calculations. Estimates are for 1997 based on information in 1997-99.

Table 2 Emissions, fuel use and output in 1997.

	Sector	TSP (combus) (kton)	Gross Output (bil. *yuan*)	Coal use (mil tons)	Oil use (mil tons)	Gas use (mil m^3)
1	Agriculture	159.7	2467.7	12.7	9.61	0.0
2	Coal mining and processing	180.7	238.0	40.8	2.72	7.2
3	Crude petroleum mining	56.9	188.1	12.7	15.09	5.0
4	Natural Gas Mining	0.3	10.9	0.1	0.24	627.6
5	Metal ore mining	22.0	115.2	5.0	1.06	2.4
6	Non-ferrous mineral mining	44.0	222.4	9.9	3.32	3.1
7	Food products, tobacco	310.4	1371.3	33.2	1.74	44.3
8	Textile goods	166.1	913.0	21.8	1.06	31.5
9	Apparel, leather	16.4	627.0	6.7	0.76	0.0
10	Sawmills and furniture	90.2	222.5	8.1	0.57	0.0
11	Paper products, printing	200.5	445.5	18.1	1.34	14.5
12	Petroleum refining & coking	71.6	308.5	20.0	8.75	421.7
13	Chemical	671.8	1488.8	148.5	32.08	4541.7
14	Nonmetal mineral products	2548.8	874.9	206.7	10.34	1442.4
15	Metals smelting & pressing	632.0	750.2	183.2	8.81	968.9
16	Metal products	38.9	477.8	18.3	1.80	69.1
17	Machinery and equipment	125.4	882.1	36.2	3.81	366.8
18	Transport equipment	42.9	570.7	12.4	1.88	247.6
19	Electrical machinery	28.0	563.3	8.1	1.93	156.1
20	Electronic & telecom. equip	8.3	488.1	2.4	0.68	260.3
21	Instruments	6.0	96.0	1.7	0.26	1.6
22	Other manufacturing	82.8	286.9	13.7	1.08	6.4
23	Electricity, steam, hot water	3953.0	380.8	384.9	14.80	538.5
24	Gas production and supply	15.5	12.4	4.4	1.40	25.4
25	Construction	120.8	1738.6	9.4	20.63	0.0
26	Transport & warehousing	361.0	506.6	17.5	23.07	2.9
27	Post & telecommunication	0.1	195.9	0.0	0.54	0.0
28	Commerce & Restaurants	118.2	1412.6	9.4	7.19	111.7
29	Finance and insurance	13.4	359.5	1.1	0.51	0.0
30	Real estate	72.3	185.5	5.8	0.19	0.0
31	Social services	221.8	564.5	17.8	6.55	36.3
32	Health, educ., other services	416.0	658.5	33.5	1.15	38.5
33	Public administration	111.7	443.4	9.0	2.76	1.5
	Households	461.7		37.1	2.11	1990.8
	Total	11369.1	20067	1350.3	189.8	11963.6

Notes: Fuel use is combustion, excluding the transformation to secondary fuels and products.

Source: Input-output table, authors' calculations.

Table 3 Output and energy use.

	Sector	TSP Emissions (kton)	Gross Output (bil. *yuan*)	Value Added (bil. *yuan*)	Energy value (bil. *yuan*)	Energy Use (mil. tce)
1	Agriculture	160	2467.7	1474.2	42.1	59.05
2	Coal mining and processing	245	238.0	118.2	23.2	57.91
3	Crude petroleum mining	108	188.1	123.0	27.2	33.25
4	Natural Gas Mining	3	10.9	5.9	1.4	2.40
5	Metal ore mining	53	115.2	39.9	12.2	8.18
6	Non-ferrous mineral mining	104	222.4	96.6	24.4	13.49
7	Food products, tobacco	326	1371.3	381.4	21.4	38.43
8	Textile goods	169	913.0	258.1	14.4	30.80
9	Apparel, leather	17	627.0	193.1	5.6	4.37
10	Sawmills and furniture	136	222.5	63.1	6.2	5.01
11	Paper products, printing	292	445.5	139.1	16.7	21.99
12	Petroleum refining & coking	148	308.5	71.9	156.4	73.89
13	Chemical	872	1488.8	402.4	136.0	192.80
14	Nonmetal mineral products	13305	874.9	276.0	97.0	123.17
15	Metals smelting & pressing	1876	750.2	159.2	87.3	214.48
16	Metal products	123	477.8	116.3	23.0	10.45
17	Machinery and equipment	150	882.1	282.4	30.5	24.48
18	Transport equipment	59	570.7	158.2	13.4	15.19
19	Electrical machinery	43	563.3	130.2	12.1	6.47
20	Electronic & telecom. equip	22	488.1	124.4	5.4	4.93
21	Instruments	9	96.0	29.3	2.0	0.83
22	Other manufacturing	182	286.9	125.5	7.8	13.25
23	Electricity, steam, hot water	4025	380.8	163.8	107.7	100.76
24	Gas production and supply	19	12.4	3.3	5.8	4.27
25	Construction	121	1738.6	499.7	63.0	11.79
26	Transport & warehousing	361	506.6	279.8	64.2	68.43
27	Post & telecommunication	0	195.9	112.6	6.2	7.00
28	Commerce & Restaurants	118	1412.6	726.3	31.0	23.94
29	Finance and insurance	13	359.5	219.5	3.4	1.82
30	Real estate	72	185.5	140.8	2.4	2.63
31	Social services	222	564.5	224.3	26.0	14.55
32	Health, Educ., other services	416	658.5	314.8	21.5	19.41
33	Public administration	112	443.4	200.0	14.7	8.61
	Households	462			62.2	163.68
	Total	24343	20067	7653.1		1381.73

Notes: Energy yuan value is total purchases, including feedstocks for secondary products (from input output table, authors' calculations). Energy use excludes transformation (*China Statistical Yearbook*).

Table 4. Concentration of pollutants in major cities.

	Conc. of TSP $\mu g / m^3$	Conc. of PM10 $\mu g / m^3$	Conc. of SO2 $\mu g / m^3$
Beijing	377	226	124
Tainjing	318	191	75
Shenyang	369	221	82
Harbin	310	186	26
Shanghai	229	137	68
Jinan	420	252	141
Wuhan	241	145	42
Guangzhou	217	130	70
Chongqing	200	120	208
Chendu	248	149	60
Xian	385	231	91
National urban average	298	178	93

Source: Fridley (2001).

Table 5 Coefficients linking emissions to national pollutant concentration, 1997.

$$C_{xt}^{N} = \gamma_{low,x} E_{low,xt}^{u} + \gamma_{medium,x} E_{medium,xt}^{u} + \gamma_{high,x} E_{high,xt}^{u}$$

	$\mu g / m^3$ PM10 per kton TSP	$\mu g / m^3$ PM10 per kton PM10	$\mu g / m^3$ SO2 per kton SO2
γ_{low}	0.05685	0.09474	0.03364
γ_{medium}	0.01026	0.01710	0.00607
γ_{high}	0.00162	0.00270	0.00096

Source: Authors' calculations updated from Lvovsky and Hughes (1997).

Table 6. Dose-Response and Valuation Estimates for PM-10 and SO_2, base case.

	Health Effect	**Cases per mil people per $\mu g/m^3$ increase**	**Valuation in U.S. in US$**	**Valuation in China *yuan 97***
	Due to PM-10:			
1	Mortality (deaths)	7.14	3,600,000	702,068
2	Respiratory hospital admissions (cases)	12	4,750	926.3
3	Emergency room visits (cases)	235	140	27.3
4	Restricted activity days (days)	57,500	60	11.7
5	Lower respiratory infection/child asthma (cases)	23	50	9.8
6	Asthma attacks (cases)	2,608	50	9.8
7	Chronic bronchitis (cases)	61	72,000	14,041
8	Respiratory symptoms (cases)	183,000	50	9.8
	Due to SO_2:			
9	Chest discomfort	10,000	50	9.8
10	Respiratory systems/child	5	50	9.8

Sources: Dose-response data and valuation in U.S. $ are from Lvovsky and Hughes (1997) and World Bank (1997). Valuation in *yuan* are authors' estimates transferred from U.S.$ figures.

Table 7. Alternative Dose-Response and Valuation Estimates for PM-10 and SO_2

Estimates of dose response

	change in mortality risk per $\mu g/m^3$	range given
World Bank (1997), citing literature		
Acute mortality, PM10	0.1%	
ECON (2000), Guangzhou study and citing literature		
Chronic mortality, PM10	0.4%	(0.0,0.6)
Acute mortality, SO2	0.12%	(.09,.16)
Levy et. al. (1999), pooled estimates of 24 studies		
Acute mortality, PM10	0.06%	(.02,0.9)
Acute mortality, SO2	0.004%	(0,.008)
Xu et. al. (1994), Beijing study		
Acute mortality, PM10	0.036%	(0.0,.068)
Acute mortality, SO2	0.12%	(.09,.16)
WHO (1999) citing literature		
Acute mortality, PM10	0.1%	(0.04,0.3)

Estimates of value of statistical life

	Valuation in study country U.S. $	Valuation in China yuan	ratio GDP per capita, China to study country
World Bank (1997)	3,600,000	702,000	0.0235
U.S. EPA	7,000,000	1,365,000	0.0235
Zhou and Hammitt (2002) China c.v. study	4,200-16,900	34,000-135,000	1
Liu, Hammitt and Liu (1997) Taiwan wage study	400,000	190,000	0.0570
ECON (2002) literature review	77,000	610,000	1
Range up to 200 times GDP/capita		1,210,000	

Notes: The ratio of GDP per capita is derived using nominal exchange rates for 1997. For valuations given in US$, these are converted to yuan values using the ratio of GDP per capita in 1997 and the nominal rate of 8.29 yuan/$. To convert the India study we used an income ratio of 1 instead of the actual 1.69.

Table 8. Alternative values of Dose-Response and Valuations for sensitivity analysis.

		Dose response Cases per mil per $\mu g/m^3$			Valuation per case *yuan 97*		
	Health Effect	**Base**	**Low**	**High**	**Base**	**Low**	**High**
	Due to PM-10:						
1	Mortality (deaths)	7.14	3.91	19.53	702,000	135000	1210000
2	Respiratory hospital admissions	12	12	12	926	926	926
3	Emergency room visits (cases)	235	235	235	27.3	27.3	27.3
4	Restricted activity days (days)	57,500	57,500	57,500	11.7	11.7	11.7
5	Lower respiratory infection/child	23	23	23	9.8	9.8	9.8
6	Asthma attacks (cases)	2,608	2,608	2,608	9.8	9.8	9.8
7	Chronic bronchitis (cases)	61	44	61	14,000	14,000	14,000
8	Respiratory symptoms (cases)	183,000	49820	183,000	9.8	9.8	9.8
	Due to SO_2:						
9	Chest discomfort	10,000	10,000	10,000	9.8	9.8	9.8
10	Respiratory systems/child	5	5	5	9.8	9.8	9.8
11	Mortality	0	0.26	0	702,000	135000	1210000

Sources: Base coefficients and values are from Table 7 (World Bank 1997). The low case DR(mortality) and DR(CB) is from Levy et.al. (1999), DR(respiratory symptoms) is from ECON (2000, Table 8.1). The low valuation for mortality is from Zhou and Hammitt (2002), while the high uses the 200 times GDP/capita suggestion of ECON (2000).

Table 9 Total health damages in 1997 using central values of DR and Valuation.

		Number of cases	Value (mil. yuan)
Due to PM			
1	Mortality	255190	179161
2	Respiratory hospital admissions	428891	397
3	Emergency room visits	8413417	230
4	Restricted activity days	2055104053	24047
5	LRI/child(asthma)	820255	8
6	Asthma attacks	93212372	909
7	Chronic bronchitis	2187346	30713
8	Respiratory symptoms	6540592031	63777
Due to SO2			
9	Chest discomfort	112910604	1235
10	Respir. systems/child	56455	1
	Total		300478

Note: These are derived using equations 9-11 and the base parameter values in Table 8.

Table 10 Sector health damage from combustion and noncombustion sources, per unit Output, and share of total damages, 1997, Method I.

	Sector	MDX^{O}_{xj} **x = PM** yuan/yuan	MDX^{O}_{xj} **x = SO2** yuan/yuan	**Share of total** %	**Emission Height class**
1	Agriculture	0.00017	0.00000	0.10	low
2	Coal mining and processing	0.00249	0.00001	0.14	medium
3	Crude petroleum mining	0.00139	0.00001	0.06	medium
4	Natural Gas Mining	0.00072	0.00000	0.00	medium
5	Metal ore mining	0.00112	0.00001	0.03	medium
6	Non-ferrous mineral mining	0.00113	0.00001	0.06	medium
7	Food products and tobacco	0.00388	0.00004	1.26	medium
8	Textile goods	0.00302	0.00004	0.66	medium
9	Apparel, leather	0.00045	0.00000	0.07	medium
10	Sawmills and furniture	0.00997	0.00006	0.52	medium
11	Paper products, printing	0.01070	0.00007	1.13	medium
12	Petroleum processing & coking	0.00783	0.00006	0.57	medium
13	Chemical	0.00955	0.00011	3.38	medium
14	Nonmetal mineral products	0.24813	0.00028	51.07	medium
15	Metals smelting and pressing	0.04080	0.00025	7.24	medium
16	Metal products	0.00421	0.00001	0.47	medium
17	Machinery and equipment	0.00277	0.00002	0.58	medium
18	Transport equipment	0.00167	0.00001	0.23	medium
19	Electrical machinery	0.00126	0.00001	0.17	medium
20	Electronic & telecom. equipment	0.00072	0.00000	0.08	medium
21	Instruments	0.00147	0.00001	0.03	medium
22	Other manufacturing	0.01036	0.00009	0.70	medium
23	Electricity, steam & hot water	0.02721	0.00037	2.47	high
24	Gas production and supply	0.02456	0.00023	0.07	medium
25	Construction	0.00697	0.00016	2.91	low
26	Transport and warehousing	0.04642	0.00054	5.59	low
27	Post & telecommunication	0.00003	0.00001	0.00	low
28	Commerce & Restaurants	0.00797	0.00013	2.69	low
29	Finance and insurance	0.00250	0.00004	0.21	low
30	Real estate	0.02609	0.00031	1.15	low
31	Social services	0.02631	0.00036	3.54	low
32	Health, Education, other services	0.04230	0.00050	6.62	low
33	Public administration	0.01686	0.00023	1.78	low
	Households			4.39	low
	Total			100.00	

Note: MD_{xj} is the value of damage to human health in urban areas in *yuan* due to the emission of pollutant x from producing one *yuan* of output from sector j, includes both combustion and noncombustion emissions. "Share of total" is the share of sector marginal total damage, $MTD_{j,}$ in national MTD^{N}.

Table 11 Sector health damage from combustion only, per unit Output, and share of total damages, 1997, Method I.

	Sector	MDX^{O}_{xj} **x = PM** yuan/yuan	MDX^{O}_{xj} **x = SO2** yuan/yuan	**Share of total** %
1	Agriculture	0.00017	0.00000	0.20
2	Coal mining and processing	0.00183	0.00001	0.20
3	Crude petroleum mining	0.00073	0.00001	0.06
4	Natural Gas Mining	0.00007	0.00000	0.00
5	Metal ore mining	0.00046	0.00000	0.02
6	Non-ferrous mineral mining	0.00048	0.00000	0.05
7	Food products and tobacco	0.00369	0.00004	2.35
8	Textile goods	0.00297	0.00004	1.26
9	Apparel, leather	0.00043	0.00000	0.12
10	Sawmills and furniture	0.00661	0.00006	0.68
11	Paper products, printing	0.00735	0.00006	1.52
12	Petroleum processing & coking	0.00379	0.00004	0.54
13	Chemical	0.00736	0.00009	5.10
14	Nonmetal mineral products	0.04753	0.00020	19.20
15	Metals smelting and pressing	0.01374	0.00011	4.78
16	Metal products	0.00133	0.00001	0.29
17	Machinery and equipment	0.00232	0.00002	0.95
18	Transport equipment	0.00123	0.00001	0.33
19	Electrical machinery	0.00081	0.00001	0.21
20	Electronic & telecom. equipment	0.00028	0.00000	0.06
21	Instruments	0.00102	0.00001	0.05
22	Other manufacturing	0.00471	0.00007	0.63
23	Electricity, steam & hot water	0.02673	0.00037	4.74
24	Gas production and supply	0.02052	0.00022	0.12
25	Construction	0.00697	0.00016	5.70
26	Transport and warehousing	0.04642	0.00054	10.94
27	Post & telecommunication	0.00003	0.00001	0.00
28	Commerce & Restaurants	0.00797	0.00013	5.26
29	Finance and insurance	0.00250	0.00004	0.42
30	Real estate	0.02609	0.00031	2.25
31	Social services	0.02631	0.00036	6.92
32	Health, Education, other services	0.04230	0.00050	12.95
33	Public administration	0.01686	0.00023	3.48
	Households			8.60
	Total			100.00

Note: MD_{xj} is the value of damage to human health in urban areas in *yuan* due to the combustion emission of pollutant x from producing one *yuan* of output from sector j. "Share of total" is the share of sector marginal total damage, MTD_j, in national MTD^N.

Table 12. Health Damage from Fuels, 1997

	Average Marginal Damage			t_f^{xv}
	National fuel use	Urban fuel use		yuan per yuan
Coal	153.07	247.10	yuan/ton	0.938
Oil	61.05	88.88	yuan/ton	0.028
Gas	0.35	0.57	yuan/1000m^3	0.001

Note: Average marginal damage (AMD_f) is valued in *yuan* per physical unit of fuel (averaged over all sectors) in eqn 16. "National" refers to using total fuel combusted in the denominator, "Urban" uses only the estimated urban combustion. t_f^{xv} is the value of damage per *yuan* of fuel combusted nationally.

Table 13 Damage per unit output estimated using intake fraction method,
(MD_j yuan of damage per yuan of output in 1997).

	Sector	iF(TSP)	50km. range Damage rate (yuan/yuan) due to Combustion emissions	50km. range Damage rate (yuan/yuan) due to Total emissions	Extended Damage due to Combustion emissions
13	Chemical	3.28E-06	0.0011	0.0014	0.0022
14	Nonmetal mineral products	3.46E-06	0.0070	0.0363	0.0141
15	Metals smelting and pressing	3.75E-06	0.0023	0.0066	0.0045
23	Electricity, Steam & hot water	2.16E-06	0.0161	0.0164	0.0322
26	Transportation		0.0376	0.0376	0.0753
	Primary TSP	7.72E-05			
	Secondary PM	3.10E-06			

Notes: The intake fractions, iF, are taken from HUCE (2002, revised Chapters 4 and 5. These are for combustion emissions, and estimated out to 50km only. In the column "due to total emissions" the damage is calculated assuming that these iF's are also applicable to the noncombustion emissions. The "Extended" results assume that the iF(whole range) = 2.0 iF(50km).

Table 14 Sector share of total health damage, iF Method versus Method I
(Damages for manufacturing and transportation, from combustion only)

	Sector	Method I share %	iF Method share %
7	Food products and tobacco	2.35	2.34
8	Textile goods	1.26	1.26
9	Apparel, leather	0.12	0.12
10	Sawmills and furniture	0.68	0.68
11	Paper products, printing	1.52	1.51
12	Petroleum processing & coking	0.54	0.24
13	Chemical	5.10	2.42
14	Nonmetal mineral products	19.20	9.18
15	Metals smelting and pressing	4.78	2.52
16	Metal products	0.29	0.29
17	Machinery and equipment	0.95	0.95
18	Transport equipment	0.33	0.32
19	Electrical machinery	0.21	0.21
20	Electronic & telecom. equipment	0.06	0.06
21	Instruments	0.05	0.05
22	Other manufacturing	0.63	0.63
23	Electricity, steam & hot water	4.74	9.14
24	Gas production and supply	0.12	0.12
26	Transport and warehousing	10.94	24.90
	Total	100.00	100.00

Note: Share of damages is the share of sector marginal total damage, $MTD_{j,}$ in national MTD^N. The "iF method" column is from Table 13 for the measured sectors, and assumes the sample average from these measure sectors for the other sectors that are not part of this study.

Table 15. Sensitivity analysis of marginal damage of combustion emissions
(*yuan* of damages per *yuan* of output).

Sector	Chemical	Nonmetal mineral products	Metals smelting	Electricity	Transpor-tation
Base case marginal damage 50km; DR=0.1%, VSL=702000	0.0011	0.0070	0.0023	0.0161	0.0376
Using low end of DR DR(mortality) = 0.06%	0.0006	0.0039	0.0013	0.0091	0.0205
Using high end of DR DR(mortality) = 0.3%	0.0021	0.0142	0.0045	0.0321	0.0767
Using low end of VSL VSL = 135000 yuan	0.0006	0.0037	0.0012	0.0086	0.0194
Using high end ofVSL VSL = 1210000 yuan	0.0015	0.0100	0.0032	0.0228	0.0539
Using low end of DR and VSL DR = 0.06%; VSL=135000	0.0004	0.0020	0.0007	0.0050	0.0106
Using high end of DR and VSL DR = 0.3%; VSL=1210000	0.0034	0.0225	0.0071	0.0504	0.1213
Larger domain of exposed population, iF(infinity)	0.0022	0.0141	0.0045	0.0322	0.0753