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RESEARCH REPORT

No. 2009-RR7

Cost-Effectiveness Analysis for Controlling Ground Level Ozone in Beijing and Its Surrounding Areas

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This EEPSEA study assesses a number of policy options that could help reduce ground level ozone pollution in Beijing. Ground level ozone pollution is one of the most significant air pollution problems in big cities in China. Because of the complex way in which ozone is formed, it is difficult for policy makers to identify optimal control options on a cost-effective basis. The study, conducted by Xie Xuxuan and Wu Dan from Peking University, assesses a range of options to address this problem. It compares the effectiveness and economic costs of these options, and then recommends the most effective sequence in which the options should be adopted to realize pollution control at the lowest cost.

The study finds that the installation of oil gas recovery systems at Beijing's 1446 gasoline stations would be the most cost-effective option. Overall, it is found that options to reduce ozone pollution by cutting vehicular emissions are much more cost-effective than options to "clean-ip" coal-fired plants. A series of options for controlling vehicular emissions have been introduced, including substituting gasoline buses with clean fuel buses and phasing out high emission vehicles (those with low emission standards) in Beijing. The study also highlights that cost-effective pollution control can be achieved by, for example, better practices when refueling vehicles. The results of this research are expected to help decision makers to bate ozone pollution in a cost-effective way.

Published by the Economy and Environment Program for Southeast Asia (EEPSEA)
22 Cross St, #02-55 South Bridge Court, Singapore 048421(www.eepsea.org)
Tel: +65-6438 7877, fax: +65-6438 4844, email: eepsea@idrc.org.sg

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ISBN: **978-981-08-4884-2**

COST-EFFECTIVENESS ANALYSIS OF GROUND-LEVEL OZONE CONTROL IN AND AROUND BEIJING

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January, 2010

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The Economy and Environment Program for Southeast Asia (EEPSEA) was established in May 1993 to support research and training in environmental and resource economics. Its objective is to enhance local capacity to undertake the economic analysis of environmental problems and policies. It uses a networking approach, involving courses, meetings, technical support, access to literature and opportunities for comparative research. Member countries are Thailand, Malaysia, Indonesia, the Philippines, Vietnam, Cambodia, Lao PDR, China, and Papua New Guinea.

EEPSEA is supported by the International Development Research Centre (IDRC); the Swedish International Development Cooperation Agency (Sida); and the Canadian International Development Agency (CIDA).

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ACKNOWLEDGEMENTS

The authors wish to acknowledge the following for their valuable contribution towards making this study a success:

- The Economic and Environmental Program for Southeast Asia (EEPSEA) for funding this research project.
- EEPSEA Director, Dr. Herminia Francisco, for approving the support for the study.
- Dr. Benoit Laplante, the EEPSEA advisor of this project, for his valuable insights and suggestions.
- Prof. Zhang Shiqiu, the authors' supervisor, for her advice and support throughout the whole study.
- Prof. Zhu Tong, Prof. Tang Xiaoyan, Prof. Shao Min, Prof. Xu Jintao, Ms. Yi Yuanyuan and Mr. Miao Weijie from Peking University.
- Dr. Wang Zifa from the Chinese Academy of Sciences.
- Members of the Environmental Economics and Policy Study Group (EEPS) in Peking University, especially Ms. Hu Qian.
- Mr. Tang Dagang, and Mr. Yin Hang in the Vehicle Emissions Control Center of the Ministry of Environmental Protection.

This study was also supported by the research program "Study on Characteristics of Pollutants' Transportation and Reaction in Beijing and Surrounding Areas, and Air Quality Control Strategy" and "Campaigns of Air Quality Research in Beijing and Surrounding Regions" of the Beijing Science and Technology Commission and the Shanghai Tongji Gao Tingyao Environmental Science and Technology Development Foundation.

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COST-EFFECTIVENESS ANALYSIS OF GROUND-LEVEL OZONE CONTROL IN AND AROUND BEIJING

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EXECUTIVE SUMMARY

Ground-level ozone pollution has become one of the most severe air pollution problems in Beijing. Because of the complex processes involved in the tranmission and chemical formation of pollutants, ozone control strategies and policies may lack the element of cost-effectiveness. Our study identified two important and controllable emission sources of ozone pollution which emit most of the nitrogen oxide (NOx) and volatile organic compounds (VOC) in and around Beijing, discussed control measures/policies for different areas and sectors/industries, and calculated the emission reduction potential and annual control costs of the said measures/policies. Taking the cost-effective approach, we applied the Ambient Least Cost Model, compared the cost-effectiveness of the measures/policies and finally formulated the optimal control path with the lowest total cost. The cost-effectiveness of emissions control was found to vary widely across areas and sectors, indicating that the cost-saving potential was large. By exploring different policy scenarios, we found that behaviour modification, improving implementation efficiencies and structural changes in certain sectors could play important roles in reducing ozone pollution at low costs.

1.0 INTRODUCTION

With the rapid economic development and urbanization in Beijing, ground-level ozone pollution has become one of the most severe challenges to air quality control in the city. Although Beijing implemented its “16 stages of air quality control policies” in 1998, control strategies for secondary pollutants such as ground-level ozone and particulate matter (PM) were not given serious attention until very recent years. This study focused on ozone control measures/policies, with their corresponding cost analysis, in order to find a cost-effective control path for certain ozone reduction targets.

1.1 Ozone Pollution

1.1.1 Environmental impact of ground-level ozone

Ozone is a strong oxidizing agent and will stimulate the human mucous membrane system. Short-term exposure can cause coughing, chest pain, fatigue, nausea, and other symptoms while long-term exposure will lead to significant damage to the lungs as well as adverse effects on the respiratory tract. High concentrations of ozone are also harmful to plant systems. In addition, the photochemical smog[1] has a destabilizing effect on polymer materials and can seriously affect visibility.

1.1.2 Regional pollution characteristics and source-receptor relationships

The formation of ozone involves chemical reactions between nitrogen oxide (NOx) and volatile organic compounds (VOC) driven by solar radiation, and occurs regionally. Atmospheric NOx anthropogenic sources include coal-fired power plant boilers, industrial boilers, civil appliances and motor vehicle exhaust emissions (Sun 2004). VOC emissions mainly come from motor vehicle exhaust emissions, elevated point sources (coal-fired power plants), industrial sources, solvent use, oil storage and transportation, and living sources (household daily energy use) (Wang and Li 2002). The time scale of ozone production is such that ozone concentrations are built up in polluted air over several days under suitable weather conditions, and ozone and its precursors (NOx and VOC) can be air-carried over considerable distances even across national boundaries. An integrated assessment model for ozone, like the Ambient Least Cost (ALC) Model or the Regional Air Pollution Information and Simulation (RAINS) Model, needs to be able to relate ozone exposure to changes in the emissions of ozone precursors. These source-receptor relationships need to be valid for long-term ozone exposure.

Several ways of condensing the results of more complex models of ozone formation in order to construct a simplified means of representing source-receptor relationships are possible but we used conversion factors, which are also used to describe the important relationships between ozone and its precursors. Section 6 of this report introduces the simplified approach developed by the research program "Study on the Characteristics of Pollutant Transportation and Reaction in Beijing and Surrounding Areas, and Air Quality Control Strategy", which was led by Peking University and which is hereafter referred to as the Beijing Program, to describe the relationships between precursor emissions and long-term ozone levels. It must be kept in mind that, in the overall context of an integrated assessment model, the aim of such an approach is merely to provide source-receptor relationships which are computationally efficient so as to enable a cost and optimization analysis of alternative emission reduction strategies to be made.

More details on ozone formation and concentration determining mechanisms involving the two precursors are described in some reports by the International Institute for Applied Systems Analysis (IIASA) (like Heyes et al. 1997), which deal with ozone pollution in Europe.

[1] In the 1950s, a new type of smog, known as photochemical smog, was identified. It forms when sunlight hits various pollutants in the air and forms a mix of inimical chemicals that can be very dangerous. A photochemical smog is the chemical reaction of sunlight, nitrogen oxide (NOx) and volatile organic compounds (VOC) in the atmosphere, which leaves behind airborne particles (called particulate matter) and ground-level ozone.

1.2 Ozone Pollution in Beijing

1.2.1 Status

From 1984-1987, data from the Beijing Environment Monitoring Center's nine ozone monitoring stations revealed that, in the summer of 1986, photochemical smog appeared in Beijing. By the 1990s, near-ground ozone levels had increased (Duan and Xu 2001). Pollution often occurs in summer and autumn, due to higher temperatures, less wind and strong sunlight. Figure 1 shows ozone exceeding days and exceeding hours[2] in August of every year from 2000 to 2006 in Beijing. We can see that although the exceeding days and hours went down and up, they were all at high levels, as there were around 60 days' or more than 100 hours' each year exceeding China's Air Quality Standards II for ground ozone pollution. Ozone pollution has become one of the most important issues in Beijing's air pollution control.

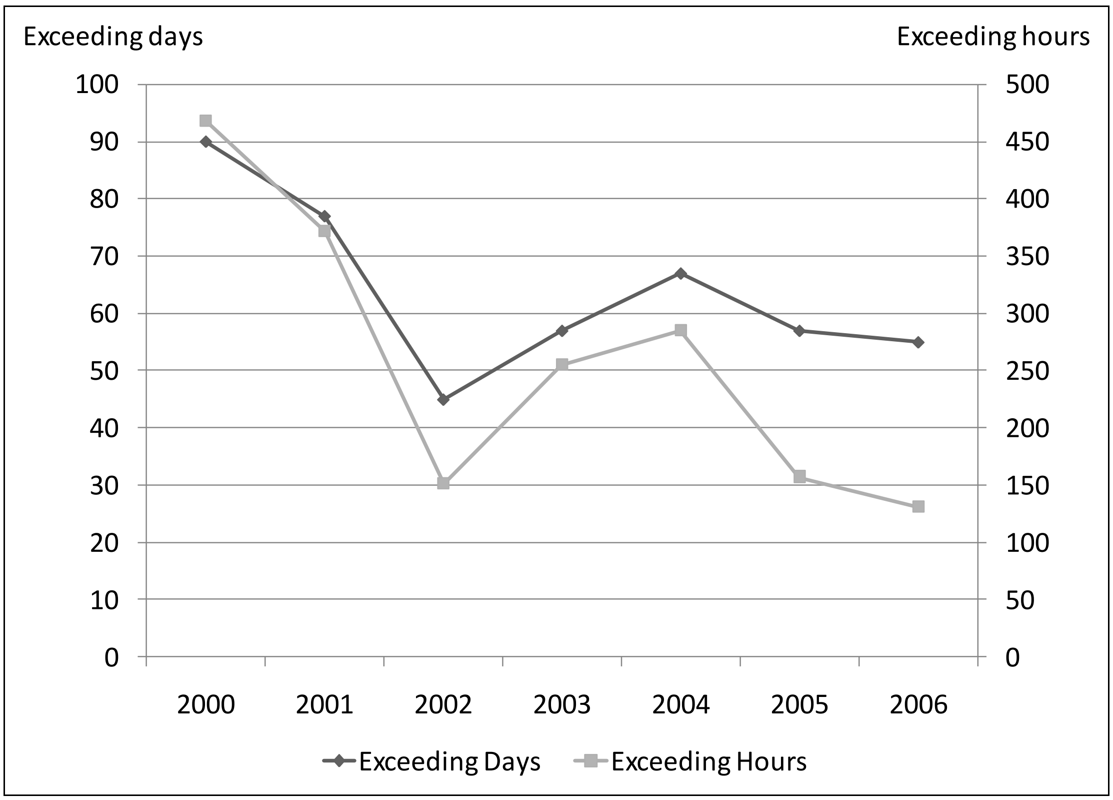

Figure 1. Ozone exceeding status in Beijing from 2000 to 2006

Source: Tsinghua University (2007)

[2] Ozone exceeding days or hours refer to when the atmospheric ozone concentration level is higher than China's National Air Quality Standards II of 200 ug/m^3.

1.2.2 The effect of socio-economic development on ozone pollution in Beijing

Because of rapid economic growth, industrialization and urbanization, more and more motor vehicles are being used in Beijing, with ozone pollution growing worse in the process (the GDP growth of provinces and vehicles increase in Beijing is shown in Appendix 1 and Appendix 2). The increase in vehicle-use, coal-fired power plants, steel factories, etc. in Beijing and its surrounding areas is the main reason for the worsening ozone pollution.

The number of motor vehicles in Beijing increased from 1.51 million in 2000 to 2.58 million in 2005, with an average annual growth of 11.3%. On May 26th, 2006, the Beijing municipal government announced that this number reached 3 million, with a daily growth rate of about 1,000 (Beijing Traffic Management Bureau 2006). In 2008, the number of motor vehicles in Beijing amounted to 3.3 million.

1.2.3 Difficulties in controlling ozone pollution

Emission sources in the surrounding areas of Beijing (Appendix 3) affect ozone formation in two ways. Like Figure 2 shows, (a) NOx, which is emitted by high level sources and which can travel long distances towards Beijing, contributes to the formation of ozone with local VOC (VOC is at a low level and its highly reactive nature does not lend itself to significant transmission qualities); and (b) the local emissions of NOx and VOC in surrounding areas react to produce ozone which is also then transmitted to Beijing.

Weather conditions namely, wind direction and speed as well as rain, play an important part in the process. Generally, the southern and southeast winds carry the pollutants from the surrounding areas to Beijing.

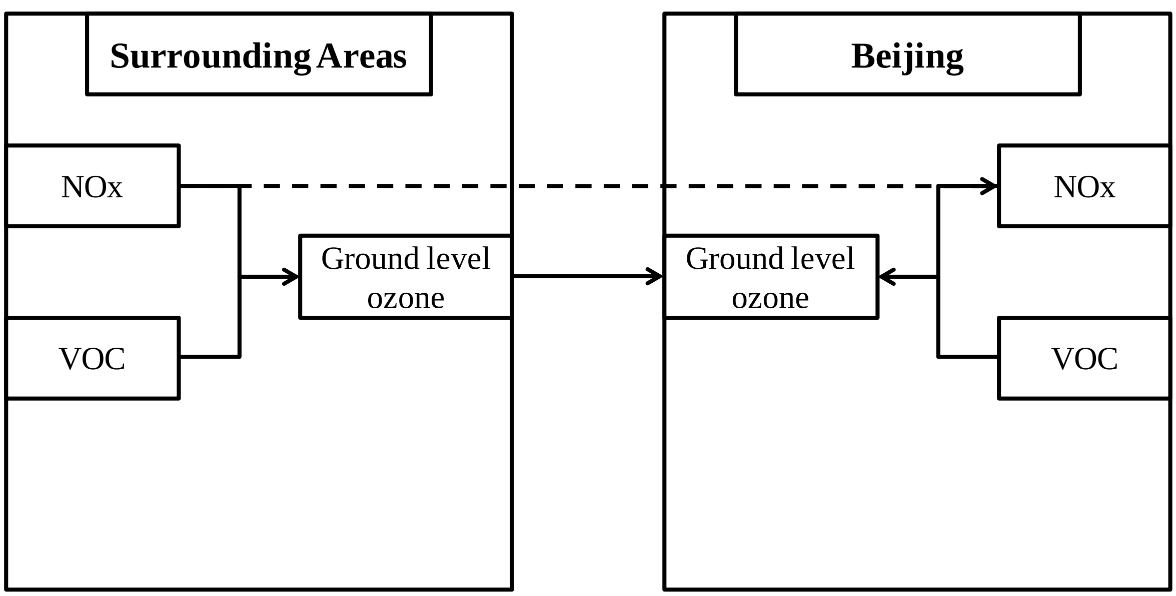

Figure 2. Emission transmission and ozone pollution in Beijing and its surrounding areas

It is due to such a complex regional transmissions effect that the effective control of ozone requires the cooperation of the different industries and regional authorities. Herein lies the problem: the current levels of pollutant control, costs of optional measures, and ozone concentrations are different across the different sectors and industries in the various sub-regions. The question therefore is: What measures can be taken and in which sub-regions and industries to achieve cost-effective ozone control?

We conducted a bottom-up cost-effectiveness analysis. Based on the identification of pollution and emission sources as well as optional measures and their costs, we applied the Ambient Least Cost (ALC) Model to track the path of selected control measures.

This study was conducted under important scientific conditions. First, the implementation of many air quality improvement policies for the 29th Olympic Games in 2008 gave us a good opportunity to conduct a real-life experiment. During the Olympic period, the air quality target (National Standard II) was achieved every day and ozone concentration declined significantly. We were able to directly evaluate the effect of the measures, identify temporary and long-term ones, and change and maintain them to form a long-run control scenario. In addition, the Beijing Program, in which we participated, provided us with two aspects of important information: emission source inventories of NOx and VOC; and scientific findings on pollutants formation and transmission within the research region.

2.0 METHODOLOGY

2.1 Cost-Effectiveness Analysis

We conducted a typical cost-effectiveness analysis using the average annual cost per unit of ozone concentration decline to represent the cost-effectiveness of different measures. The ALC model shows the relationship between local emissions and the receptor's ozone concentrations, and the optimization process, which are described in the following sections.

We followed the steps shown in the research framework in Figure 3:

a) the identification of the emission industries and emission sources of NOx and VOC;

b) the evaluation and screening of alternative control technologies and measures in the emission industries;

c) the estimation of NOx and VOC abatement potential in the different areas and industries under different additional abatement technologies and measures scenarios;

d) the estimation of ozone concentration reduction under various NOx and VOC abatement levels;

e) the estimation of the average cost per ozone concentration unit decline based on the local NOx and VOC abatement costs, followed by the formulation of a cost-effective control path constructed by single control measures on every emission source or category of sources; and

f) discussing control measures/policies for the real situation in Beijing, with conclusions and suggestions for long-term ozone control strategies and plans by the government.

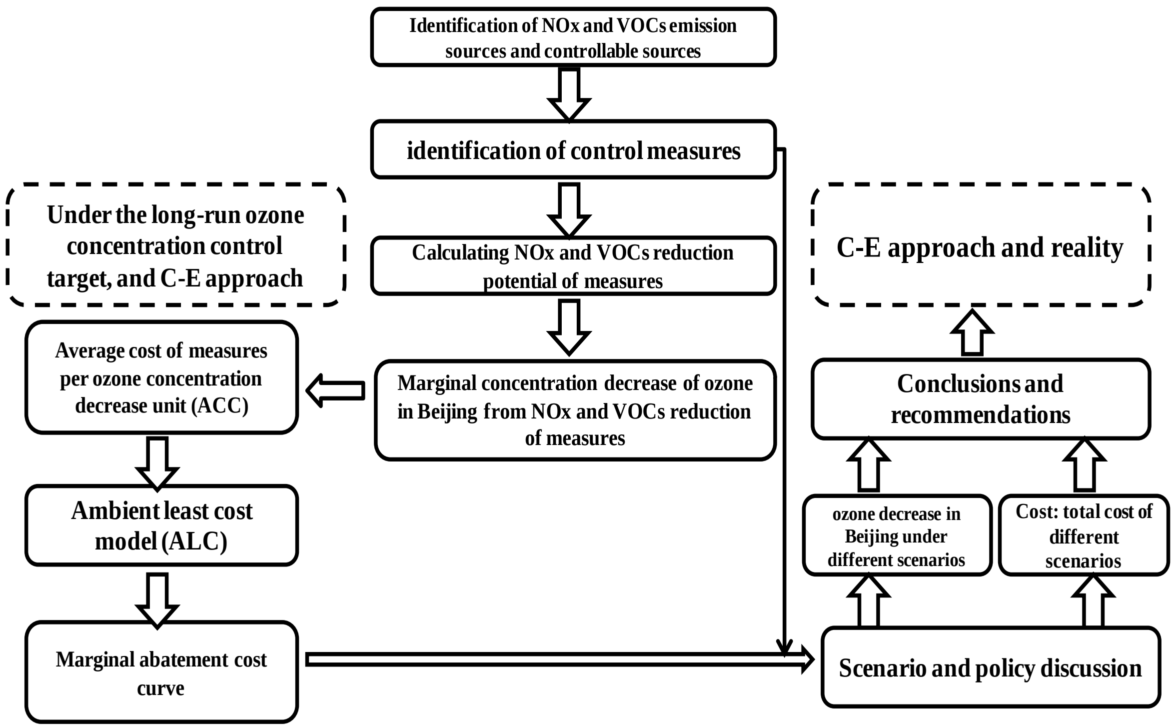

Figure 3. Research framework

2.1.1 Emission sources identification and emission calculations

Except for the inventory of the "Beijing Program", we identified the key emission sources of pollution through the collection and calculation of the following data:

a) For the industrial sector

- environmental quality standards for various areas and industries
- NOx and VOC emissions data (collected through surveys and interviews)
- fuel usage and quality
- information related to production technology, production scale and product yield
- emission factors of different emission industries or production processes
- air pollution abatement technologies and measures used and removal efficiencies
- equipment installation and operating conditions
- socio-economic development planning and business development planning
- environmental planning data and information

b) For vehicles

- numbers of types of motor vehicles
- emission factors of different modes of vehicles
- data on vehicle use such as the annual mileage (km)

The secondary data/information sources were: environmental statistics bulletins, reports on environment quality, the Environmental Yearbooks, environmental statistics, sewage discharge registration data, Beijing Statistical Yearbooks, the statistical yearbooks of related industries, national and local socio-economic development plans, national and local industry development plans, local environmental protection plans, and related studies and literature.

The emission calculation method used was that of Klimont et al. (2002) in accordance with the activity level and emission factors of the different emission sources.

$$E_k = \sum_{l} \sum_{m} \sum_{n} A_{k,l,m} ef_{k,l,m} (1 - \eta_{l,m,n} \alpha_{k,l,m,n}) * X_{k,l,m,n} \quad \text{(Equation 1)}$$

where

k: districts

l: sectors

m: categories of fuels and production activities

n: equipment

E: VOC emissions

A: activity level

ef: emission factor

η: removal efficiency

α: maximum usage rate of the equipment

X: actual usage rate of the equipment

2.1.2 Cost calculations

2.1.2.1 Technical options (requiring equipment)

The costs of measures generally include the investment costs (I), fixed operating costs (OM^{fix}) and variable operating costs (OM^{var}). The general cost function of coal power plants (as an example) was used by Cofala and Sanna (1998) in the RAINS model to calculate the cost of NOx abatement measures in Europe (Equation 2). Option cost calculation methods for other technical options are similar, except for the investment costs of construction. Technical options are: NOx abatement technical options for power plants;

ternary catalytic convertors for vehicles which meet China's National Standard I for vehicle emissions (CNSV I) or China's National Standard II for vehicle emissions (CNSV II); Gasoline Vapor Recovery System Stage II (GVRS II) for gasoline stations; and normal gasoline buses and diesel buses converted to compressed natural gas (CNG) buses (investment equal to the cost of buying new CNG buses).

Investment costs

The investments include the expenditure accumulated until the start-up of an installation, such as delivery of the equipment, construction, civil works, ducting, engineering and consulting, license fees, land and capital. The model uses investment functions where these cost components are aggregated into one function. The shape of the function is described by its coefficients ci^f and ci^v. The coefficients are given separately for three capacity classes: 50 to 100 MW, above 100 to 300 MW and above 300 MW. When the existing plant is retrofitted with add-on controls (SCR or SNCR), investments are multiplied by a retrofit cost factor r. The coefficients of investment functions describe only the construction costs of the equipment. In order to calculate the total investment costs, the cost of the catalyst for combustion is then added (if applicable). Since the lifetime of the catalyst is much shorter than that of the plant, subsequent replacements of the catalyst are included under 'variable operating costs'.

$$I = (ci_1^f + \frac{ci_1^v}{bs}) + (ci_2^f + \frac{ci_2^v}{bs}) * (1 + r) + \lambda^{cat} * ci^{cat}$$ (Equation 2)

where

ci_1^f, ci_1^v, ci_2^f, ci_2^v : investment function coefficients, cited from the RAINS model;

bs: boiler size;

λ^{cat}: catalyst volume (per unit of installed capacity);

ci^{cat} : unit cost of the catalyst; and

r: the retrofit cost factor.

The investments were annualized over the technical lifetime of plant lt, using the real interest rate q (in percentage) (Equation 3).

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1}$$ (Equation 3)

Operating costs

The fixed operating cost is a standard percentage of the total investment.

$$OM^{fix} = I * f$$ (Equation 4)

where I is the total investment and f is a coefficient (standard percentage) depending on the sector.

The variable operating costs were calculated using Equation 5.

$$OM^{\text{var}} = \lambda^e c^e + ef\,\eta\lambda^s c^s \qquad \text{(Equation 5)}$$

where

λ^e : additional electricity demand;

c^e : energy price;

λ^s : demand for sorbents (materials used to absorb liquids or gases)

c^s : price of sorbents;

ef : unabated NOx emission factor; and

η : removal efficiency.

2.1.2.2 Non-technical options

The costs of non-technical options encompass policy implementation costs and social costs, which are hard to quantify. If we take, for example, a policy to encourage the reduction of old vehicles and assume that the direct cost of stopping the use of a vehicle is low, this does not mean that car owners will be prepared to give up their cars. If the policy is made mandatory on the other hand, the social costs for car owners may be high and will be hard to quantify. So, in such a case, it is best to use substitution to calculate the policy costs and social costs. We assumed a government subsidy for car owners to eliminate their old cars, the emission status of which cannot even meet China's National Standard I for vehicle emissions (CNSV I, which is the lowest and earliest emission standard). We used the average prices of second-hand (5-8 year old) cars of different types to substitute the willingness to accept (WTA) of the owners of old cars to simulate the cost of this option. Another similar option would be the substitution of traditional oil-paint by water-based paint.

2.1.2.3 Data

We used boiler size, production capability, coal consumption and other basic information on power plants in and around Beijing as provided by the Beijing Program inventory. Some cost parameters came from the GAINS online model[3] and EPA website. The local electricity prices, coal prices and labour prices in the provinces were used. The quantities of vehicle types, emission factors and annual mileage of the different types of vehicles used were the same as in the emission section (2.1.1). The prices of equipment such as ternary catalyst convertors, fuel truck nozzles, installation fees, and so on were obtained from the field survey in Beijing, literature or online sources.

[3] http://www.iiasa.ac.at/rains/gains-online.html?sb=9

2.2 Optimization: Ambient Least Cost (ALC) Model

If the emissions abatement potential and cost data and contribution to the recipient from emission sources are known, we can use the mathematical optimization method to identify optimal cost control scenarios to achieve the environmental objectives.

The ALC Model was first proposed by Atkinson and Lewis (1974), and was revised by Loughlin (1998). It minimizes the cost of the pollution control techniques by the different sectors in the different areas under set constraints and targets.

The minimum cost objective function is:

$$MinC = \sum_{i=1}^{N} \sum_{t=1}^{Ti} ((u_i * e_{i,t}) * c_{i,t} * x_{i,t}) \quad \text{(Equation 6)}$$

where

C: the total control cost;

i: the number of pollution sources;

t: the kind of technology in use;

u_i : the emission level without any control measures;

$e_{i,t}$: the reducing efficiency in pollution source i using technology t;

$c_{i,t}$: the cost per every emission reduction in pollution source i, using technology t; and

$x_{i,t}$: a dummy, when using technology t, it is 1; if not, it is 0.

The objective function aims at total cost minimization. Equation 7 shows that the atmospheric pollutant concentration in the recipient location at least equals the reduction targets. Equations 8 and 9 show that among the control measures applied to all sources of emissions of pollutants, each source can only have one control measure.

$$\Psi[\underline{u}, \underline{e}, \underline{x}] \geq S_j, \forall j = 1, M \quad \text{(Equation 7)}$$

$$x_{i,t} \in \{0,1\}, \forall i = 1, N; t = 1, T_i \quad \text{(Equation 8)}$$

$$\sum_{t=1}^{T} x_{i,t} = 1, \forall i = 1, N \quad \text{(Equation 9)}$$

where

M: the total number of recipients;

Ti: the total number of available technologies;

Ψ: the predicted pollutant concentration in the recipient;

j: the number of recipients;

u: a set of all kinds of pollution emissions;

e: a set of pollution reductions;

S_j : the reduction target; and

$x_{i,t}$: a dummy, when using technology t, it is 1; if not, it is 0.

In this study, we assumed that the pollutants (NOx and VOC) did not react during the transportation process, so we used a non-reacting or linear-reacting ALC model. In this way, the function Ψ could be changed by using a coefficient matrix (S-R matrix). An S-R matrix is an N*M matrix in which N is the number of pollution sources and M is the number of recipients. In our study, we had only one recipient; Beijing. Every element in the matrix represents the contribution from the pollution sources to the recipient's ozone concentration. So when using the S-R matrix, Equation 7 becomes Equation 10:

$$\sum_{i=1}^{N}\sum_{t=1}^{T_i}\left(u_i * e_{i,t} * a_{i,j} * x_{i,t}\right) \geq S_j \quad \forall j = 1, M$$

(Equation 10)

where $a_{i,j}$ is the coefficient of sources contributing to the recipient.

3.0 IDENTIFICATION OF CONTROLLABLE EMISSION SOURCES

Several research studies on emission sources have been done in Beijing. The main emission sources of NOx are: coal-fired utility boilers, industrial boilers, civil appliances and motor vehicle exhaust emissions (Sun 2004). The main emission sources of VOC are: vehicles (55-58%), volatile petrol (10 -22%), architectural painting (9-14%), oil refineries (3-7%), liquefied petroleum gas (LPG) (2-6%) and asphalt evaporation from roads and production processes (2-4%) (Liu et al. 2005).

In this section, we introduce the calculation and aggregation methods for the unknown emission sources and show the results of NOx and VOC emission levels in Beijing and its surrounding areas. We identified the main emission sources of NOx and VOC.

3.1 VOC Emission Calculations

In Europe, solvent use, industrial processes, fuel production and storage (35.43%), and mobile sources (vehicles) (33%) emit most of the VOC (Grosslinger, Radunsky and Ritter 1996), followed by combustion (4.49%), natural sources (8.64%) and agriculture (17.17%). In the United States, solvent use, chemical production, storage and transportation are the main sources (78%) in which the solvent use contributes 32% (USEPA 2004) Streets et al.'s (2003) large-scale study of Asia found a VOC emission level of 15.6 Tg (million tonnes) against the Chinese government's figure of 17.4 Tg. Klimont et al. (2002) calculated China's VOC emission inventory in 1990 and 1995 by activity and emission factor. His study found that stationery fuel combustion emitted about 50%; transportation contributed about 20%; waste disposal, 8%; paint, 6%; solvent use, 5% and the chemical industry contributed 5%.

In Beijing, researchers used the chemical mass balance (CMB) method and got different results for Beijing's VOC emission sources. Liu et al. (2005) of Peking University studied the anthropogenic sources of VOC, finding that 55-58% of the emissions came from vehicle use, 10-22% from volatile gasoline, 9-14% from paint used in construction, 2-6% from liquefied petroleum gas (LPG) and 2-4% from pitch. Song et al. (2007) found that gasoline-related emissions, petrochemicals and LPG contributed 52%, 20%, and 11%, respectively, to the total ambient VOC while VOC emissions from natural gas (5%), painting (5%), diesel vehicles (3%), and biogenic emissions (2%) were also identified. Meanwhile, Shao et al. (2005) found that 35% of the anthropogenic emission in Beijing came from vehicles. Lu et al. (2006) found that mobile sources were the largest VOC emission source in Beijing, accounting for about 42% of the total emissions followed by gasoline storage and usage at about 37.7% and industrial sources at 13.7%.

According to the studies (Liu et al. 2005; Shao et al. 2005; Lu et al. 2006; Song et al. 2007) using the CMB method, the main sources of VOC emission in Beijing were mobile sources (vehicles), volatile gasoline (mostly from gasoline stations), solvent and paint use, chemical and other related industries, industrial sources, life sources (people's daily energy use), and natural sources. However, as natural emissions were much more significant in forests and rural areas than in cities and not easy to control, we did not include natural sources in Beijing in our study.

As this study focused on how effective and how costly control measures would be, a detailed inventory of emission sources was necessary. The Beijing Program provided us with information about emission sources in Beijing and the surrounding provinces, counties, and most sectors and companies. In addition, we used data on vehicle types from the 2007 Beijing Transport Annual Report and emission factors from the Tsinghua University study (2007), Hu et al. (2006), and Jing et al. (2006), and calculated the emission levels for different types of vehicles, gasoline stations and paint use in Beijing.

3.2 NOx Emission Calculations

Compared with the complex categories of emission sources for VOC, NOx concentrations in Beijing are predominantly affected by power plants and large industrial boilers in the city and surrounding areas, while vehicles in the city are the next largest source. However, NOx emission reduction techniques using industrial boilers are not yet broadly adopted in China nor are special NOx emission standards so we did not include industrial boilers as a control measure in this study. Instead, we focused on vehicles in Beijing (emissions from vehicles do not travel far) and power plants in the surrounding areas as the two main and controllable sources of ozone pollution.

3.3 Results: Heavy-contribution Areas and Important Sources

We integrated the total emissions of NOx and VOC (a) by province for all sectors (industries) (Figure 4), (b) by sector (industry) in all provinces (Figure 5) ; and (c) by sector only in Beijing (Figure 6) since the influence of local emissions should be large.

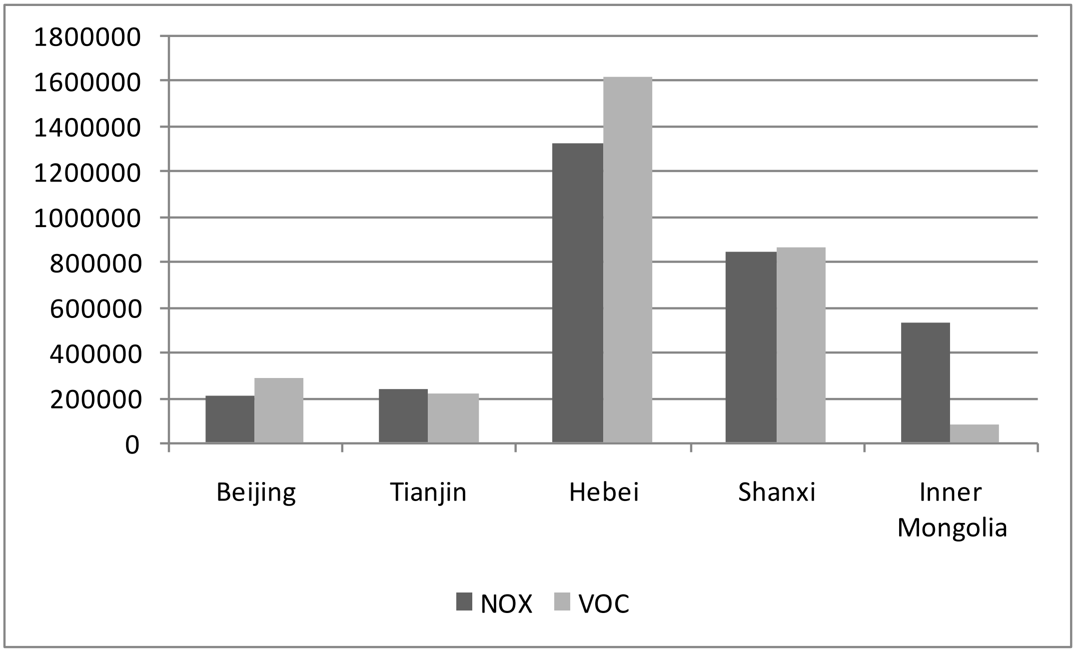

Figure 4. Total emissions of NOx and VOC by province for all sectors (tonnes/year)

Source: Beijing Program (Peking Univesity 2007)

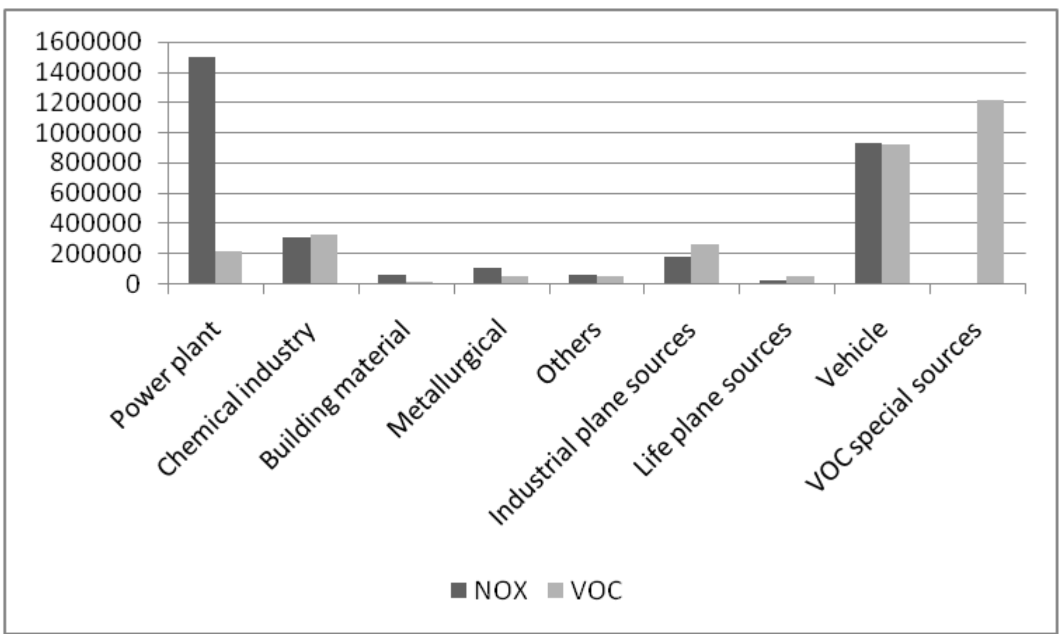

Figure 5. Total emissions of NOx and VOC by sector in all provinces (tonnes/year)

Source: Beijing Program (Peking University 2007)

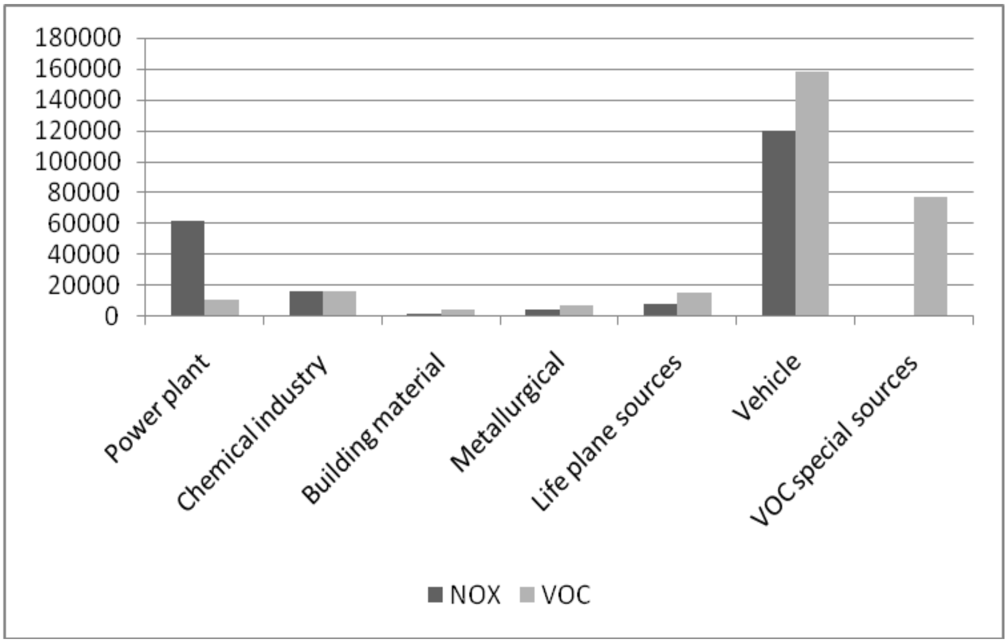

Figure 6. Total emissions of NOx and VOC by sector in Beijing (tonnes/year)

Source: Beijing Program (Peking University 2007)

For VOC, some specialized emission sources are especially important such as vehicles, gasoline stations, agricultural burning and natural sources (Shao et al. 2005; Liu et al. 2005; Lu et al. 2006; Song et al. 2007). The results are shown in Table 1 below. The gasoline stations in particular are considered as an important controllable emission source of VOC.

Table 1. Emissions from special VOC emission sources (tonnes/year)

Province	**Total**	**Gasoline stations**	**Natural sources**	**Agricultural burning**
Beijing	77,156	-	-	-
Tianjin	42,809	5,373	31,756	5,680
Hebei	556,265	9,740	546,526	-
Shanxi	534,541	-	534,541	-

Source: Beijing Program (Peking University 2007)

We further used the research results of the atmospheric pollutant transport models to identify the important emission areas. The results are shown in Table 2.

Table 2. Area contribution to ozone concentration in Beijing and its surrounding areas

Areas		Normal limit (%)	Upper limit (%)
Heavy-contribution areas	Beijing	22.8	34
	Baoding	28.1	59.5
	Langfang	11.1	24.5
	Tianjin	5.0	22.6
	Zhangjiakou	12.9	28.9
Medium-contribution areas	Handan-xingtai	6.7	8.5
	Chengde	6.1	20.7
	Shijiazhuang-Hengshui	12	18.6
	Shandong	9.9	17.7
	Tangshan-Qinhuangdao	7.0	18.2
	Taiyuan-Yangquan-Xizhou-Jinzhong	1.2	2.5

Source: Beijing Program (Peking University 2007)

According to the emission calculations for the different areas and sectors, the study on atmospheric contribution from source to receptor, and data availability, we included the following areas and sectors in our cost-effectiveness analysis:

- Vehicles in Beijing
- Power plants in Beijing
- Power plants in Baoding, Langfang, Tianjin, and Zhangjiakou (four cities to the south and east of Beijing)
- Paint used in Beijing
- Gasoline stations in Beijing

4.0 CONTROL MEASURES

4.1 Control Measures for Vehicles

Control measures for vehicles can be categorized as two types: command and control, and market-based/economic tools that can act as incentives or disincentives to respectively encourage or discourage certain behavior. Command and control measures include controls on new car emissions, fuel quality management, inspection and maintenance (I/M) systems, and speeding up the elimination of old cars. Economic tools include taxes and fees on purchasing new cars, annual consumption tax, car registration tax, fuel tax, and congestion charges.

In this study, based on different types of emissions and cost calculation methods, vehicle control options were divided into two categories: vehicle quantity control and emissions control. Taking into account the specific operating conditions in Beijing, we analyzed the following policies, requirements and measures.

4.1.1 Vehicle quantity reduction

- *Control on vehicle quantity increase through administrative and economic policies:* Environmental standards for new car production, checking the consistency of new environmentally-friendly production systems, installing I/M systems, and eliminating old cars.
- *Encouraging the use of the public transportation system:* The identification of changes in car-use behaviour after the improvement of the public transportation system is a key issue. We did some investigations in this regard, but the results were not sufficient to support this study. However, it could be considered for the next phase of this research or for related future research.
- *Limited vehicle use on special roads and at special times:* An example would be the driving restriction policies implemented during the Olympic Games in Beijing such as the "Ban on the Last Single or Double Digit of the Vehicle's License Plate", "Dedicated Olympic Lanes", and "Traffic Control". However, these measures are not suitable for a long-term use as Davis (2008) showed in his study on Mexico City. As people increase their usage of vehicles especially the use of high-emission ones and buy more new cars, such policies will not achieve emission reduction effects but instead only incur high implementation costs. Our study did not include such long-term alternative control measures for Beijing. Instead we included the first and second categories: control on vehicle quantity increase and increasing the use of public transportation.

4.1.2 Vehicle emissions reduction

- *More strict emission standards:* Beijing has implemented National Standard I (similar to the European Standard I) for new vehicle emissions from 1999, and since March 2008, the light type car has to adhere to National Standard IV (similar to the European Standard IV).
- *Strengthening the vehicle emissions I/M policy in Beijing:* According to the current I/M policy, vehicles have to be inspected every year by the Transportation Department. If the emission status of a vehicle does not meet the emission standards, it should be equipped with new exhaust gas treatment equipment or it will be declared as not road-worthy. At present, China's most important vehicle exhaust gas treatment technology is the ternary catalytic converter system, but some old vehicles (that meet CNSV I or CNSV II) have not been installed with these converters. Equipping these old vehicles with ternary catalytic converter systems can help them meet the new emission standards.
- *Fuel quality control:* The successful elimination of leaded petrol vehicles; low sulphur gasoline; implementation of the "Motor Gasoline Harmful Substances Control Standards"; and use of alternative fuels.
- *Reducing emissions from buses and taxis:* Eliminating old buses and taxis and substituting them with clean energy ones, and improving the fuel quality.

In this study, the following different control measures/policies were analyzed in terms of their characteristics (Table 3):

- Control and Command or Market-based measures;
- Technical or Behavioral Changes (i.e., whether the measures involve new technical requirements for vehicles or behavioral changes in driving);
- Costing or Substituted Costing or No-Costing, which means calculating the direct costs, using the substitution method to calculate indirect costs, or if we could not get costs, then to discuss the feasibility of the measures; and
- The long-term or short-term effects of the measures.

Table 3. Vehicle control measures

Control Measures	**Control and Command (CC) / Market-Based (MB)**	**Technical (T)/ Behavioral (B) Changes**	**Costing (C)/ Substituted Costing (SC)/ No-Costing (NC)**	**Long (L)/ Short (S) Term**
Emission standards for new vehicles	CC	T	NC	L
Management and improvement of oil quality	CC	T	NC	L
Inspection and maintenance (I/M) of vehicles	CC	T+B	NC	S
Elimination of old vehicles	CC	B	SC	S
Tax/Fee when buying cars	MB	B	NC	L
Tax/Fee for having cars	MB	B	NC	L
Tax/Fee when using cars	MB	B	NC	S
Petrol/Fuel Tax	MB	B	SC	S
Road tax	MB	B	SC	S
Congestion tax	MB	B	SC	S
Parking fee	MB	B	SC	S
Subsidy of public transport	MB	B	SC	S

4.2 Control Measures for Power Plants

4.2.1 Technical options

NOx control techniques can be categorized as pre-burning period and post-burning period techniques. The first, called the Low NOx Burning (LNB) Techniques, reduces NOx emissions during the coal-burning process. The second is called the Smock

Denitration Technology and reduces emissions by acting on the NOx after emission. These techniques are common in NOx control and are described below.

Low NOx Burning (LNB) Techniques

- Controlling the temperature in the Circulating Fluidized Bed Boilers (CFB): Keeping the temperature at 850~900℃ can reduce large amounts of NOx production.
- Adjusting operating parameters (AOP): NOx production can be controlled by adjusting the operating parameters in the boilers, for example, reducing the percentage of air and lowering the burning temperature
- Fuel Staging (FS). Adding air into the combustion chamber in two stages. In the first stage, adding less air than what is required to burn coal completely will reduce NOx production. Then, in the second stage, adding air to let the coal burn completely. As the temperature of the new air is lower, NOx production is reduced.
- Flue Gas Recirculation (FGR). Recycling the low temperature flue gas at the tail of the chimney by redirecting it into the combustion chamber. As this flue gas reduces both the temperature and concentration of oxygen in the air in the combustion chamber, the production of NOx is reduced.

Boilers using any kind of these techniques are called Low NOx Burning Boilers. In Beijing, most of Low NOx Burning Boilers use the FS technique.

Smock Denitration Technology

The most common smock denitration technologies are Selective Catalytic Reduction (SCR) and Selective Non-catalytic Reduction (SNCR).

Among the techniques mentioned above, Low NOx Burning Boilers using the FS technique are the most suitable for most power plant boilers and are the most commonly used in Beijing. SNCR and SCR technologies have, however, begun to be used. The former is more popular with small and medium-scale power plants while as SCR requires a large room, it is more suitable for large-scale power plants. Combining desulfurization and denitration techniques is still on trial in China, so we did not analyze its implementation in Beijing. LNB, SNCR and SCR are the main techniques considered in our cost study.

4.2.2 Categorizing the power plants

As the capacity and age of the power generators are different even in one power plant, NOx control and emission reduction costs may be different. So our study analyzed each plant unit and categorized them by production capacity and age (according to year of construction).

Production capacity

In 2005, the National Development and Revolution Commission (NDRC) set the Readjustment of the Industrial Structure Guidelines in which generator capacities below 50 MW would be eliminated by December 31st, 2006. So in our study, we categorized the generators into three groups: small-scale (50-100 MW), medium-scale (>100-300 MW) and large scale (>300 MW).

Year of construction

Air pollutant emission equipment will be different if the generators were installed at different times in China. The Tenth National Five-Year Plan ruled that generators installed after 2000 had to follow the LNB system, and the Coal-Fired Power Plant Emission Standards 2003 required that, after January 1st 2004, generators should use the Smock Denitration System. So if all the generators were installed according to these policies, we can categorize them according to three periods: before 2000, 2000 to 2003, and from 2004 onwards.

4.2.3 Different options for different kinds of power plants

LNB can suit all kinds of power production plants while SNCR is more suitable for small and medium scale plants. In our study, we assumed an emission rate of 4,000 tonnes per power plant per year, meaning that 300 MW SNCR generators will suffice. However, as the SCR system needs more space, and since the Coal-fired Power Plant Emission Standards 2003 stipulated that after January 1st, 2004, all new plants should install SCR systems, the new approved power plants are mostly large-scale. So we assumed that for large-scale power production plants (>300 MW), SCR would be an option.

4.2.4 Emission reduction efficiencies for different categories

Generally speaking, LNB, SNCR and SCR can achieve reduction efficiencies of 30-50%, 20-50% and 80-90%, respectively. Considering that the level of management of power plants in China is still not that strong, we assumed the efficiencies to be: 30%, 35%, and 80%, respectively.

Considering the combination of emission reduction equipment, we calculated the combined efficiency using the following function:

$$e_{i,t} = e_{i,t'} + (1 - e_{i,t'}) * e_{i,t''} \qquad \text{(Equation 11)}$$

where

$e_{i,t}$: source i's reduction efficiency with technique (equipment) t;

$e_{i,t'}$: source i's reduction efficiency with the first technique (equipment); and

$e_{i,t''}$: source i's reduction efficiency with added technique (equipment).

Table 4 summarizes the technical options for different types of power plants, as analyzed in this study.

Table 4. Control measures/policies for power plants

Category of power plant		Techniques already used	New technique options	Reduction efficiency (%)
Before 2000	<50 MW (coal-fired)	None	shut down	100
	50~100 MW (coal-fired)	None	LNB	30
	20~100 MW (heat power)	None	SNCR	35
		None	LNB+SNCR	54.5
		None	SNCR+LNB	54.5
	>100~300 MW	None	LNB	30
		None	SNCR	35
		None	LNB+SNCR	54.5
		None	SNCR+LNB	54.5
	>300 MW	None	LNB	30
		None	SCR	80
		None	LNB+SCR	86
		None	SCR+LNB	86
2000-2003	50~100 MW(coal-fired)	LNB	SNCR	35
	20~100 MW (heat power)	None	SNCR	35
	>100~300MW	LNB	SNCR	35
	>300 MW	LNB	SCR	80
from 2004 onwards	>100~300 MW	LNB	SNCR	35
	>300 MW	LNB	SCR	80

4.3 Paint

In developed countries such as the United States and those in Europe or developing metropolises like Beijing, paints and solvents are among the biggest emission sectors of VOC. However, the paint and solvent industry comprises too many sub-industries and sub-sectors with a variety of control measures. We could not do a complete survey of all these sub-sectors but we did estimate the emission quantities based on a large amount of oil paints used for construction (civilian/public use) and industry (mainly automobile production and renovation). We estimated that water-based paint use in Beijing was currently under 30%, far lower than the 80% used in Europe. As a result, substituting oil-based paint with water-based paint in Beijing will achieve significant VOC emissions reduction.

4.4 Gasoline Stations

VOC control options for gasoline stations include three systems: 1) Stage I of the Gasoline Vapor Recovery System (GVRS I) which is fixed to the underground oil tank and pipes connected to the oil tanks; 2) Stage II of the Gasoline Vapor Recovery System (GVRS II) which works on the refueling process by sealing the air circulation system; and 3) the Gasoline Vapor Recovery System for Vehicles (ORVR) (Figure 7). However, ORVR is much more expensive than GVRS II which has the same effect of reducing gasoline vapor and spillage.

Beijing has installed and implemented GVRS I, and since the convening of the Olympic Games, by the end of June 2008, all 1,446 gasoline stations in Beijing had installed GVRS II. As the baseline scenario in our study is based on 2007, the GVRS II is discussed here. Table 5 summarizes the types of control options (measures/policies) analyzed in our cost-effectiveness study.

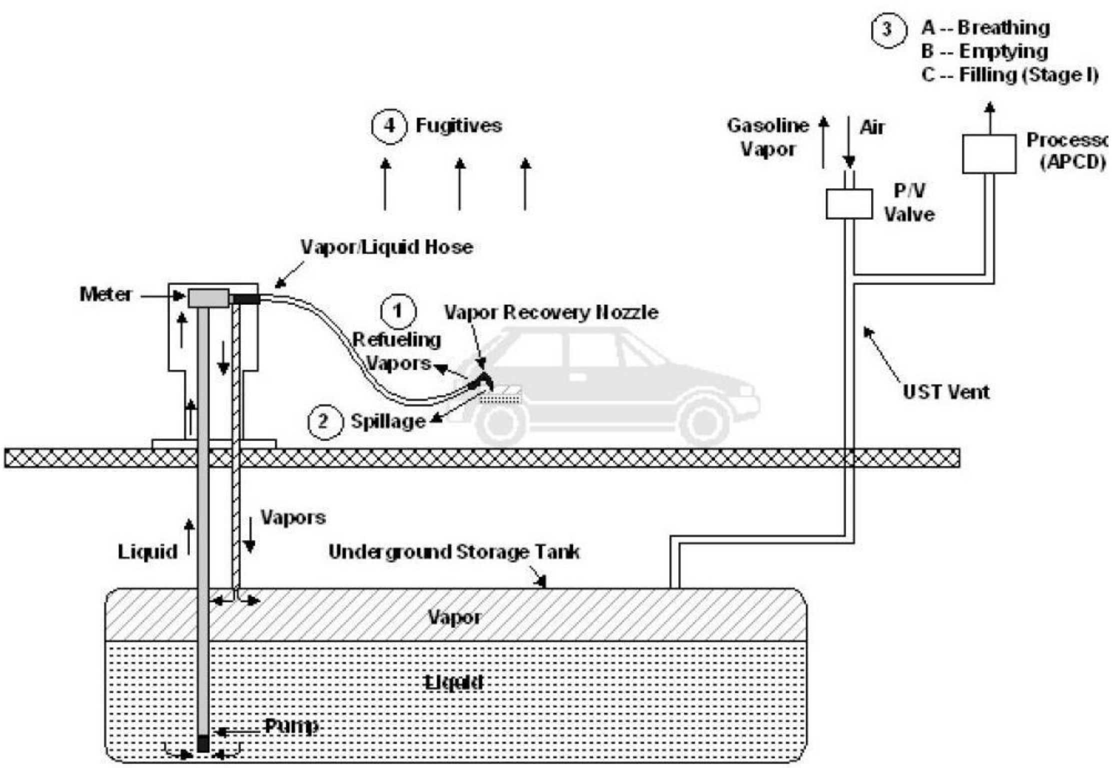

Figure 7. Gasoline vapor recovery system in a gasoline station

Source: USEPA 2004

Table 5. Control measures/policies analyzed in this study

Control options	**Explanation**	**Technical Measures (T) / Policy (P)**	**Direct (D) / Indirect costs (I) calculated**
Baseline	Business as usual scenarios in 2010 and 2015		
Changing normal buses to CNG buses	Beijing has about 10,000 gasoline and diesel buses which should be substituted by CNG buses, some of which are already being used in Beijing.	P	D
Changing old taxis to new CNSV IV taxis	Now in Beijing, most taxis meet CNSV III. However, some are old (CNSV I & II). With the high frequency of taxi use, the government should impose stricter emission standards for taxis.	P	D
Eliminating vehicle before CNSV I	Before the implementation of CNSV I, there were some vehicles in Beijing more than 8 years old, most of them with emissions exceeding the new permitted levels and which needed to be eliminated. However, the direct cost of eliminating them is not zero. We calculated the cost using the subsidy substitution method.	P	I
Equipping CNSV I vehicles with TCCs	Beijing implemented CNSV I for new car emissions in 1999. CNSV I cars were not equipped with three-way catalytic converters (TCCs). TCCs needed to be replaced after long time use. Installing TCCs or changing old TCCs to new ones can reduce emissions significantly.	T	D
Banning car use one day per week	On trial from October 2008 to April 2009, this policy is like the car use ban in Mexico City. Based on the last digit/s of the license plate number, a car will be banned from the roads one day per week.	P	I
Doubling the oil tax	China has started to use an oil tax instead of road use fee, because the price of oil and the oil tax together should reflect the whole social cost of oil use. We want to find out how much emissions can be reduced and how much the social cost will be if we double the oil tax.	P	I
Upgrading coal power plants in Beijing	To adopt different options of LNB, SNCR, SCR and their combinations for different generators for different production capacities in coal power plants in Beijing.	T	D
Upgrading coal power plants in Baoding	The same as for coal power plants in Beijing except that they are in different areas and their emission contributions to ozone concentrations are different.	T	D
			(continued)

Table 5 concluded

Upgrading coal power plants in Langfang	The same as for coal power plants in Beijing except they are in different areas and their emission contributions to ozone concentrations are different.	T	D
Upgrading coal power plants in Tianjin	The same as for coal power plants in Beijing except they are in different areas and their emission contributions to ozone concentrations are different.	T	D
GVRS II for gasoline stations	Beijing has 1,446 gasoline stations and all of them installed GVRS II before the 29th Olympic Games in China	T	D
Increasing public use of water-based paint by 20%	About 80,000 tonnes of paint were used by the public in Beijing, but less than 30% was water-based paint (compared with 80% used in Europe). We assumed the percentage increases by 20% in 2010.	P	I
Increasing industrial use of water-based paint by 20%	Almost the same situation as the above	P	I

Notes:
CNG = Compressed Natural Gas
CNSV = China's National Standard for Vehicle Emissions
TCC = Three-way Catalytic Converters
LNB = Low NOx Burning
SNCR = Selective Non-catalytic Reduction
SCR = Selective Catalytic Reduction
GVRS II = Gasoline Vapor Recovery System Stage II

5.0 OPTIMAL CONTROL PATH

We discuss the optimization process here in four steps. First, we chose the baseline scenarios, calculated the emission amounts and simulated the ozone pollution situation (using the index of Maximum Hour-Concentration of atmospheric ground-level ozone). Next, we formed the conversion factors matrix and established a relationship between local emissions and the receptor's (Beijing's) ozone concentration. Third, we set up the control targets for ozone pollution. Finally, we used the Ambient Least Cost (ALC) Model to determine the optimal control path by considering different types of control measures/policies.

5.1 Baseline and Control Scenarios

This study aimed at calculating and comparing the future effects and costs of different control measures. However, as we only had the emission sources inventory for 2005 (industrial sources) and 2007 (vehicles, paint use, gasline stations, and other sources), we could only calculate the emission amounts for 2005 or 2007. The emission amounts in the future will be different from that in 2005 or 2007 due to the development of the economy and society. We wanted to estimate the emission amounts in the future, so we created baseline scenarios, and then calculated and compared the emission reduction effects and relative costs of the control measures based on these baseline scenarios. We chose 2010 and 2015 as the baseline scenario years because we had the emissions inventory of industries for 2005 and the vehicle and other data (see in yellow above) for 2007.

China issues "Five-Year Development Plans" for social and economic development and the 11^{th} Five-Year Development Plan will end in 2010, when the 12^{th} plan will begin. The latter will end in 2015. Due to the rapid development and changes in the economy of Beijing, we could not predict too far into the future. So we choose 2010 and 2015 as the short and medium-term baseline scenarios. Due to the rapid change in policies in recent years, we conducted a detailed quantitative study for the 2010 scenario using the optimization process (described in Section 5.4) and a more qualitative analysis for the 2015 scenario. Figure 8 shows the relationships between the different scenarios while Table 6 lists the assumptions for the estimations to explain how we got the emission amounts for the baseline years 2010 and 2015 based on emission data in 2005 or 2007. Appendix 4 contains the emission calculation results for vehicles in the baseline scenarios.

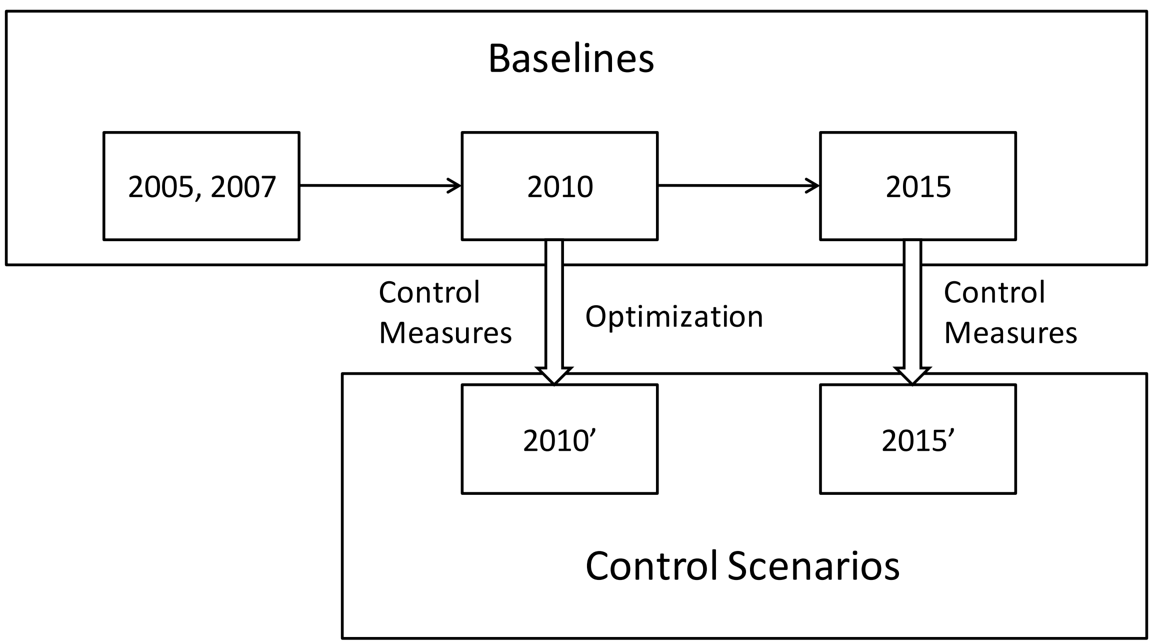

Figure 8. Baseline and control scenarios

Table 6. Assumptions for estimating the baseline scenarios

Emission sources inventory for 2005 or 2007	Assumptions for estimating the baseline scenarios in 2010 and 2015
VEHICLES (2007)	Average yearly rate of increase in the number of new vehicles in Beijing from 2007 to 2010 and 2015 is the same as from 2000-2007.
	Government starts to implement new emission standards for new vehicles every 4 years. For example, CNSV III took effect from 2004, CNSV IV started in 2008, and CNSV V will start in 2012.
	The rate of eliminating old cars is the same as for 2000-2007.
	Emission factors of different vehicles are the same as for 2007.
POWER PLANTS (2005)	All new generators are installed with SCR or SNCR, according to their capacities (based on the Coal-Fired Power Plant Emission Standards 2003 which stipulated that after January 1, 2004, all generators should use the Smock Denitration System)
	Elimination of small and old power plants according to government's five-year plan.
	The NOx reduction rate is as per the reduction rate of the equipment. (The assumption is that all the technical measures will achieve their full designed emission reduction rates, which is unlikely in the real world.)
GASOLINE STATIONS (2007)	Average increase in gasoline use in Beijing is the same as from 2000-2007.
	Gasoline volatilization/evaporation rates in gasoline stations in 2010 and 2015 are the same as in 2007
PAINT (2007)	The average increase in paint use by public and industrial sectors is the same as from 2000-2007.
	The paint volatilization/evaporation rates for public and industrial sectors in 2010 and 2015 are the same as in 2007
OTHER INDUSTRIES	New industries are built according to government's five-year plans.
	Emission factors of NOx and VOC in new industries are the same as the emission factors of similar industries in 2005

5.2 Conversion Coefficients

The conversion coefficients represent the relationships between the local emission sources and the ozone concentrations in Beijing (the receptor). We got these conversion coefficients from the pollutants atmospheric transport research data collected under the Beijing Program, which used Model3/CMAQ and Model5/CMAQ. These models simulate pollutant concentration and distribution based on the emission amounts of emission sources and meteorological predictions.

The conversion coefficients were determined by three parameters:

a) Area parameters. Downtown Beijing and the surrounding areas of Tianjin, Hebei, Shanxi and Inner Mongolia will have different influences on ozone concentration. These parameters were obtained from the atmospheric model simulation conducted in the Beijing Program.

b) Precursor parameters. By studying atmospheric models, we found that the contribution rate of local VOC concentration could be twice that of NOx, and we worked out the regression function and figures (Appendix 5 based on Liu et al. 2005).

c) High level emission sources (like power plant chimneys) and low level sources (like vehicles) have different effects, so we used Li, Hao and Hu's (2005) results.

The conversion coefficients were calculated using the following function.

$$a_{l,m,n} = c_{NOx,m,0} * a_l * a_n \quad \text{(Equation 12)}$$

where

$a_{l,m,n}$ is the conversion coefficient for the different areas, precursors and sectors in (ug/m^3)/10,000 tonnes;

$c_{NOx,m,0}$ is the ug/m^3 contribution from tonne/year reduction of NOx emission;

a_l is the precursor factor; and

a_n is the area factor.

Miao (2008) used the MM5-CAMx model and ozone source identification technology (OSAT), and simulated the contribution to ozone concentration in Beijing and surrounding areas, using motoring data from August 2006. The results revealed that downtown Beijing, Southern Hebei, and the southern city districts and counties of Beijing had the biggest effect on maximum hour average ozone concentration, with a contribution rate of 32.4%, 14.8%, and 14.5% respectively. Meanwhile, the mobile sources (vehicles), VOC unorganized sources (including paint use, gasoline stations and natural sources) and power plants contributed to Beijing's ozone volumes by 42%, 14%, and 8.5%, respectively.

For the precursor parameters, the Beijing Program had conducted sufficient and accurate studies, with one of the main conclusions being that Beijing was a VOC-dominated ozone pollution area. Due to the non-linear reaction relationship between NOx and VOC, when the concentration of NOx is sufficient, ozone concentration becomes mainly dependent on VOC concentration. The non-linear dynamic relationship between NOx and VOC is shown in Appendix 5. However, another situation could arise if the NOx concentration declines or VOC concentration increases; when the latter is sufficient, NOx can become the dominator, which means that ozone concentration will be mainly dependent on NOx concentration then. So, for long-term control strategies, NOx should be controlled with VOC as well. According to the coefficients between ozone concentration and NOx and VOC concentrations (Appendix 5), we set the contribution effect of VOC as twice the effect of NOx (shown as the different precursors' contribution in Table 7).

For high level emission sources, Li, Hao and Hu (2005) modeled the contribution of power plants and vehicles to ozone concentration in Beijing, and estimated the relationships between NOx emitters and ozone concentration. We calculated the average of their results and obtained a contribution of 8.7% from power plants and 63.9% from vehicles, and determined the relationship between ozone concentration and high-level emission sources (like power plants) and low-level emission sources (like vehicles), respectively, at 1.048(ug/m^{3})/10,000 tonnes and 7.879(ug/ m^{3})/10,000 tonnes. The conversion coefficients are shown in Table 7.

Table 7. Conversion coefficients

Different precursors		**Different types of emitters（(ug/m^{3})/10,000 ton)**		
NOx	VOC	High level (like power plants)	Low level (like vehicles)	
1	2	1.048	7.879	
Different areas				
Beijing city area	Near outskirts	Far outskirts	High-contribution areas in surrounding provinces	Medium-contribution areas in surrounding provinces
1	0.6	0.3	0.2	0.05

5.3 Control Targets

The damage effects of ozone pollution are different from other ordinary pollutants such as sulfur dioxide (SO_2) or NOx. A short-duration ozone explosion can cause disease and harm to plant life. So the World Health Organization (WHO) uses the maximum one-hour mean concentration (MHMC) measurement; every hour has a mean concentration of ozone and we choose the maximum from among the 24 hours in a day, to show the ozone pollution situation and health risk of the day. WHO set 160 ug/m^{3} as the MHMC limit for a day in the event of an ozone explosion. If the MHMC of one day is higher than 160 ug/m^{3}, there will be health risks, and such a day is called an Exceeding Day (ExD). WHO counts the number of ExDs in one year or in August (because usually the most serious ozone pollution happens in August in China due to the high temperature) to show the ozone pollution situation in different places. It also counts the total number of hours exceeding the one-hour concentration limit and calls these Exceeding Hours (ExHrs) in the whole year or in August to show the ozone pollution situation in different places. In 2005, WHO changed its air quality guidelines from the one-hour concentration limit to an eight-hour mean concentration limit because scientists proved that a longer (8 hours or more specifically) ozone explosion caused more significant damage to human health and plant life. However, in China, only air quality standards using the one-hour concentration limit for ozone pollution exist. So in this study, we only considered the MHMCs, ExDs, and ExHrs as the indices of ozone pollution.

As China's air quality standards use the one-hour limit of 160 ug/m^3 for the China Air Quality National Standard I for Ozone Concentration (CNSO I), and 200 ug/m^3 for CNSO II (almost 93 ppb), we set 160 ug/m^3 as the long-term ozone concentration limit to satisfy CNSO I and 200 ug/m^3 to satisfy CNSO II. Based on our analysis of the monitoring and observation data for 2007 under the Beijing Program (Peking University 2007), the MHMC limit for ozone reached about 326 ug/m^3. Meanwhile, we estimated the MHMCs of the 2010 and 2015 baseline scenarios at 285 ug/m^3 and 276 ug/m^3, respectively.

We also simulated the relationship between the ExHrs and MHMCs, based on the monitoring data (see Appendix 6), and we estimated the ExDs from the ExHrs using a linear relationship. Thus, we first got the ozone concentration contribution from the emission reduction calculations and conversion coefficients, then simulated the ExHrs/ExDs declines through measures/policies.

5.4 Optimization Results

Figure 9 shows the MHMC declining and the marginal average cost increasing as measures/policies are implemented one by one. The marginal average cost is the average annual cost of measures achieving one unit of ozone concentration reduction. The unit for the MHMC is ug/m^3 and the unit for the marginal average cost is million RMB.

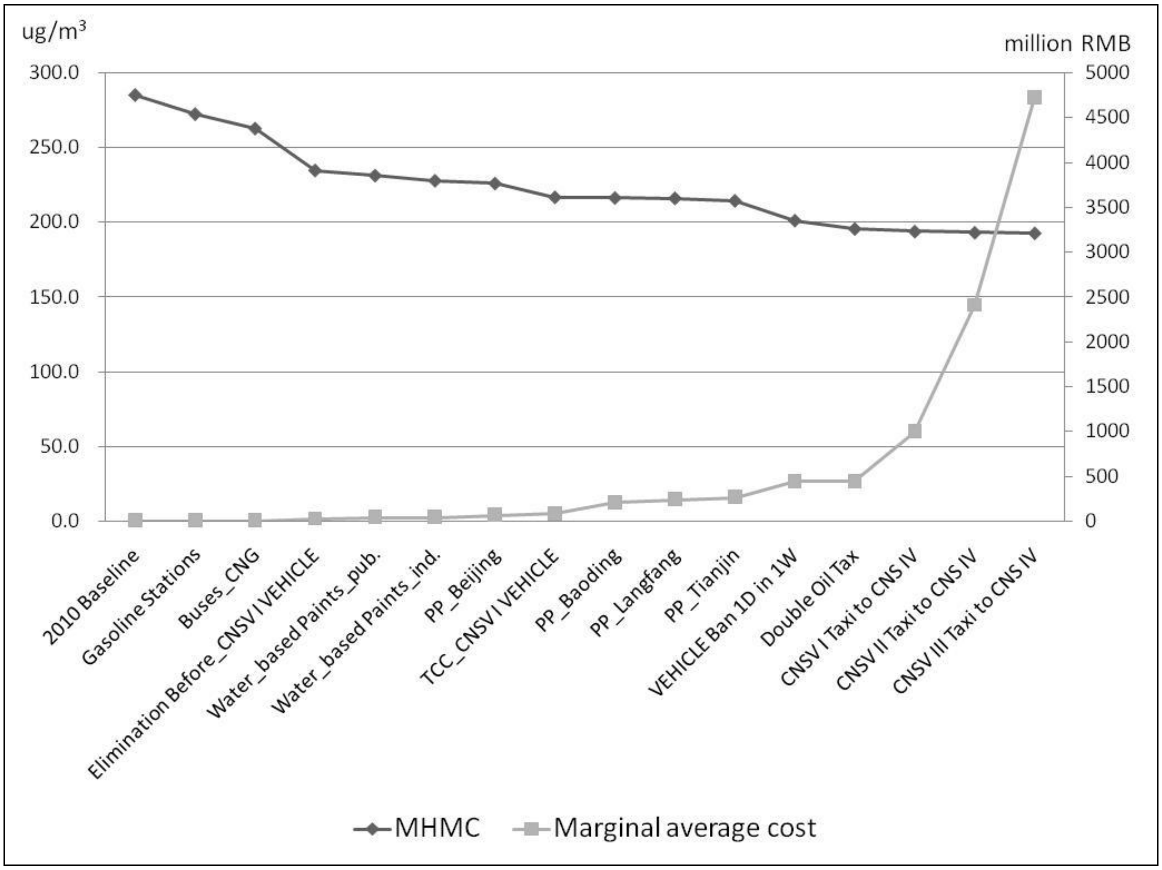

Figure 9. MHMC curve and marginal average cost curve

Notes:

2010 Baseline = Baseline scenario in 2010

Gasoline Stations = Equipping gasoline stations with Gasoline Vapor Recovery System Stage II (GVRS II)

Buses_CNG = Changing normal buses to Compressed Natural Gas (CNG) buses

Elimination Before_CNSV I VEHICLE = Eliminate vehicles that cannot meet China's National Standard for vehicle emissions (CNSV I)

Water_based Paints_pub. = Public use of water-based paint increases by 20%

Water_based Paints_ind. = Industrial use of water-based paint increases by 20%

PP_Beijing = Adopting different options of LNB, SNCR, SCR and their combinations for different generators with different production capacities in coal power plants in Beijing.

TCC_CNSV I VEHICLE = Installing TCCs or changing old TCCs to new TCCs for vehicles that meet CNSV I

PP_Baoding = Adopting different options of LNB, SNCR, SCR and their combinations for different generators with different production capacities in coal power plants in Baoding.

PP_Langfang = Adopting different options of LNB, SNCR, SCR and their combinations for different generators with different production capacities in coal power plants in Langfang.

PP_Tianjin = Adopting different options of LNB, SNCR, SCR and their combinations for different generators with different production capacities in coal power plants in Tianjin.

VEHICLE Ban 1D in 1W = Banning vehicle use one day per week
Double Oil Tax = Doubling the oil tax on all vehicles
CNSV I Taxi to CNS IV = Changing taxis meeting CNSV I to new taxis meeting CNSV IV
CNSV II Taxi to CNS IV = Changing taxis meeting CNSV II to new taxis meeting CNSV IV
CNSV III Taxi to CNS IV = Changing taxis meeting CNSV III to new taxis meeting CNSV IV

Figure 10 shows the ozone ExHrs and ExDs declining, the marginal average cost (annual cost per ug/m^3 of ozone concentration) increasing and the aggregated cost (total annual costs of all conducted measures/policies) increasing under CNSO II which is the standard generally considered in China currently while CNSO I is a higher target.

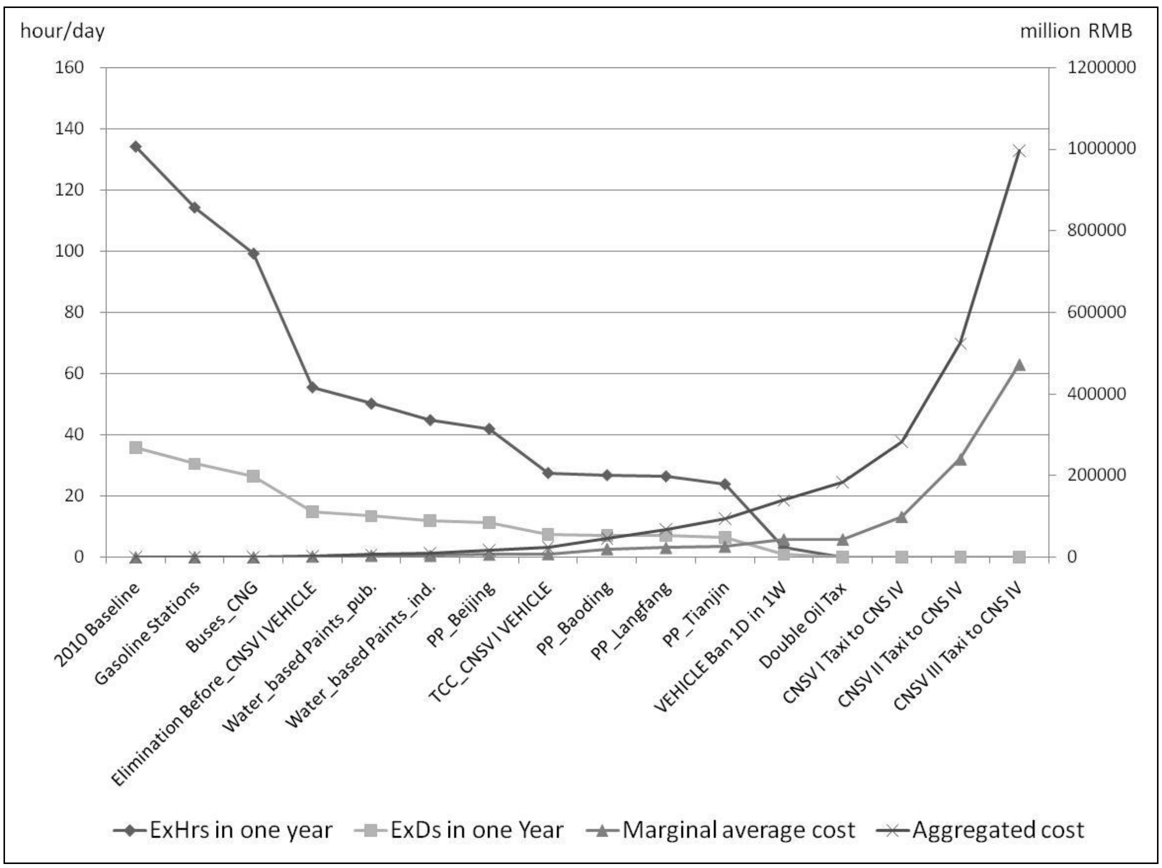

Figure 10. ExHrs, ExDs, marginal average cost and aggregated cost curves (under CNSO II)

Note: Definitions of x-axis items are the same as given for Figure 9.

Figure 11 shows the ozone ExHrs and ExDs declining and the marginal and aggregated costs increasing in reference to CNSO I (160 ug/m^3) for ozone pollution. Details of the measures and the emission reductions, ozone contributions and costs of each one can be found in Appendix 7.

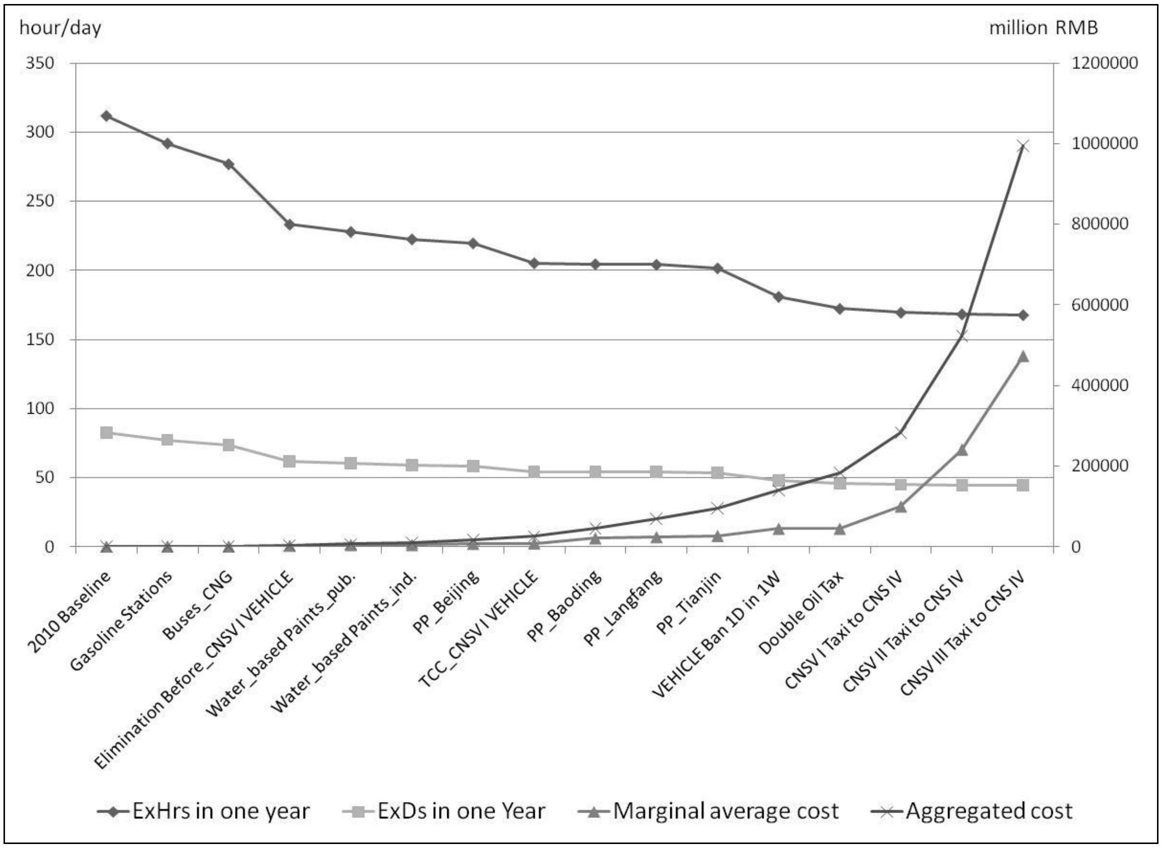

Figure 11. ExHrs, ExDs, marginal average cost and aggregated cost curves
(under CNSO I)

Note: Definitions of x-axis items are the same as given for Figure 9.

The results of the marginal average cost in Figure 9 showed that the Beijing's 1,446 gasoline stations meeting GVRS II was the most cost-effective control measure for ozone reduction in terms of the pollution situation and technical feasibility; followed by the policy to substitute Beijing's gasoline and diesel buses with CNG buses. The 20% increase in water-based paint (replacing oil paints) for civil and industrial use was also found to be cost-effective. Among all the measures, those controlling the vehicle sector, such as hastening the elimination of old cars and installing TCCs or changing old TCCs to new ones for vehicles that meet CNSV I emission standards were the most effective options, since vehicles were the largest emitters of NOx and VOC.

Also the cost of controlling vehicles was much less than controlling power plants. There are two main reasons for this. Firstly, most power plants are located out of Beijing, so their ozone concentration effect on Beijing is much less than vehicle emissions in the city. Secondly, the cost of the technology used in power plants is relatively higher. However, the regulation of vehicles carried a higher cost. According to our calculations, a double oil tax for vehicles in Beijing (a market-based policy) would be less cost-effective than a one-day ban per week on car use (a command and control measure). This is contrary to most studies such as Eskeland and Feyzioglu (1995) and Davis (2008) which have found market-based options more cost-effective than command and control ones. This is probably because in our study, the ozone concentration was considered as the only benefit of control measures. If we factor in the full loss of social welfare into the effects of the two kinds of policies, the cost-effectiveness results could be different.

In general, in comparing the two biggest sectors i.e., vehicles and power plants, we can see that vehicle control in local Beijing is much more cost-effective than power plant control in the surrounding areas. However, the latter is also necessary if greater air quality improvement is desired. As we can see in Figure 10, if the policy aim is to improve air quality to 40 ExHrs and 10 ExDs, the government should conduct the various control measures up to that of adopting different options for coal power plants in Beijing. If more ExHrs and ExDs reductions are required, the government should implement further measures of installing or changing TCCs for vehicles meeting CNSV I, controlling coal power plants in Baoding, Langfang, Tianjin and so on.

All the above quantitative analyses were based on various assumptions (Table 6). We discuss three kinds of scenarios in the following section which are closer to real-life situations: (a) measures that do not have any direct cost; (b) realistic emission reduction rates as we assumed that all the technical measures would achieve their full designed emission reduction rates which is unlikely in the real world; and (c) a sensitivity analysis (Section 6.2) using different real reduction rates, simulating the ozone concentration decrease effects and relative costs, and comparing whether the cost-effectiveness order of the measures changes. In section 6.3, we discuss the effect of changes in structure or scale of operations on ozone pollution reduction.

6.0 SCENARIOS AND POLICIES

6.1 "No Cost" Behaviors

From our field interviews and surveys, we noticed that during the refueling process in gasoline stations and during paint use, there were big emission reduction potentials generated by better behaviors such as filling up to only 90% of the tank; fitting the nozzle securely into the oil tank; and closing the cover of the paint tin immediately upon stopping spray painting. We assumed a reduction of 10% - 30% paint evaporation through these better behaviors and calculated their contribution to ozone decline.

Table 8. The effect of better behaviors on ozone reduction

Emission sources	**Reduction of volatilization/evaporation**	**Contribution to ozone concentration (ug/m^3)**
Gasoline stations	10%	1.51
	30%	4.54
Paint use	10%	4.29
	30%	12.86

Compared with the other control measures/policies, the reduction effect of better behaviors was significant with no direct or indirect costs, which means these kinds of action can be very cost-effective. However, it may take a long time of government education initiatives to form good habits.

6.2 Sensitivity Analysis of Real Reduction Rates Achieved by Technical Measures

In Section 5, we assumed the efficiency reduction rate of technical measures to be the Designed Reduction Efficiency Rate (DRR). The DRR of GVRS II equals 90%; the DRR of LNB equals 30%; the DRR of SCR equals 80%; and the DRR of SNCR equals 35%. However, we found that some equipment was not in good condition or had even been turned off during our survey. Thus, the cost-effectiveness could be much lower than we had calculated in the optimization part. The real reduction rates could also be much lower. We assumed them to be at different levels and then re-calculated the cost-effectiveness of the technical measures. Table 9 shows that gasoline stations meeting GVRS II as the best cost-effective measure falls to third ranking, and the cost-effectiveness of denitration equipment in power plants in Beijing (BJ), Baoding (BD), Langfang (LF), and Tianjin (TJ) also falling. The cost per ug/m^3 of ozone concentration decline increases significantly as the contribution to ozone decreases.

Table 9. Sensitivity analysis results of the cost-effectiveness of technical measures

Technical Measure	Efficiency	Cost-effectiveness order	Ozone concentration (ug/m^3)	Marginal average cost of measure (million RMB)
Gasoline Station	90%	2	12.76	192
	60%	3	8.51	289
	30%	3	4.25	577
PP_BJ Denitration efficiency	Baseline	7	1.85	6,746
	20% decrease	8	1.48	8,433
	50% decrease	8	0.92	13,492
PP_BD Denitration efficiency	Baseline	9	0.45	20,463
	20% decrease	9	0.36	25,578
	50% decrease	9	0.23	40,925
PP_LF Denitration efficiency	Baseline	10	0.25	23,399
	20% decrease	10	0.20	29,249
	50% decrease	12	0.12	46,798
PP_TJ Denitration efficiency	Baseline	11	1.64	26,484
	20% decrease	11	1.31	33,105
	50% decrease	13	0.82	52,968

6.3 Structural and Scale Changes

Even without any of the measures/policies we planned to use, several industrial structural changes and technical advancements during the rapid developent of China's economy have significantly contributed to air pollution reduction. We analyzed some structural and scale changes in the business-as-usual baseline scenarios in 2007, 2010, and 2015 to determine the ozone concentration reduction effects of these changes (Figure 12).

In the VEHICLE sector, without any control measures/policies (such as the elimination of old cars and substitution by new low emission cars), although the total number of vehicles was assumed to increase by 10% each year from 2007 to 2015, total NOx and VOC emissions do not increase by the average increase rate of the period 2000-2007, but rather by a much slower rate, at times even decreasing, due to the emission reduction technologies used in new vehicles.

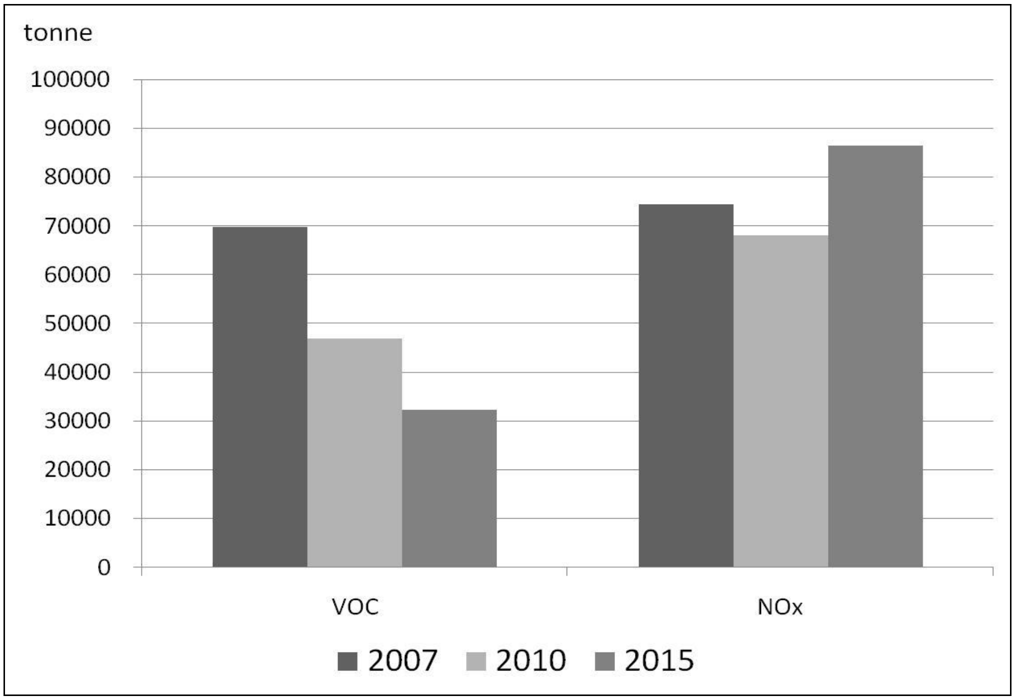

Figure 12. Emissions of baseline scenarios without any control measures/policies

The NOx and VOC emissions by different emission standards vehicles in the three baseline scenarios are shown in Table 10, which also highlights which short-term or long-term control strategies should be different. In 2007, old cars (CNSV I and before CNSV I) account for most of the NOx emissions, 65% and 17%, respectively, so the elimination or substitution of old cars would be cost-effective. But in 2010, and especially in 2015, with new and high emission limits cars dominating the market, emission contributions increase significantly. At such times, car elimination would achieve little, and the control strategy should be changed to improving new car emission limits.

Table 10. Emissions of different standard cars for baseline scenarios (in tonnes)

VOC						
	2007		**2010**		**2015**	
Standard	**Emission**	**Share**	**Emission**	**Share**	**Emission**	**Share**
Before CNSV I	45,265	**65%**	14,189	**30%**	0	0%
CNSV I	11,907	**17%**	17,292	**37%**	10,314	**32%**
CNSV II	6,426	9%	6,806	**15%**	6,806	**21%**
CNSV III	6,076	9%	5,885	**13%**	5,885	**18%**
CNSV IV	0	0%	2,729	6%	3,981	**12%**
CNSV V	0	0%	0	0%	5,261	**16%**
NOx						
Standard	**Emission**	**Share**	**Emission**	**Share**	**Emission**	**Share**
Before CNSV I	37,438	**50%**	7,112	**11%**	0	0%
CNSV I	19,593	**26%**	23,939	**35%**	14,279	**17%**
CNSV II	8,218	11%	10,747	**16%**	10,747	**12%**
CNSV III	9,126	12%	11,437	**17%**	11,437	**13%**
CNSV IV	0	0%	14,743	**22%**	21,506	**25%**
CNSV V	0	0%	0	0%	28,426	**33%**

Note: Share means the proportion of emissions from the kind of vehicle in question over the total amount of emissions from all vehicles.

In the power plants sector, shown in Figure 13, the total NOx emissions increase rate (40%) was found to be much lower than the total installed capacity, coal usage, and production capacity increase rates (93%, 69%, and 72%, respectively) from 2003 to 2007. Zhuang (2009) found the reasons to be: (a) large installed capacity power plants were built recently (under the 11th Five-Year Plan from 2006) instead of small-scale ones, and production efficiency had increased; (b) almost all new power plants were equipped with LNB; and (c) elimination policies for old and small power plants according to the Industrial Structural Adjustment Long-Term Plans.

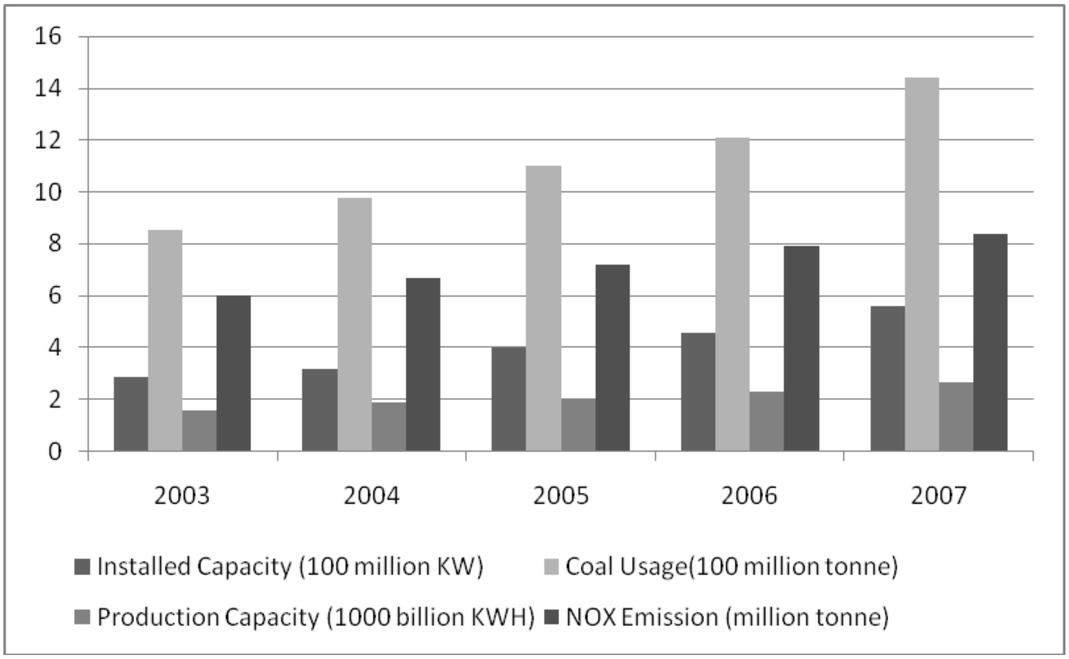

Figure 13. Power plant increases in installed capacity, coal usage, production capacity and NOx emission in Beijing areas

Source: Zhuang (2009)

7.0 CONCLUSIONS AND POLICY RECOMMENDATIONS

In this study, we first identified the main NOx and VOC emission sectors in Beijing and its surrounding areas which directly contributed to ground-level ozone pollution in Beijing. We found that power plants were the biggest emitters of NOx, followed by vehicles and chemical industries. For VOC emissions, special sources included solvent/paint usage, gasoline volatilization from gasoline stations, the coating of vehicles during production, and laundry shops. Laundry shops were the biggest emission source as a group, and vehicles and power plants were the second and third largest contributors of VOC.

Second, we identified all the feasible measures/policies in the main source sectors in Beijing and its surrounding areas using conversion coefficients and transferring NOx and VOC emission reductions to ozone concentration decline in Beijing.

Third, based on the cost analysis of all measures in different areas and sectors, we applied the Ambient Least Cost Model, and simulated the marginal ozone decline curves and marginal abatement cost curves, by considering the measures individually. Comparing the types of control measures, we found that their cost-effectiveness varied largely by area and sector, influenced by NOx and VOC emission reduction potentials, annual control costs, location (how far and which direction from Beijing), type of emission source, and different contribution rates of NOx or VOC. In order to meet certain air quality standards, all the 72 measures for the different types of emission sources should follow the cost effective order, i.e., the Optimal Control Path. Grouping the 72 measures/policies into 15 sectoral groups such as VEHICLES, POWER PLANTS, GASOLINE STATIONS, PAINT

USED, etc., with the marginal cost increasing, the cost-effective control path should be as follows:

(a) Gas Vapor Recovery System Stage II (GVRS II) used by the 1,446 gasoline stations in Beijing

(b) changing normal buses to CNG buses in Beijing

(c) eliminating old cars (before CNSV I) in Beijing

(d) increasing the use of water-based paints by civil sectors by 20% in Beijing

(e) increasing the use of water-based paints by industrial sectors by 20% in Beijing

(f) installing denitration equipment in power plants in Beijing

(g) equipping CNSV I vehicles in Beijing with three-way catalytic convertors (TCCs)

(h) installing denitration equipment in power plants in Baoding

(i) installing denitration equipment in power plants in Langfang

(j) installing denitration equipment in power plants in Tianjin

(k) implementing a vehicle ban one day per week in Beijing

(l) doubling the oil tax in Beijing

(m) substituting CNSV I taxies with CNSV IV taxis in Beijing

(n) substituting CNSV II taxies with CNSV IV taxis in Beijing

(o) substituting CNSV III taxies with CNSV IV taxis in Beijing

Fourth, we conducted semi-quantitative and qualitative analyses on Better Behaviors, Implementing Efficient Techniques, and Structural/Scale Changes in certain sectors. These measures could play important roles in ozone pollution reduction at very low or even no cost.

In conclusion, vehicles and power plants are the two most potent sectors for ground-level ozone control in Beijing. However, measures for vehicles are much more cost effective than measures for power plants. In the short term, eliminating old cars with subsidies or replacing old cars with new cars are good policy strategies. However, in the long term, as new cars with strict emission limits begin to dominate the vehicle market in Beijing, policies aiming at reducing vehicle use frequency should be the main focus. Controlling VOC sources (like gasoline stations and paint use) could be more cost-effective than controlling NOx sources, because nowadays most areas in Beijing are VOC dominated areas (ozone concentration is determined by the concentration of VOC in the atmosphere). Better Behaviors, Implementing Efficiencient Techniques, and Structural/Scale Changes could have large potential for ozone reduction at minimal costs.

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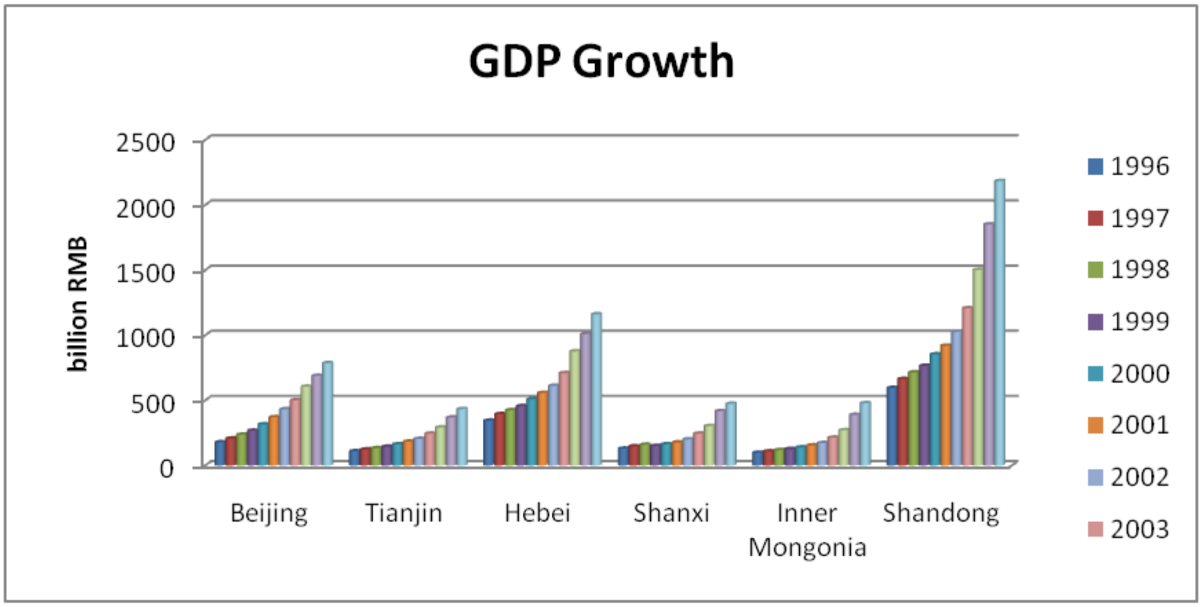
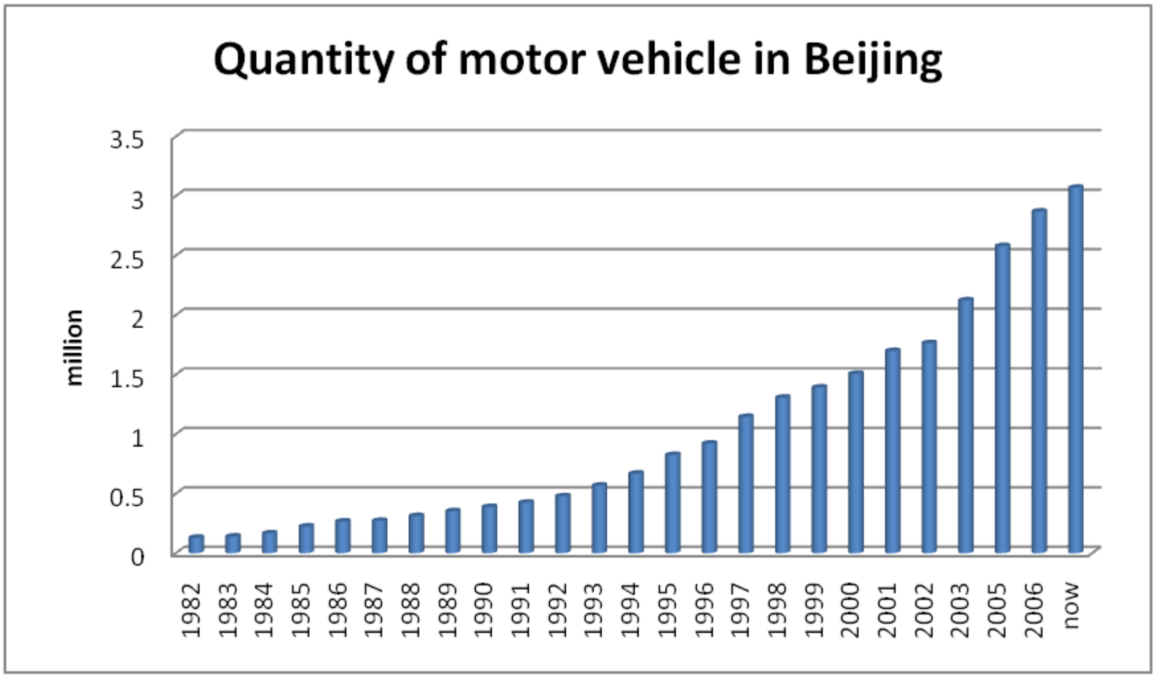
APPENDICES

Appendix 1. GDP growth in Beijing and surrounding provinces



Sources: Beijing Municipal Bureau of Statistics (1997-2004), Tianjin Municipal Bureau of Statistics (1997-2004), Hebei Bureau of Statistics, Shanxi Bureau of Statistics (1997-2004), Inner Mongonia Bureau of Statistics and Shandong Bureau of Statistics (1997-2004).

Appendix 2. Vehicle increase in Beijing



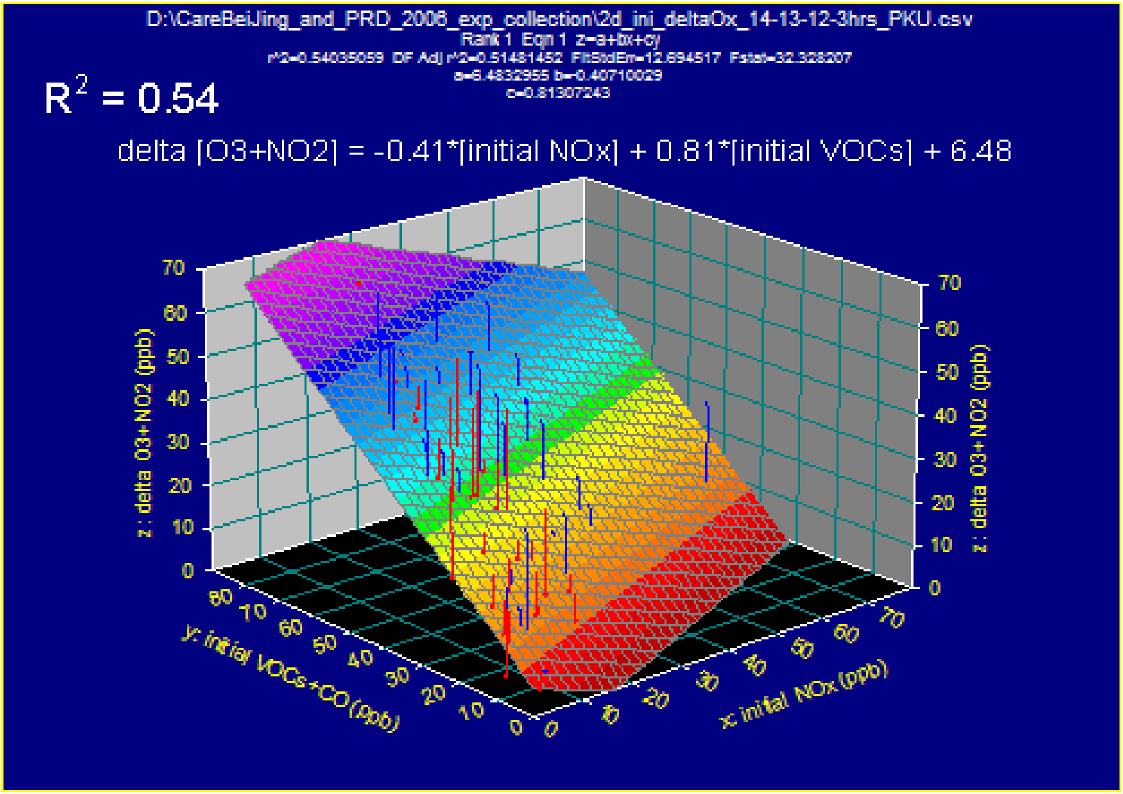
Source: Beijing Municipal Bureau of Statistics (1983-2008)

Appendix 3. Location of Beijing and surrounding provinces

Appendix 4. NOx and VOC emissions of vehicles in 2007, 2010 and 2015 (in tonnes)

VOC						
	2007		**2010**		**2015**	
Standard	**Emission**	**Share**	**Emission**	**Share**	**Emission**	**Share**
Before CNSV I	45,265	65%	14,189	30%	0	0%
CNSV I	11,907	17%	17,292	37%	10,314	32%
CNSV II	6,426	9%	6,806	15%	6,806	21%
CNSV III	6,076	9%	5,885	13%	5,885	18%
CNSV IV	0	0%	2,729	6%	3,981	12%
CNSV V	0	0%	0	0%	5,261	16%
NOx						
Standard	**Emission**	**Share**	**Emission**	**Share**	**Emission**	**Share**
Before CNSV I	37,438	50%	7,112	11%	0	0%
CNSV I	19,593	26%	23,939	35%	14,279	17%
CNSV II	8,218	11%	10,747	16%	10,747	12%
CNSV III	9,126	12%	11,437	17%	11,437	13%
CNSV IV	0	0%	14,743	22%	21,506	25%
CNSV V	0	0%	0	0%	28,426	33%

Appendix 5. The relationship between ground ozone concentration and local NOx and VOC concentrations



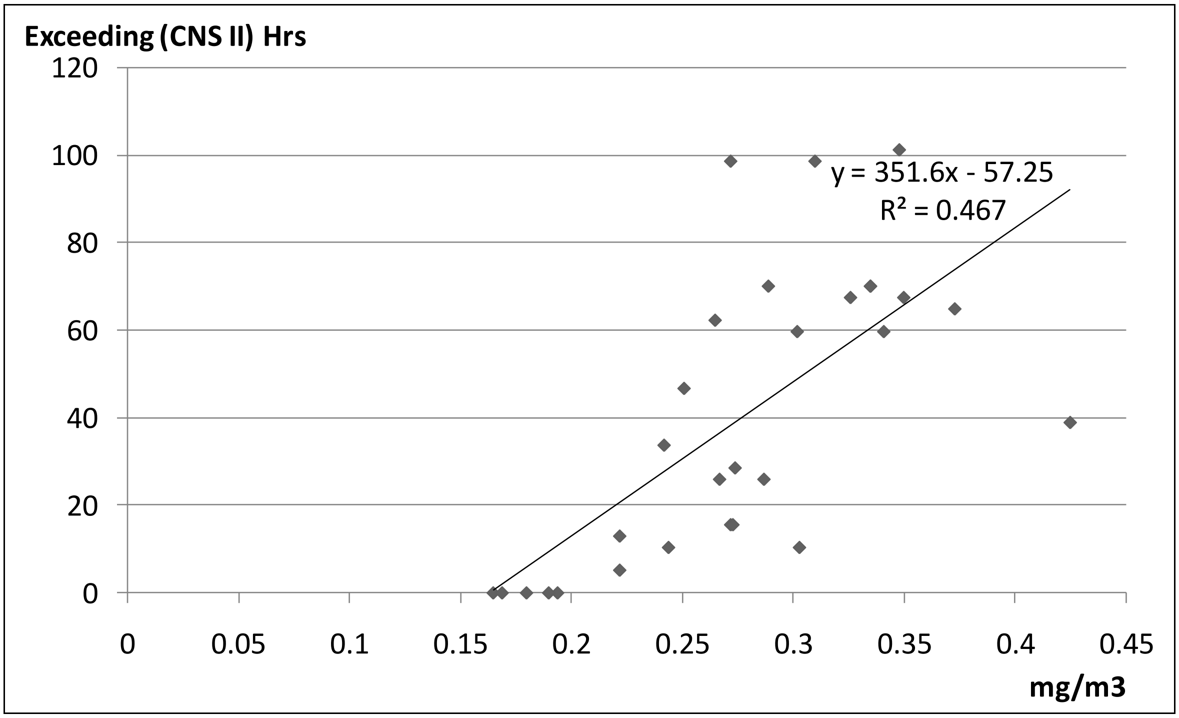
Source: Beijing Program (Peking University 2007)

Note:

In this three dimensional figure, the x-axis denotes the concentration of NOx, The y-axis denotes the concentration of VOC and CO represents the concentration of VOC, and the vertical z-axis denotes the concentration of O3 and NO2 represents the concentration of ozone.

The relationship between ground ozone concentration and local NOx and VOC concentrations is shown as the function: delta [O3+NO2] = -0.41*[initial NOx] + 0.81*[initial VOC] + 6.48

Appendix 6. The relationship between the Maximum One-hour Mean Concentration (MHMC) and Exceeding Hours in August (from 2002 to 2005)



Appendix 7. Effects and costs of all 72 control measures/policies

Sectors	Areas	Emission source	Control measure	Code of measure	Nox reduction (tonnes/ yr)	VOC reduction (tonnes/yr)	Annual cost (10,000 RMB)	O_3 concentration decline in BJ (ug/m3)	Cost per O_3 concentration decline (10,000 RMB)
VEHICLES	BEIJING	Large LPG buses	Elimination	VC_BJ_BCNSI_LPGBUS_E	515.1	318.8	86.6	0.9	95.3
VEHICLES	BEIJING	Large gasoline buses	Elimination	VC_BJ_BCNSI_GBUS_E	493.8	305.7	83.0	0.9	95.3
VEHICLES	BEIJING	Large gasoline buses	Install TCC	VC_BJ_BCNSI_GBUS_TCC	355.7	220.2	99.6	0.6	158.8
VEHICLES	BEIJING	Large LPG buses	Install TCC	VC_BJ_BCNSI_LPGBUS_TCC	371.0	229.6	103.9	0.7	158.8
GASOLINE STATIONS	BEIJING	Gasoline guns	GVRS II	GS_BJ_GG_SiiOGRS	0.0	8100.0	2455.2	12.8	192.4
VEHICLES	BEIJING	Gasoline or diesel buses	Changed to CNG	VC_BJ_BUS_CNG	9057.4	1585.5	1863.1	9.6	193.4
VEHICLES	BEIJING	Large diesel buses	Elimination	VC_BJ_BCNSI_DBUS_E	815.1	244.5	287.7	1.0	280.0
VEHICLES	BEIJING	Large gasoline passenger cars	Elimination	VC_BJ_BCNSI_LgGP_E	302.8	187.4	154.5	0.5	289.3
VEHICLES	BEIJING	Taxis	Elimination	VC_BJ_BCNSI_TAXI_E	112.5	2535.8	1469.3	4.1	359.7
VEHICLES	BEIJING	Large gasoline passenger cars	Install TCC	VC_BJ_BCNSI_LgGP_TCC	218.1	135.0	185.4	0.4	482.2
VEHICLES	BEIJING OUTSKIRTS	Large gasoline trucks	Elimination	VC_BJ_BCNSI_LgGT_E	53.1	32.8	27.1	0.1	482.2

(continued)

VEHICLES	BEIJING	Medium gasoline passenger cars	Elimination	VC_BJ_BCNSI_MGP_E	1811.4	1962.3	2322.3	4.5	513.8
VEHICLES	BEIJING	Large diesel buses	Install TCC	VC_BJ_BCNSI_DBUS_TCC	516.6	158.5	345.3	0.7	525.8
VEHICLES	BEIJING OUTSKIRTS	Medium gasoline trucks	Elimination	VC_BJ_BCNSI_MGT_E	298.7	323.6	257.5	0.4	575.9
VEHICLES	BEIJING	Medium diesel passenger cars	Elimination	VC_BJ_BCNSI_MDPP_E	253.8	66.5	205.4	0.3	674.0
VEHICLES	BEIJING OUTSKIRTS	Large gasoline trucks	Install TCC	VC_BJ_BCNSI_LgGT_TCC	38.2	23.7	32.5	0.0	803.7
VEHICLES	BEIJING	Medium gasoline passenger cars	Install TCC	VC_BJ_BCNSI_MGP_TCC	1304.6	1413.3	2787.7	3.3	856.4
VEHICLES	BEIJING	Large diesel passenger cars	Elimination	VC_BJ_BCNSI_LgDP_E	359.3	48.1	311.7	0.4	868.5
VEHICLES	BEIJING OUTSKIRTS	Medium gasoline trucks	Install TCC	VC_BJ_BCNSI_MGT_TCC	215.2	233.1	309.1	0.3	959.8
VEHICLES	BEIJING	Medium diesel passenger cars	Install TCC	VC_BJ_BCNSI_MDPP_TCC	152.3	39.9	246.6	0.2	1348.0
VEHICLES	BEIJING	Large diesel passenger cars	Install TCC	VC_BJ_BCNSI_LgDP_TCC	215.7	28.9	374.2	0.2	1736.9
VEHICLES	BEIJING OUTSKIRTS	Large diesel trucks	Elimination	VC_BJ_BCNSI_LgDT_E	351.9	40.1	493.7	0.2	2416.9
POWER PLANTS	BEIJING	Jinghua	LNB	PP_BJ_M_JH_LNB	4999.0	0.0	809.4	0.3	2574.9
VEHICLES	BEIJING OUTSKIRTS	Medium diesel trucks	Elimination	VC_BJ_BCNSI_MDT_E	242.5	56.2	518.6	0.2	3091.5
POWER PLANTS	BEIJING	Guohua Beijing	SNCR	PP_BJ_M_GH_SNCR	3308.3	0.0	766.0	0.2	3682.4
PAINTS	BEIJING	Oil-based paint	20% substitution with water-based paint	PT_BJ_CU_WB20%	0.0	2176.0	13019.6	3.4	3797.0

(continued)

PAINTS	BEIJING	Oil-based paint	20% substitution with water-based paint	PT_BJ_IU_WB20%	0.0	2176.0	13019.6	3.4	3797.0
VEHICLES	BEIJING	Small gasoline passenger cars	Elimination	VC_BJ_BCNSI_SGP_E	142.1	724.1	4799.0	1.3	3830.3
VEHICLES	BEIJING	Light gasoline passenger cars	Elimination	VC_BJ_BCNSI_LGP_E	1310.0	7115.1	48238.4	12.2	3939.7
VEHICLES	BEIJING	Taxis	Install TCC	VC_BJ_BCNSI_TAXI_TCC	208.3	168.8	1763.7	0.4	4100.8
VEHICLES	BEIJING	Light gasoline trucks	Elimination	VC_BJ_BCNSI_LGT_E	27.5	210.4	1648.2	0.4	4665.5
VEHICLES	BEIJING OUTSKIRTS	Large diesel trucks	Install TCC	VC_BJ_BCNSI_LgDT_TCC	211.2	24.1	592.7	0.1	4833.8
POWER PLANTS	TIANJIN	Guohua Panshan	LNB	PP_TJ_L_GP_LNB	5802.7	0.0	701.3	0.1	5766.0
POWER PLANTS	BEIJING	Huaneng	SNCR	PP_BJ_S_HN_SNCR	5477.1	0.0	2055.0	0.3	5966.9
VEHICLES	BEIJING OUTSKIRTS	Medium diesel trucks	Install TCC	VC_BJ_BCNSI_MDT_TCC	145.5	33.7	622.5	0.1	6183.1
POWER PLANTS	LANGFANG	Sanhe	LNB	PP_LF_L_SH_LNB	4132.6	0.0	566.2	0.1	6536.4
POWER PLANTS	TIANJIN	Junliangcheng	LNB	PP_TJ_M_JLC_LNB	5418.6	0.0	809.4	0.1	7126.6
POWER PLANTS	BEIJING	Huaneng	SNCR	PP_BJ_M_HN_SNCR	929.5	0.0	443.9	0.1	7595.1
POWER PLANTS	BAODING	Datang Baoding	SNCR	PP_BD_S_DT_SNCR	1752.9	0.0	294.8	0.0	8025.3
POWER PLANTS	BAODING	Datang Baoding	SNCR	PP_BD_S_DT_SNCR	482.0	0.0	82.3	0.0	8147.2
POWER PLANTS	TIANJIN	The first thermo-electric plant	SNCR	PP_TJ_S_1STT_SNCR	843.7	0.0	147.3	0.0	8330.7
POWER PLANTS	BEIJING	Huaneng	SNCR	PP_BJ_M_HN_SNCR	1239.3	0.0	654.5	0.1	8399.4

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POWER PLANTS	BEIJING	Datang Gaojin	SCR	PP_BJ_M_DT_SCR	11691.7	0.0	6420.3	0.7	8733.1
POWER PLANTS	TIANJIN	The first thermo-electric plant	LNB	PP_TJ_M_1STT_LNB	1446.4	0.0	267.0	0.0	8807.4
POWER PLANTS	BEIJING	Jinghua	LNB+SNCR	PP_BJ_M_JH_LNB+SNCR	1749.7	0.0	1319.7	0.1	11995.4
VEHICLES	BEIJING	Light diesel passenger cars	Elimination	VC_BJ_BCNSI_LDP_E	0.4	0.3	14.1	0.0	17356.5
POWER PLANTS	BAODING	Guohua Dingzhou	SCR	PP_BD_L_GD_SCR	19100.9	0.0	8539.2	0.4	21329.1
POWER PLANTS	TIANJIN	Datang Panshan	SCR	PP_TJ_L_DT_SCR	19803.8	0.0	9472.4	0.4	22820.2
VEHICLES	BEIJING	Light diesel trucks	Elimination	VC_BJ_BCNSI_LDT_E	22.1	16.7	1016.4	0.0	23289.7
POWER PLANTS	TIANJIN	Yangliuqing thermo-electric plant	SCR	PP_TJ_L_YLQ_SCR	9144.7	0.0	5164.9	0.2	26946.5
POWER PLANTS	TIANJIN	Guohua Panshan	LNB+SCR	PP_TJ_L_GP_LNB+SCR	10831.6	0.0	6980.1	0.2	30745.3
VEHICLES	BEIJING	Light diesel passenger cars	Install TCC	VC_BJ_BCNSI_LDP_TCC	0.3	0.2	16.9	0.0	31364.2
POWER PLANTS	LANGFANG	Sanhe	LNB+SCR	PP_LF_L_SH_LNB+SCR	7714.2	0.0	5244.0	0.2	32432.7
POWER PLANTS	TIANJIN	Junliangcheng	LNB+SNCR	PP_TJ_M_JLC_LNB+SNCR	1896.5	0.0	1390.2	0.0	34973.6
VEHICLES	BEIJING	Light gasoline passenger cars	Install TCC	VC_BJ_BCNSI_LGP_TCC	738.5	680.2	57905.0	1.7	35015.6
POWER PLANTS	TIANJIN	Chentang	SCR	PP_TJ_L_CT_SCR	5518.7	0.0	4351.6	0.1	37620.6
POWER PLANTS	TIANJIN	Dagang	SCR	PP_TJ_L_DG_SCR	11789.7	0.0	9370.5	0.2	37919.8

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POWER PLANTS	TIANJIN	Dongbeijiao thermo-electric plant	SCR	PP_TJ_L_DBJ_SCR	5233.1	0.0	4275.4	0.1	38979.0
POWER PLANTS	TIANJIN	The first thermo-electric plant	LNB+SNCR	PP_TJ_M_1STT_LNB+SNCR	506.2	0.0	420.0	0.0	39584.8
VEHICLES	BEIJING	Private cars	1 day ban in 1 week	VC_BJ_PC_1DANBAN	6881.2	4962.6	583771.9	13.2	44085.6
VEHICLES	BEIJING	Private cars	Double oil tax	VC_BJ_PC_2TIMETAX	2890.1	2084.3	245184.2	5.6	44085.6
VEHICLES	BEIJING	Light gasoline trucks	Install TCC	VC_BJ_BCNSI_LGT_TCC	20.3	17.9	1978.5	0.0	44680.0
VEHICLES	BEIJING	Light diesel trucks	Install TCC	VC_BJ_BCNSI_LDT_TCC	15.7	9.2	1220.0	0.0	45487.0
VEHICLES	BEIJING	Small gasoline passenger cars	Install TCC	VC_BJ_BCNSI_SGP_TCC	60.7	42.1	5760.7	0.1	50470.7
POWER PLANTS	BAODING	Datang Baoding	SNCR+LNB	PP_BD_S_DT_SNCR+LNB	75.7	0.0	80.2	0.0	50522.4
POWER PLANTS	BAODING	Datang Baoding	SNCR+LNB	PP_BD_S_DT_SNCR+LNB	275.5	0.0	304.9	0.0	52805.0
POWER PLANTS	TIANJIN	The first thermo-electric plant	SNCR+LNB	PP_TJ_S_1STT_SNCR+LNB	132.6	0.0	152.7	0.0	54934.0
VEHICLES	BEIJING	taxis	Change to CNSV IV	VC_BJ_CNSI_TAXI_CNSIV	833.7	710.9	176372.6	1.8	99252.4
VEHICLES	BEIJING	taxis	Change to CNSV IV	VC_BJ_CNSII_TAXI_CNSIV	91.6	426.5	179015.6	0.7	240525.6
VEHICLES	BEIJING	taxis	Change to CNSV IV	VC_BJ_CNSIII_TAXI_CNSIV	0.0	246.5	183498.4	0.4	472476.6

Appendix 7 concluded