Cost-Effective Control of Ground-Level Ozone Pollution in and around Beijing

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Abstract

Ground level ozone pollution has become a concerned air pollution problem in Beijing. 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. This paper identifies and assesses a range of options for addressing this problem. We apply the Ambient Least Cost Model and compare the economic costs of control options, then recommend the most effective sequence to realize pollution control at the lowest cost. The study finds that installing of Stage II gasoline vapor recovery system at Beijing’s 1,446 gasoline stations would be the most cost-effective option. Overall, options to reduce ozone pollution by cutting vehicular emissions are much more cost-effective than options to “clean up” coal-fired power plants.

Key words: Ground level ozone pollution, Ambient Least Cost Model, Beijing
1 Introduction

The severe ground-level ozone pollution problem as manifested by the frequently-occurring photochemical smog requires the actions to abate its precursors. However, the highly non-linear relationship between ground-level ozone and its precursors (NOx and VOCs) makes it difficult to develop effective options to abate ground-level ozone. Ground-level ozone is produced by the reaction of NOx and VOCs, and under favorable meteorological conditions ground-level ozone can be accumulated and then transported over considerable distance. The contribution of ozone transported from surrounding industrial provinces to Beijing’s ozone pollution has been identified by Streets et al. (2007), and Wang et al. (2009). Streets et al. (2007) estimated that about 35–60% of ozone during high ozone episodes can be attributed to sources outside Beijing. While Wang et al (2009) proved that the transport of ozone was responsible for about 70% of the regional ozone contribution to Beijing urban areas, and transport of ozone precursors accounted for the remainder. This regional transportation of ozone even further complicated the problem of identifying effective options to abate ozone pollution in Beijing.

Although the ground-level ozone pollution in Beijing has been identified since the 1980s (Tang et al. 1995; Sun et al., 2004; Ding et al. 2008; Xu et al. 2008), the efforts for addressing ground-level ozone pollution has been limited. In the 1980s and the earlier 1990s, the major environmental targets was “dust” and “smoke” from coal-burning which caught more attention aesthetically at that time. In the late 1990s, the deterioration of air pollution triggered the development of a “master environmental plan” for improving the air
quality in Beijing. The bidding for and staging of the 2008 Olympics had been a catalyst for the implementation of these plans. Since then, substantial efforts have been made to clean the air in Beijing. There measures include increasing access to natural gas, electricity, and geothermal energy; converting all coal-burning stoves and residential boilers to cleaner energy; and enforcing more stringent emission standards for vehicles. To assure the air quality during the Olympics meet the promised standards, additional temporary and long-term measures have been taken to improve the air quality, which include reducing coal consumption, installing emission control equipment, increasing natural gas use, tightening vehicle emission standards, and introducing airborne PM and evaporative VOC controls (Peking University 2007). Albeit these substantial efforts are being made to improve the air quality in Beijing, the long-term mechanism for abating ground-level ozone pollution has not been developed yet. As one of the precursors of ground-level ozone, nitrogen dioxide has been routinely monitored and more often than not ambient nitrogen dioxide meets the CNAAQS. Thus, in the past, the abatement of nitrogen oxides has not been among the priority list in the agenda. As the other important precursor of ground-level ozone, VOCs was given limited attention as well in the past.

Concerning of the social resource constrain, cost effective control strategies have been studied on air pollution control (e.g. Atkinson and Lewis 1974, Newell and Stavins 2003, Cofala et al 2004). However as the complicated non-linear and regional pollution process, economical control strategies for ground ozone pollution have been studied relatively much less by researchers (Krupnick and Portney 1991, Street et al. 2001, Shih et al. 2003, Guariso, Pirovanob and Volta 2004), and to our best knowledge, no similar study has been
conducted in developing countries yet. In this paper, we follow the ambient least cost model constructed by Atkinson and Lewis (1974) which is able to solve the non-uniformly mixed air pollution problems, and compare the economic costs of control options, then recommend the most effective sequence to realize pollution control at the lowest cost.

2 Methods

The Ambient Least Cost (ALC) Model is applied to track the path of selected control measures, based on the identification of pollution and emission sources as well as optional measures and their costs. The model shows the relationship between local emissions and the receptor’s ozone concentrations, and the optimization process, which are described in the following sections.

The optimization processes are discussed in four steps. First, we chose the baseline scenarios, calculated the emissions 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, the control targets for ozone pollution are set up. And finally, we used the Ambient Least Cost Model to determine the optimal control path by using different types of control measures/policies.

2.1 Baseline and Control Scenarios

This paper aimed at calculating and comparing the future effects and costs of different control measures. The emission amounts in the future are simulated based on
emission sources inventory of 2005 (industrial sources) and 2007 (vehicles, paint use, gasoline stations, and the others sources). We chose 2010 and 2015 as the baseline scenario years. Because China has the “Five-Year Development Plans” for social and economic development every five years, and the 11th Five-Year Development Plan will end in 2010, when the 12th 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.

2.2 Conversion Coefficients

An integrated assessment model for ozone pollution, like the Ambient Least Cost (ALC) Model or the Regional Air Pollution Information and Simulation (RAINS) Model, needs to be able to relate ozone concentration in receptor to changes in the emissions of ozone precursors. 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. Similar method has been applied in other researches of non-uniformly mixed air pollution problems (Krupnick and el al. 2000, Cofala and et al. 2004). 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. The conversion coefficients were determined by three parameters: Area parameters, Precursor parameters and the height of emission sources.
For the area parameters, Miao 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 vehicles sources, 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, we adopted the results of “Research on the characteristics of pollutant transportation and reaction in Beijing and surrounding areas and air quality control strategies” (hereafter named as Beijing program, Peking University 2007), with one of the main conclusions being that Beijing was a VOC-dominated ozone pollution area, which means due to the high concentration of NOx, NOx amount is excessive for the chemical reaction between NOx and VOC in the atmosphere, so the amount of VOC is limit to the ozone production. However, if the NOx concentration declines or VOC concentration increases, NOx can become the dominator. So, for long-term control strategies, NOx should be controlled with VOC too. According to the coefficients of relation function between ozone concentration and NOx and VOC concentrations, we set the contribution effect of VOC as twice as effect of NOx.

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 concentration. We calculated the average of their results and obtained a contribution of 8.7% by power plants and 63.9% by 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/m3)/10,000 tonnes and 7.879(ug/m3)/10,000 tonnes.

2.3 Control Targets

The damage effects of ozone pollution are different from other ordinary pollutants such as SO2 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 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 one-hour concentration limit for a day in the even 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 exceeding the one-hour concentration limit is called an Exceeding Day (ExD). The WHO counts the number of ExDs in one year or in August (because usually the most serious ozone pollution happens in August due to the high temperature in China) to show the ozone pollution situation in different places. It also counts the total 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 time period’s (8 hours specifically) ozone explosion caused more
significant damage to human health and plant life. However, in China, there still only exist
air quality standards using the one-hour concentration limit for ozone pollution. So in this
study, we only considered the MHMC, ExDs, and ExHrs as the indices of ozone pollution.

As China’s air quality standards use the one-hour limit, 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
maximum one hour mean concentration (MHMC) limit for ozone reached about 326 ug/m$^3$.
Meanwhile, we estimated the MHMCs of the 2010 and 2015 baseline scenarios were 285
ug/m$^3$ and 276 ug/m$^3$, respectively.

2.4 Optimization

The mathematical optimization method is based on the emissions abatement
potential, control options cost data and contribution to the recipient from emission sources,
and identifies optimal cost control scenarios to achieve the environmental objectives. The
ALC Model was first proposed by Atkinson and Lewis (1974). It minimizes the cost of
different sectors’ pollution control techniques in different areas under set constraints and
targets.

The minimum cost objective function is:
\[ MinC = \sum_{i=1}^{N} \sum_{t=1}^{T_i} (u_i * e_{i,t} * c_{i,t} * x_{i,t}) \]  

(Equation 1)

The objective function aims at total cost minimization. Equation 2 shows that the atmospheric pollutant concentration in the recipient location at least equals the reduction targets. Equations 3 and 4 show that among the control measures applied to all sources of emissions of pollutants, each source can only have one control measure.

\[ \Psi[u, e, x] \geq S_j, \forall j = 1, M \]  

(Equation 2)

\[ x_{i,t} \in \{0, 1\}, \forall i = 1, N; t = 1, T_i \]  

(Equation 3)

\[ \sum_{t=1}^{T_i} x_{i,t} = 1, \forall i = 1, N \]  

(Equation 4)

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; \( x_{i,t} \): a dummy, when using technology t it is 1, if not it is 0; j: the number of recipients; u: a set of all kinds of pollution emissions; e: a set of pollution reductions; \( \Psi \): the predicting pollutants concentration in the recipient; and \( S_j \): the reduction target.

An S-R matrix is used to predict the ozone concentration changes in the receptors from emission amount changes in sources. The S-R matrix is a 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 3 becomes as follows:

$$\sum_{i=1}^{N} \sum_{j=1}^{T} (a_{i,j} * e_{i,j} * a_{i,j} * x_{i,j}) \geq S_j \quad \forall j = 1, M$$

(Equation 5)

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

2.5 Data and calculation of emission and Cost

2.5.1 Emission data

We adopted the emission sources inventory from the Beijing program, which also includes information of emission reduction technologies and equipments, production scales and yields, to calculate the emission amount of industrial sectors in different years and scenarios. For vehicles and other VOC related sources, we followed Klimont et al. (2002)’s method (as shown in Equation 6), in accordance with the activity level and emission factors of the different emission sources. We used data on vehicle types from the 2007 Beijing Transport Annual Report, and the emission factors from the Vehicle Emission Control Center of Chinese Ministry of Environmental Protection, Hu et al. (2006), and Jing et al. (2006).
Where \(k\) denotes districts, \(l\) denotes sectors, \(m\) denote categories of fuels and production activities, \(n\) denotes equipment, \(E\) denotes VOCs emissions, \(A\) denotes activity level, \(ef\) denotes emission factor, \(\eta\) denotes removal efficiency, \(\alpha\) denotes maximum usage rate of the equipment, \(X\) denotes actual usage rate of the equipment.

2.5.2 Data and calculation of control costs

Technical options

The costs of measures generally include the investment costs \((I)\), fixed operation costs \((OM^{fix})\) and variable operation 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 7). Option cost calculation methods for other technical options are similar, except for the investment costs of construction.

The investments include the expenditure accumulated until the start-up of an installation, such as delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement 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 \(c_{i}^{f}\) and \(c_{i}^{v}\). The coefficients \(c_{i}\) of power

\[
E_{k} = \sum_{l} \sum_{m} \sum_{n} A_{k,l,m} ef_{k,l,m,n} (1 - \eta_{l,m,n} \alpha_{k,l,m,n}) \times X_{k,l,m,n}
\]

(Equation 6)
Plants are given separately for three capacity classes: from 50 to 100 MW, from 100 to 300 MW and above 300 MW. When existing plant is retrofitted with add-on controls (SCR, SNCR) investments are multiplied by a retrofit cost factor. The coefficients of investment functions describe only the costs for construction of the equipment. In order to calculate total investment costs, cost of catalyst is then added (if applicable). Since the lifetime of catalyst is much shorter than the lifetime of the plant, subsequent replacements of catalyst are included in the cost item ‘variable operating costs’.

\[
I = \left( c_{1f} + \frac{c_{1v}}{b_s} \right) + \left( c_{2f} + \frac{c_{2v}}{b_s} \right) * (1 + r) + \lambda^{cat} * c^{cat}
\]

(Equation 7)

Where \( c_{1f}, c_{1v}, c_{2f}, c_{2v} \): investment function coefficients, cited from the RAINS model; \( b_s \): boiler size; \( \lambda^{cat} \): catalyst volume (per unit of installed capacity); \( c^{cat} \): unit cost of catalysts; and \( r \): the retrofit cost factor (When existing plant is retrofitted with add-on controls (SCR, SNCR) investments are multiplied by a retrofit cost factor \( r \)).

The investments were annualized over the technical lifetime of plant \( l_t \), using the real interest rate \( q \) (in percentage) (Equation 8).

\[
I^{an} = I * \frac{(1 + q)^{l_t} * q}{(1 + q)^{l_t} - 1}
\]

(Equation 8)

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

\[
OM^{fix} = I * f
\]

(Equation 9)
The variable operation costs were calculated using Equation 10.

\[ OM_{var} = \lambda^e c^e + \eta \lambda^s c^s \]  
(Equation 10)

Where \( \lambda^e \): additional electricity demand; \( c^e \): energy price; \( \lambda^s \): demand for sorbents (materials used to absorb liquids or gases) \( c^s \): price of sorbents; \( ef \): unabated NOx emission factor; and \( \eta \): removal efficiency.

**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.
We used boiler size, production capability, coal consumption and other basic information on power plants in Beijing and the surrounding areas as provided by the Beijing Program inventory. Some cost parameters came from the GAINS online model (http://www.iiasa.ac.at/rains/gains-online.html?sb=9) 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. 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, and literatures.

2.6 Identification of feasible control measures

Control Measures for Vehicles

Taking into account the specific operating conditions in Beijing, we analyzed the following policies, requirements and measures.

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 vehicle owners increase their usage of vehicles and motorcycles, or increase the use of high-emission vehicles, and buy more new cars, these policies do no achieve emission reduction effects while incurring high implementation costs. Our study did not include such policies as
alternative control measures in Beijing's long-term arrangement. Instead we included the first and third categories, control on vehicle quantity increase and public transportation.

*Strengthening the vehicle emissions inspection and maintenance (I/M) policy in Beijing:* According to the 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 not road-worthy eliminated mandatorily. At present, China's most important vehicle exhaust gas treatment technology is the three way catalytic converter system, but some old vehicles (that meet CNSV I or CNSV II) have not been installed with ternary catalytic converters. Equipping these old vehicles with ternary catalytic converter systems can help them meet the new emission standards.

*Reducing emissions from buses and taxis:* Eliminating old buses and taxis and substituting them with clean energy ones, and improving the fuel quality.

**Control Measures for Power Plants**

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 Denitrification Technology and reduces emission by acting on the NOx after emission. These techniques are common in NOx control are described below. Low NOx Burning Boilers using the FS technique is the most suitable for most power plant boilers and is implemented most commonly in Beijing. SNCR and SCR have begun to be used, especially for small and
medium-scale power plants. As SCR requires a large fixed room, it is more suitable for large-scale power plants. Combining desulfurization and denitrification techniques is still on trial in China, so we will not analyze its implementation in Beijing. LNB, SNCR and SCR are the main techniques considered in our cost study.

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 we analyzed each plant unit and categorized them by production capacity and age (according to year of construction).

**Paint use**

In developed countries such as the United States and those in Europe or developing metropolises like Beijing, paint and solvent are one of the biggest emission sectors of VOC. However, the paint and solvent industry includes 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) and industry (mainly automobile production and renovation). We estimated that water-based paint used in Beijing was currently less than 30%, far less than the 80% used in Europe. As a result, substituting oil-based paint for water-based paint in Beijing will achieve significant VOC emissions reduction.

**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). 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 the GVRS I, and since the convening of the Olympic Games, by the end of June 2008, all 1,446 gasoline stations in Beijing completed the installation of GVRS II. As the baseline scenario in our study is based on 2007, the GVRS II is discussed here.

3 Results: Optimization of cost effective control

Conducted the Ambient Least Cost model by all control options indentified in this study, we got the results of optimal route of cost effective control. Figure 1 shows the maximum one-hour mean concentration (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 reduction in ozone concentration. The unit for MHMC is ug/m³ and the unit for the marginal average cost is million RMB.
Figure 1 MHMC curve and marginal average cost curve

Notes:

2010 Baseline = Baseline scenario in 2010

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

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

Elimination Before_CNSV I VEHICLE = Eliminate vehicles where their emission status 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 whose emission status 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 = Ban on 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 emission standards to new taxis meeting CNSV IV standards

CNSV II Taxi to CNS IV = Changing taxis meeting CNSV II emission standards to new taxis meeting CNSV IV standards

CNSV III Taxi to CNS IV = Changing taxis meeting CNSV III emission standards to new taxis meeting CNSV IV standards
The results showed that the Gasoline Vapor Recovery System Stage II (GVRS II) in Beijing’s 1,446 gasoline stations 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, 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 in Beijing is much less than vehicle emissions in the city. Secondly, the cost of the technology used in power plants was 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 the market-based options more cost-effective than command and control ones. This is 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 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 plants control in the surrounding areas. However, control over power plants in the surrounding areas is also necessary if more air quality improvement is desired.

4 Conclusions

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 conducting measures/policies individually. Comparing the types of control measures/policies, 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 from and which direction to Beijing), type of emission sources, and different contribution rates of NOx or VOC. In order to meet certain air quality standards, measures/policies for the different types of emission sources should follow the cost effective order, with the marginal cost increasing, the cost-effective control path should be as follows: (a) Stage II of the Gasoline Vapor Recovery System (GVRS II) used in 1446 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% and (e) by industrial sectors by 20%; (f) installing denitration equipments in Beijing power plants; (g) equipping CNSV I vehicles in Beijing with three-way catalytic convertors (TCC); (h) installing denitration equipments in power plants in Baoding, (i) Langfang, and (j) Tianjin; (k) implementing a Vehicle Ban
One Day Per Week in Beijing; (l) doubling the oil tax in Beijing; (m) substituting CNSV IV taxies for CNSV I, (n) CNSV II, and (o) CNSV III taxies in Beijing.

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 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).

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