Munich Personal RePEc Archive

VOCs's Cost functions in the Design of Emission Abatement Strategies

Mariam, Yohannes and Barre, Mike

1996

Online at https://mpra.ub.uni-muenchen.de/658/
MPRA Paper No. 658, posted 04 Nov 2006 UTC

VOCs's Cost functions in the Design of Emission Abatement Strategies

Yohannes K. G. Mariam
Mike Barre
Regulatory and Economic Assessment Branch
Environment Canada
351 St. Joseph Boulevard, 16th floor
Hull, Quebec
K1A OH3

VOCs's Cost functions in the Design of Emission Abatement Strategies

Abstract

VOCs and NOx are the primary precursors in the formation of ground-level ozone (SMOG). The rate of formation is a function of concentrations, temperature and sunlight strength. Both pollutants as well as the ozone itself can be transported over very long distances. Therefore, it can affect regions that are close or far from the sources of emissions. In fact approximately 50% of the ozone problem found in the Windsor - Quebec corridor can be attributed to US emissions.

Ozone can affect the health and productivity of humans, crops, forests and other ecosystems. It is now recognized that there is no thresh-hold level below which no effects are felt.

Strategies to reduce emission of VOCs involve either cost or emission optimization. Cost optimization requires the availability of abatement cost functions. The current study presents methodologies to derive cost functions for VOCs in Canada. Abatement cost functions are mathematical representations of discrete emission reduction points and their corresponding total annualized cost. The objective for which cost functions are derived determines the procedure employed in deriving cost functions. In this study, cost functions are derived based on cost estimates from engineering models by analyzing plant-level data on end-of-pipe abatement technologies and their related costs.

Emissions of VOCs were gathered by plant, by sector, by region and nationally. Commonly used, VOCs control technologies were identified. Engineering cost models were used to generate total annualized costs and the corresponding emission reduction for individual plants. The Statistical Package for Social Sciences (SPSS) software was used to fit different functional forms to the total annualized cost and removal data.

Four kinds of cost functions were derived. These include national, regional, sectoral and plant specific cost functions. The results showed that cost functions derived for the four categories indicated above, can be represented by different types of curves such as exponential, quadratic or even power. These curves could be used to facilitate the design of bilateral or multilateral, national, inter-provincial, or intra-provincial air pollution management strategies. The uses of these cost functions in pollution abatement not only treat countries, regions, sectors or plants equitably but also produce realistic cost data compared to average cost data. Furthermore, these functions could be incorporated into an integrated assessment model so that the resulting emission abatement strategies would cost the industry and/or the public minimum amount.

VOCs's Cost functions in the Design of Emission Abatement Strategies

VOCs's Cost functions in the Design of Emission Abatement Strategies

1. Introduction

Volatile Organic Compounds (VOCs) are defined as compounds containing at least one carbon atom but excluding carbon dioxide and carbon monoxide. VOCs are subgroups of the larger hydrocarbon family, but these compounds differ from other hydrocarbon species in that they can react in the atmosphere and contribute to the formation of ground-level ozone, and to a lesser extent, acid rain. Some VOCs, such as benzene, are also toxic air pollutants.

Management of emissions of VOCs is required because of the environmental and health impacts of ground-level ozone. Ozone is the prime ingredient of smog. Ozone is not emitted directly into the air but rather is formed by gases called nitrogen oxides (NOx) and volatile organic compounds (VOCs) that react with oxygen in the air in the presence of strong sunlight.

Ground-level ozone is harmful to human health, vegetation and materials (textile dyes and fibers, rubber and certain kinds of paints). When inhaled, ozone can damage the lungs. Relatively low amounts of ozone can cause chest pain, coughing, nausea, throat irritation, and congestion. It may also worsen bronchitis, heart disease, emphysema, and asthma. Furthermore, ground-level ozone interferes with the production and storage of starches within plants, reducing their growth rates. It damages the quality of crops (such as corn, wheat, and soybeans), making them less valuable on the market and can substantially reduce crop yield. Ground-level ozone also reduces the ability of trees and plants to fight disease and damage tree seedlings.

VOCs are released from natural and human sources. In Canada, natural emissions of VOCs, primarily from forests, are by far the largest source of these compounds. In the more populous and industrialized parts of the country, however, VOCs emissions from human sources can be much greater than natural emissions. Human sources of VOCs include the burning of organic materials, various industrial processes, and the evaporation of liquid fuels, solvents, and organic chemicals. Other important sources of VOCs include the application of surface coatings, drycleaning operations, vehicle exhaust emissions and fuel wood burning.

Emissions of VOCs can be reduced by regulating vehicle emissions, gasoline filling stations, industrial processes, and various other activities. However, reduction of VOCs should be matched by reductions of NOx emissions because of the non-linearity of ozone formation. To this effect there are various initiatives underway at federal and provincial levels in Canada.

Past Canadian approach with respect to VOCs emissions abatement can be viewed as single-pollutant model. This approach assumes little or no interaction with other pollutants (except NOx), and that the benefit of reducing one pollutant would not be counterbalanced or enhanced by decreases or increases in emissions of other pollutants. However, this is not reflective of the processes that take place in the atmosphere and within ecosystems. Thus, it is necessary to search for a prototype that examines multiple pollutants and multiple effects. This prototype must follow multi-disciplinary approach in designing an environmental management plan. Such a model can identify a strategy that is not only cost-effective but also results in minimal human health and ecosystem impacts.

The objective of this paper is to present past approaches to estimation of cost of reducing emissions of pollutants and how they were used to achieve environmental goals, and describe methods of deriving cost functions. The paper also discusses how these functions would be incorporated into Canada's Integrated Assessment Model and the benefit of such an approach.

2. Management of VOCs Emissions

2.1. International Issues

Ozone and its precursors are frequently transported to Canada from sources in the Northeastern United States. In fact, pollutants drifting up from the United States are the dominant factor in ozone episodes in many parts of Canada. Thus, it will obviously be necessary to reduce precursor emissions in both countries to resolve Canada's ozone-related air quality problem.

Despite the origin of pollutants, there is a need to find ways of reducing emission of VOCs and NOx in order to attain the desired ozone concentration objective. Reduction measures involve both regional (national) and interregional (international) management plans. The Convention on Long-Range Transboundary Air Pollution (LRTAP) was ratified by Canada in 1981. Under the Convention, several protocols were developed for many substances including NOx and VOCs. In fact, the protocol on the control of emissions of VOCs or their transboundary fluxes was adopted under LRTAP convention in 1991 in Geneva.

2.2. National Issues

2.2.1. The NOx/VOCs Management Plan

Nationally, the government of Canada approved a plan to attain the maximum acceptable air quality objective for ozone of 82 ppb by the year 2005. It is estimated that this would require a reduction of VOCs emissions in 2005 by about 16% compared to the 1985 level.

The NOx/VOCs Management Plan is aimed at fully resolving ground-level ozone problems in Canada by the year 2005. The Plan is intended to solve domestic NOx/VOCs related environmental problems and to meet international obligations.

The Plan was prepared through a comprehensive stakeholder consultation process to assist the allocation of emission reductions. The basic principles that were used in this process include equity and fairness, need to prevent future air quality problems and resolve existing ones, avoid undue restriction on technological innovations and choice of emission reduction options, and the ability of control options to solve more than one environmental problem.

In the early 1990's there was no empirical model or prototype to examine multi-pollutant/multi-effect issues. The principle of searching for controls which may resolve more environmental problems is based on the premise that plants that emit VOCs may also emit other pollutants. Thus, a control applied at a specific source to reduce one pollutant may result in reduction of other pollutants. While this statement is true, the Management Plan can be viewed as the traditional single-pollutant model.

The Management Plan was divided into three phases. Phase I include the establishment of a strong prevention program, setting reduction targets in ozone non-attainment areas, and undertake studies to provide the bases for setting caps for non-attainment regions for the year 2000 and 2005. Phase II of the plan establishes final NOx and VOCs caps for non-attainment regions, and identifies additional control measures for non-attainment areas. Phase III involves final adjustment to the ozone non-attainment area emission caps and emission reduction programs.

The effectiveness of the plan was thought through a reduction of NOx and VOCs by 11 and 16% by the year 2005 from the 1987 level respectively, with about 25-40% reductions in serious ozone problems areas. The plan was also expected to reduce transboundary flows of NOx and VOCs by 25 to 40% in selected areas, and about 20 to 60% reduction in some sources of VOCs because of their toxicity. Moreover, the plan was anticipated to reduce exceedances of acceptable ozone concentration by 40 to 60%. All these and other components of the plan were estimated to cost about half a billion dollars per year by the year 2005.

Review of progress made with respect to the Phase I of the Management Plan indicate that the required emissions reductions are not progressing in the desired direction. Furthermore, the committed reductions of NOx emissions have not yet materialized. Thus, ground-level ozone will continue to be an air quality problem in Canada. It means that there must be additional management plans to further reduce emissions of VOCs and NOx or to ensure the attainment of the objectives of the NOX/VOCs Management Plan. The ideal situation would be to identify a plan that is not only cost effective but also reduces human health risk and damages to ecosystems. To identify least-cost emission reduction strategy(ies), there need to be cost functions for controllable sources.

2.2.2. Multi-Pollutant/Multi-Effect Plan: Canada's Integrated Assessment Model

In the past, environmental decision making was based on scenario analysis of policy options and the design of preventive strategies using disparate single-model analysis. It was impossible to obtain a coherent and systematic analysis of an environmental issue by running a single model. Generally there are several pollutants involved in any environmental problem and a coherent solution is required to solve the problem in the most cost effective manner. Because of the codependent nature of pollutants, strategies to reduce the impact of one pollutant may actually result in an increase in the impact from another pollutant.

Considering the interconnectedness of ecosystems, best environmental protection policies would come from a holistic analysis. Often individual policy options may have repercussive effect on several ecosystems. Integrated assessment modeling enables us to examine these kinds of issues by creating logical and scientific relationships between the functioning of various ecosystems and the manner in which they respond to external stimuli (e.g., reduced deposition as a result of reduced emission).

Until very recently, integrated assessment modeling of the types used in Europe (RAINS model) or the US (TAF Model) were single pollutant-based. However, different kinds of reactions between pollutants take place in the presence of light, water, etc., while in the atmosphere or after being deposited on vegetation, soil or water. Consequently, their net impact on humans and ecosystems may be different compared to the impact from one pollutant. Thus, it is essential to examine the net effect of pollutants on ecosystems.

The trend in environmental management is a move from single pollutant to multi-pollutant/multi-effect approach. For example in June 1996, the UN-ECE Executive Body for the Convention on Long-Range Transboundary Pollution requested the task force on Integrated Assessment Modeling (IAM) to bring together current knowledge on emissions reduction options for nitrogen oxides (NOX), volatile organic compounds (VOCs) and Ammonia and their effects on acidification, eutrophication, and tropospheric ozone formation. Thus, the European prototype of IAM (RAINS) is moving toward examining multi-pollutant /effect approach. That is, the IAM would identify a strategy that simultaneously reduces acidification, ozone formation and eutrophication.

The management of ground-level ozone, despite the actual plans, presents an ideal situation for multi-pollutant/multi-effect model. NOx, besides being the major precursor in ozone formation, is an important contributor to acidification of aquatic and terrestrial ecosystems. Some sources of VOCs, besides contributing to ground-level ozone, may also be toxic pollutants. Thus, the use of integrated assessment model would enable us to examine the impact of reducing emissions on vegetation, water quality, crops, human health, buildings, etc., from reductions of NOx and VOCs. With the availability of data on emissions, depositions or concentration, source-receptor matrix or source apportionment data, costs, parameters for aquatic and terrestrial ecosystems, the IAM can be used to identify optimal emission reduction strategy(ies).

The Canadian version of IAM, also known as RAISON (Regional Analysis using Intelligent Systems on Micro Computers), was developed from being a water quality or fish model to becoming a prototype similar to RAINS. In addition to fisheries, wild life, biodiversity, forestry and water chemistry models, agricultural and socioeconomic models will be included into IAM. The IAM also incorporates outputs from atmospheric models for SO2 and NOx, uncertainty analysis, emission and depositions of nitrogen and sulfur oxides.   Not only will cost optimization be incorporated into IAM, but also appropriate software language will be written to enable IAM to interact with Environment Canada's Air Quality Valuation Model. Future development of the IAM will involve the inclusion of VOCs to enable a holistic assessment of damages to ecosystem and human health from the formation of ground-level ozone.

3. Emissions of VOCs

3.1. National, Provincial and Sectoral Emissions

About half of the estimated 1.8 million tonnes of VOCs emitted in Canada in 1985 originated from the distribution, marketing and use of gasoline. In 1990, total anthropogenic emissions of VOCs increased to 2.8 million tonnes, an increase of about 60% compared to the 1985 level. Assuming that the 1985 emissions data was accurate, the forecasted emission in the early 1990s was expected to be about 3% below the 1985 level. However, the 1990 actual VOCs emission data suggest that there has been a major increase in the emissions of VOCs. Moreover, emission from anthropogenic sources is expected to increase by about 3% by 2010 compared to the 1990 level (Table 1). Thus, there is a need for further VOCs emissions reduction in order to attain the desired ozone-related air quality objective.

Based on the 1990 emission, 91% of total emissions are produced by three sectors, incineration/miscellaneous (33%), industrial sources (30%) and transportation (28%) (Table 1). Emission levels for both the incineration/miscellaneous and industrial source sectors grew over the forecast period by 20% and 14% respectively, while emissions from the transportation sector show a decrease of 25%. The remaining two sectors, nonindustrial fuel combustion and power generation, account for 9% and less than 1% of 1990 VOCs emissions (see Table 1). Despite these changes, the relative contributions of the various sectors to total VOCs emissions have not changed significantly between 1990 and 2010.

Table 1. Forecast of Emissions of Volatile Organic Compounds by Sector

Sectors	1990	1995	2000	2005	2010
	KT(%)[1]	KT(%)	KT(%)	KT(%)	KT(%)
Incineration/Miscellaneous	926(33)	933(35)	971(36)	1035(37)	1110(38)
Industrial Sources	843(30)	857(32)	878(33)	921(33)	959(33)
Transportation	804(28)	647(24)	592(22)	584(21)	604(21)
Fuel Combustion	254(9)	239(9)	238(9)	239(9)	239(8)
Power Generation	2(0)	3(0)	3(0)	3(0)	3(0)
TOTAL	2829(100)	2679(100)	2682(100)	2782(100)	2915(100)

Source: Pollution Data Branch, Environment Canada, 1996.

[1] Where KT indicates Kilotonnes

With respect to provincial emissions, Ontario, Alberta and Quebec account for about 30, 27, and 15% of national VOCs emissions respectively (Table 2). This implies that, at least 70% of total emissions originate from these three provinces. The percentage provincial share of emission is not expected to change. However, emissions in Ontario, Alberta, British Columbia and Yukon/North West territories is anticipated to increase slightly but will decline in other provinces.

Table 2. Forecast of Emissions of Volatile Organic Compounds by Province

Provinces	1990	1995	2000	2005	2010
	KT(%)	KT(%)	KT(%)	KT(%)	KT(%)
Newfoundland	50(2)	45(2)	44(2)	44(2)	45(2)
PEI	21(1)	19(1)	19(1)	19(1)	20(1)
Nova Scotia	74(3)	66(2)	63(2)	64(2)	66(2)
New Brunswick	41(1)	37(1)	36(1)	36(1)	38(1)
Quebec	426(15)	384(14)	374(14)	382(14)	398(14)
Ontario	868(31)	791(30)	788(29)	828(30)	883(30)
Manitoba	93(3)	78(3)	77(3)	78(3)	81(3)
Saskatchewan	254(9)	238(9)	238(9)	243(9)	250(9)
Alberta	707(25)	720(27)	718(27)	735(26)	755(26)
British Columbia	257(9)	260(10)	277(10)	300(11)	326(11)
Yukon/NWT	11(0)	11(0)	11(0)	12(0)	13(0)
TOTAL	2829(100)	2679(100)	2682(100)	2782(100)	2915(100)

Source: Pollution Data Branch, Environment Canada

3.2. Emissions from Point and Area sources

Controllable sources, including mobile sources, account for only 11%, while area sources account for almost 90% of total manmade emissions of VOCs emissions in 1990 (Table 3). The share of emissions from this group of sources is not expected to change until 2010. However, natural sources such as forest fires and biogenic sources emit the largest. For example, based on 1990 emissions, emission from forest fires was about 76% and 10% of point and area source emissions respectively. Biogenic sources (excluding forest fires) emit 44 and 6 times more the emissions from point and area sources in 1990.

Table 3. Anthropogenic Emissions of VOCs from Point and Area Sources

Category	1990	(%)	1995	(%)	2000	(%)	2005	(%)	2010	(%)
Point	322.90	11.41	305.72	11.41	306.18	11.41	317.46	11.41	332.86	11.41
Area	2506.47	88.59	2373.15	88.59	2376.70	88.59	2464.25	88.59	2583.76	88.59
Total	2829.37	100.00	2678.88	100.00	2682.88	100.00	2781.71	100.00	2916.61	100.00

4. Approaches to VOCs Emission Reduction

In this section two approaches of estimating costs of VOCs emission reduction will be described. The first section will describe methods to calculate point estimates of costs while the second section presents procedures for deriving cost functions.

4.1. Sources of Data

The main source of data on air pollutants is Environment Canada's Residual Discharge Information System (RDIS). It is the result of voluntary submission of data related to pollutants by private companies, organizations or institutions to provincial Ministries of Environment. This data was the basis for the development of Environment Canada's cost and control technology database known as CANTEC.

The development of CANTEC took about three years. To obtain the most-up-to-date information on control technologies, a comprehensive search for national and international material was conducted on more than 180 on-line databases. About 250 experts from federal and provincial governments, industry, and associations were consulted to ensure that the database was correct and relevant for Canada. Furthermore various section of the study was sent to about 100 reviewers for ground-truthing the information.

CANTEC uses Standard Classification code (SCC), Standard Industrial Code (SIC), provincial code, plant identification number, contaminant code, plant capacity, plant production, capacity and production units, emissions rate, fuel type (coal, oil), unit type (boiler, heater, etc.), existing control device, exhaust gas flow rate and unit, exhaust gas temperature from RDIS. These parameters are used to calculate plant- and process-specific cost of applying specific control technologies using a well defined cost-estimating algorithms (CEA). The results from the CEA would give an order of magnitude estimates which are accurate within plus or minus 30%. For area and mobile sources, emission factors, obtained form the literature were used. During much of the data collection and generation process, a great deal of effort was directed toward obtaining as much Canadian data as possible. When possible, the cost-estimating algorithm based only on Canadian data was used.

4.2. Methodology

4.2.1. Traditional Approach (Single-Point Estimate)

To calculate the cost of reducing emissions of a specific pollutant from a given plant, Cost Estimating Algorithms (CEA) were used. These CEA vary by technology. CEA are sequential equations represented by linear, exponential, etc. functional forms (see Senes, 1995). These CEA require stack parameters such as exhaust temperature, contaminant flow concentration or type of fuel.

CEA use power law correlations to estimate capital and operating costs for control of a contaminant at a plant based on known costs at a reference plant, and the relative capacities of the plants. The equations are of the general form:

$$C_i = C_0 * (CAP_i / CAP_r)^{exp} \qquad \text{................................} \quad (1)$$

Where C_i and C_0 Refer to capital and operating costs for plant i and a reference plant (r), CAP_i and CAP_r are capacity of the plant i and reference plant (r), and exp is a value that accounts for non-linearity of the relationship (a typical value is about 0.6).

The CEA used in this study closely follows and adapts the methodology described in the Office of Air Quality Planning and Standards (OAQPS) control costs manual. The CEA are composed of two types of costs: capital, and operating and maintenance costs. Let capital cost be CC and operating costs be OC. CC include costs to purchase the equipment needed for the control system, labor and material for installation, site preparation and building, and other indirect costs. OC includes direct (DOC) and indirect costs (IOC) and recovery credits (RC). DOC are costs that vary proportionally to quantity of exhaust gas processed by the control system per unit of time. These include raw materials, electricity, water, waste treatment, disposal, parts, maintenance labor, etc. IOC are costs that do not vary with exhaust flow rate. These include administrative charges, taxes, insurance, etc. There are also costs recovered (RC) as a result of recycling or reusing. The value of these credits must also be offset by the cost of their processing, storage, transportation, etc.

$$OC = DOC + IOC - RC \qquad \text{..} \quad (2)$$

In order to evenly distribute fixed initial investments over several years and derive uniform costs on a yearly basis, the capital costs have to be converted into yearly flow rates. That is, the OC and CC would be used to calculate the annualized cost of abatement using the following equation:

$$ANC=OC+[CC*K(r)] \quad \text{.. (3)}$$

Where ANC is total annualized cost, K(r) is a capital recovery factor which converts capital costs to an equivalent stream of equal annual future payments. The anualization of costs is considered to be end-of-year payments in constant (real) dollars which do not reflect the effects of inflation.

$$K(r)= r/(1-(1+r)^{-t} \quad \text{.. (4)}$$

Where t is the economic life of the control system, and r is a real interest rate. The real interest rate or discount rate is given as:

$$r=(1+i)/(1+I)^{-1} \quad \text{.. (5)}$$

Where i is the annual or nominal market rate of interest and I is the inflation rate. The discount rate is chosen as a function of a sector, based on weighted average cost of capital (WACC) concept. WACC is used instead of the discount rate to account sector variability in funding environments (see Senes, 1995).

The parameters to be used in CEA for mobile sources are not the same as those used for stationary sources. The principal distinction between costing stationary and a mobile source is that in the latter it is not feasible to retrofit or change all vehicles on the road at once. This implies that there will be a gradual replacement of old cars and purchases of new ones. The cost of introducing new technologies is dependent on the number of new cars purchased. The total cost is assumed to be cost accumulated over the year until all vehicles are replaced and being controlled. MOBILE 5.1C, a program that calculates emission and other parameters from mobile sources, was used to provide essential information to calculate cost of controlling emission from the transportation sector.

Given the number of new vehicles(V), the total cost per year is given by:

$$C_t = (P_{veh,t} * V_t) \qquad \text{...(6)}$$

where C_t is total cost of implementing a specific control technology in year t, $P_{veh,t}$ is the price of a vehicle in year t and V_t is the number of new vehicles in year t.

$$P_{veh,t} = (P_{veh,t})_{t-1} - (P_{veh,t})_{t-1} * (EXP) \qquad \text{...........(7)}$$

Where EXP is a truncated continuous variable that lie between 0 and 1, and indicates the rate of learning or experience in which the cost of implementing control technology declines as experience or learning time increases.

Annualizing investments into equal end-of-year payments enable us to compare costs of several control technologies. Given the annualized costs and removal efficiencies of control technologies,
four kinds of decision parameters can be obtained from CANTEC without resorting to cost functions. These parameters are either quantity, control technology or cost related. These include:
I) Lowest Achievable Emissions rate (LAER): this parameter identifies a control technology which offers the highest emission removal rate regardless of whether a cost calculation has been done.
ii) Lowest Achievable Emission rate-cost (LAER-C): this parameter identifies the lowest achievable emission rate for control technologies for which costs are calculated.
iii) Lowest Cost Effectiveness (LCeff): this parameter indicates a control technology which is most cost effective, that is a technology with the lowest cost per tonne of pollutant removal.
iv) Lowest Cost (LC): this parameter indicates the control technology which is the least expensive.

Environmental management decisions at federal or provincial level in Canada have been based on the principle of Best Available Control Technology (BACT) or Best Available Control Technology Economically Achievable (BACTEA). These principles are related to either technology, cost or both. They are also linked to the above parameters that are computed from CANTEC.

The four parameters identified above have been used to determine either the minimal emission reduction possible or the minimal cost of reducing emissions given the availability of efficient technologies. However, most strategies have tended to rely on the cost-effective parameter. This parameter gives a point estimate of cost per tonne of pollutant removed. This point estimate is not amenable to derive cost function at a plant level. However, it has been used to derive aggregate sector, province, region or national cost functions.

4.2.2. Multi-Pollutant/Multi-Effect Management Plan

Cost functions are mathematical representations of combinations of discrete emission reduction points and their corresponding total annualized cost. Each point on the curve represents minimal cost of removal. Each level of removal corresponds to a particular control technology with a given level of removal efficiency.

Cost functions for policy analysis could be derived from a minimal amount of data as opposed to cost functions for engineering type site-specific analysis. Plant-specific engineering data for Canadian VOCs emitters was obtained from RDIS (Residual Discharge Information System) of Environment Canada. Naturally, these sets of information are by far less than what is required for detailed engineering cost function analysis.

Cost functions derived without plant-level detailed engineering data are accurate ±30%. This is based on more or less better understanding of the controls available, operating environment, policies, markets, etc. Prediction of the type of future control technologies is possible. However, where and how technologies might be used, what kind of policy would exist, domestic and international markets, etc. cannot be predicted with any degree of certainty. Consequently, we have to base our analysis based on what is known. That is, from our knowledge of current technologies and operating business environment. Experts in the industry indicated that the cost of control technologies will continue to decline in the future. Therefore, cost functions derived based on existing situations (status quo) would form an upper bound to determine the cost of current or future emission reductions.

Several steps were followed in deriving VOCs cost functions. The costs of abatement are derived at a process level. At each level of removal, the incremental cost of switching to a more efficient control is calculated for each process. Controls that are more expensive but less efficient are eliminated. Incremental reduction and cost will then be calculated for each control. The control with the lowest incremental cost among the next least efficient controls in each process is selected. The process will continue until all options are exhausted. The resulting data would be cumulative costs and their corresponding emissions reductions. The cumulative costs and reductions could, in most cases, be represented by a monotonically increasing function. Mathematically,

$$C_i = \text{Min } \Sigma c_{ij} s_{ij} \qquad \text{...(8)}$$

Where C_i is total cost of abatement at source i, c_{ij} is the cost of implementing control technology j by source i, and s_{ij} is a binary variable taking 1 if source i adopts control j and 0 otherwise. Equation (8) will identify controls until the following condition is satisfied:

$$\Sigma e_{ij} s_{ij} > E_{target,i} \qquad \text{...(9)}$$

Where e_{ij} is reduction at source i associated with the control j, and $E_{target,i}$ is a total reduction requirement (target) of source i . Equation (9) implies that sources will continue to adopt controls until the desired reduction is at least equal to the targeted reduction.

In summary, for each source subject to control, control technologies and the capital and operating cost of applying these technologies were identified. The capital costs are annualized and added to annual operating costs. This yields a total annual cost. Then, the emission reduction associated with each of the sources is calculated based on a representative removal efficiency. For each source, the ratio of cost to emission reduction is calculated. It is important to note that the unit or average cost in $ per ton of VOCs removed is a strong function of the amount of removal. A source with relatively low emissions will have a high average cost. Control of such sources is less cost effective than control of larger sources. The cost per tonne of VOCs reduced is used to rank all sources in a given region according to cost effectiveness of control. Then, each control is added one at a time in order of increasing average cost and effectiveness. The resulting incremental cost and reduction are compiled by plants, sub-sectors, sectors and provinces.

Once the cumulative incremental costs and reductions are derived, functional form of the following type was fitted to the data set:

$$C_i = f(E_i) \qquad \text{...(10)}$$

Where C_i is the cumulative incremental cost for source i and E_i is the corresponding reduction achieved at source i.

Several functional forms (e.g., quadratic, exponential, logarithmic, cubic, power, etc.) were fitted to each data set. The functional form that best mimics the actual observation was chosen. Selected findings of the analysis are presented for the purposes of exposition (see Tables 4, 5, 6 and 7). In addition, sample charts are provided in Appendix A.

The findings indicated that most of the data set can be described by either quadratic or exponential functions. However, cubic and power functions have also been found to be the best fit in a few cases. An important observation is that the functions for plants, sectors, sub-sectors or provinces show significant variations with respect to the magnitude of the estimated parameters. This implies that there will be comparative advantages for plants, sectors, or provinces to trade or use other economic instruments to attain the targeted VOCs emissions reduction in a cost-effective manner.

Table 4. Selected Estimates of VOCs Cost Functions for Selected for Plants		
Plant ID	Functional Form	Remark
1	$77716919.54-83175.95X+ 21.02X^2$, R^2=.92, F(29,2)=0.0001	
2	$24489617.3-44108.66X+8.484X^2$, R^2=.85, F(43,2)=0001	
3	$3946380.27-10663.55X+ 2.345X^2$, R^2=.64, F(46,2)=.00001	
4	$9604626.36 -34061.92X+9.29X^2$, R^2=.87, F(39, 2)=0.00001	
5	$-2332605.29+30904.4X-23.234X^2+.004x^3$, R^2=.92 F(41,2)=.0001	

Table 5. Selected Estimates of VOCs Cost Functions for Selected for Sub-Sectors		
Sub-Sectors	Functional Form	Remark
Diesel Agriculture/Construction	$-1471376568.81+2993319X-13.14X^2$ R2= .99 F(6,2)=0.0344	
Fuel Marketing - Other	$2.745X^{1.86}$ R2=.98,F(12,1)=.00001	
Fuel Transfer-Motor Vehicles	$12052744.51-9913.46X+14.09X^2$, R2=.99, F(5,2)=.0001	
Fuel Transfer-Tank Truck	$20939.5\exp^{.0009X}$, R2=.99, F(14,1)=0.0001	
Iron/Steel Production	$182181.59\exp^{.0002X}$, R2=.91, F(5,1)=0.001	
Petrochemicals-Process	$10172.98\exp^{.0014X}$, R2=.92, F(51,1)=0.0001	
Petroleum Refining-Fugitive	$92614048.89-24946.11X+.74X^2$, R2=.79, F(40,2)=0.0002	
Petroleum Refining-Storage	$37945161.84-18621.41X+2.09X^2$, R2=.74, F(80,2)=0.0008	
Plastics Fabrication-Process	$33.49\exp^{.002x,}$ R2=.98, F(74,1)=.0001	
Plywood/Veneer	$-346441766.09+3.363X^2$, R2=.99, F(7,1)=0.0001	
Residential Combustion	$-9073798.96+1006.46X-.0018X^2$, R2=.99, F(7,2)=0.0004	
Underground Tanks-Breath Losses	$4623179.48-5919.14X+1.598X^2$, R2=.99, F(23,2)=0.0002	

Table 6. Selected Estimates of VOCs Cost Functions for Selected for Sectors		
Sector	Functional Form	Remark
Miscellaneous	$90262476.3-28654.98X + .948X^2$, R2=.89, F(226,2)=0.0001	
Industrial	$797013023.28-47032.5X+.422X^2$, R2=.83, F(492, 2)=0.0001	

Transport	$-195121870.4+35380.23X-.123X^{2}$, R2=0.99, F(8,2)=0.0001	
Residential/commercial	$-9073798.96+1006.46X-.0018X^{2}$, R2=.99, F(7,2)=.0004	

Table 7. Selected Estimates of VOCs Cost Functions for Selected for Provinces

Province	Functional Form	Remark
Alberta	$44916050.74-14154.68X+.785X^{2}$, R2=.98, F(212,2)=0.00001	
British Columbia	$112682538.18-41579.86X+3.01X^{2}$, R2=.99, F(87,2)=0.0002	
Manitoba	$7139159.35-10683.76X+2.18X^{2}$, R2=.99, F(66,2)=0.0001	
New Brunswick	$37345.93exp^{.003X}$, R2=.98, F(43,1)=0.0001	
Nova Scotia	$27051705.43-17484.71X+.924X^{2}$, R2=.85, F(49,2)=0.0001	
North West	$2703411.05-18170.67X+3.88X^{2}$, R2=.56, F(70,2)=0.0001	
Ontario	$292969312.2-21993.19X+.1813X^{2}$, R2=.89, F(370,2)=0.0002	
Prince Edward Island	$35702.05exp^{.0008X}$, R2=.94, F(39,1)=0.0001	
Quebec	$453882320.12-43036.92X+.609X^{2}$, R2=.91, F(251,2) =0.00001	
Saskatchewan	$12991466.99-10125.13X+1.454X^{2}$, R2=.99, F(70,2)=0.0001	
Yukon	$8619.07^{exp0.031X}$, R2=.93, F(23,1)=0.0002	
National	$776823869.64-24331.72X+.0863X^{2}$, R2=.94, F(1412,2)=0.0001	

5. Approaches to Incorporation of VOCs Cost Functions into the Integrated Assessment Model (IAM)

Canada's prototype IAM is being developed to incorporate linear and nonlinear cost functions. It is intended to include VOCs into the IAM. However, information such as cost functions and atmospheric inputs such as those linking sources to concentration levels, and chemical and physical processes that characterize NOx, VOCs and SO2 are required to run the full scale IAM platform. With the availability of such information, the Canadian prototype should be able to produce results that resemble outputs from the RAINS model.

The cost functions are incorporated into the IAM via an optimization scheme. There are several kinds of optimization models. These models could minimize concentration levels, cost of attaining certain concentration levels, etc. Common to most models is that they are single-objective optimization schemes. That is, their objective function is either minimization of cost or concentration. Realistic assessment of pollution abatement strategies cannot be accomplished using a framework based on a single criterion or objective. Multiobjective optimization models promote appropriate roles for participants in planning and decision-making processes, enable identification of a wide range of alternatives and provide a more realistic perception of the problem because of inclusion of many objectives. Therefore, a simple yet realistic multiobjective optimization model can be used to incorporate VOCs cost functions into the IAM. This model assumes that it may not be feasible to attain the desired ozone-related air quality objective. Therefore, allowances are made for over or under-achieving the ozone concentration levels. The optimization scheme can be called least-cost concentration-relaxed model.

Following Ellis (1988, 1990), the mathematical formulation for least-cost concentration-relaxed model is given as:

$$\text{Minimize } (z_1 + z_2 + z_3) = Z = \sum_{i=1}^{n} C_i R_i + \sum_{i=1}^{n} LC_i \lambda_i + \sum_{j=1}^{m} (W_j^{\,u} U_j + W_j^{\,v} V_j) \quad \text{.........................(11)}$$

Subject to:

$$\sum_{i=1}^{n} (EC_i - R_i) T_{ij} + \sum_{k=1}^{o} EU_k T_{kj} + BD_j - V_j + U_j \leq (1+\mu_j) CL_j \quad \text{..........................(12)}$$

$$R_m = \Delta(EC_m + EU_m) \quad \text{..........................(13)}$$

$$0 \leq \lambda_I \leq 1 \quad \text{..........................(14)}$$

$$\sum_{i=1}^{n} R_i = EA \quad \text{..........................(15)}$$

$$R_i \geq 0 \quad \text{..........................(16)}$$

$$0 \leq V_j \leq \mu_j CL_j \quad \text{..........................(17)}$$

$$0 \leq \mu_j \leq 1 \quad \text{...........................(18)}$$

$$U_j \geq 0, \ \forall j \quad \text{................................(19)}$$

Where W_j's are user-specified objective function weights for affected region j (j=1...m), C_i is the marginal cost of emission removal at controlled point source(EC) i (i=1... n), R_i is the amount of emission removed from controlled source i (decision variable), EC_i is existing emission rate at controllable source i, T_{ij} is the unit transfer coefficient that relates the rate of concentration at receptor j and the rate of emission from controllable source i , EU_k is existing emission rate at non-controllable source k (k=1...o), T_{kj} is transfer coefficient that links affected area j and uncontrollable source k, BD_j background concentration level at affected area j, AD_j is the maximum allowable concentration rate at area j; CL_J is ambient concentration level at affected area j; U_j is the magnitude of over achievement (concentration less than the ambient) at affected area j, V_j is the magnitude of violation (concentration exceeding ambient) at affected area j , EA is predetermined aggregate emission reduction level, LC_i is employment at a point source i, λ_i is the proportion of losses in employment as a result of the chosen control option at source i and μ_j is the proportion of violation of ambient concentration at receptor j. Equation 13 states that the amount of pollutant removed from source m should be a certain percentage or fraction (Δ) of total unabated emission from source m. The reason for inclusion of this constraint is that some regions or sources of emission may have already implemented control strategies to satisfy the regional emission quota while others may have not. This constraint, therefore, avoids an unnecessary burden to those sources of emission that have made progress toward cleaner environment. The above formulation can be modified to include constraints specific to each affected area or sources of emission. Equation 17 sets an upper limit to the violation of concentration. Equations 11 to 19 could be simplified by dropping the underachievement variable (U) and others as may be necessitated by the availability of the data set.

This equation will be incorporated into the IAM prototype so that the selected feasible emission reduction strategy will satisfy socioeconomic and environmental criteria that are included in the optimization scheme as constraints. Since the cost functions as well as the optimization scheme could be linear or nonlinear, the IAM prototype is being developed to run nonlinear models. With the completion of this development, and availability of data from atmospheric research service of Environment Canada, the IAM prototype can be run to select strategies in a multi-pollutant/multi-effect platform.

6. Conclusions/recommendations

The discussion in this paper indicates that the NOx/VOCs Management Plan is not progressing toward the attainment of the targeted emission reductions. While non-controllable or biogenic sources continue to be the major sources of emissions, emissions from anthropogenic sources may greatly influence urban-air Quality problems.

Canada will continue to have ozone-related air quality problems as long as i) emissions of VOCs, continue to increase, ii) transboundary flows of VOCs emissions are not reduced, iii) reductions in NOx are less than adequate, and iv) similar air Quality standard is set in the USA. Past approaches to management plans, that is the use of a single-point estimate of costs to determine cost of abatement or feasible reductions, should be modified. Multi-pollutant/multi-effect approach should be adopted to provide an optimal holistic solution, that is to identify a strategy that is not only cost effective but also results in reduced human health risk and damages to aquatic and terrestrial ecosystems. Control measures for sources of emissions, their costs, expected benefits, etc., can only be modeled in a holistic manner if Canada's prototype Integrated Assessment Model is utilized. Without such model, the resulting strategies would be less than optimal or would not be globally optimal. That is, they would not bring the maximum environmental benefit from any measure that relies on a single pollutant management plan.

7. References

Eaton, B. P, Gray, G. A., Johnson, W.P., and Hundert, E. , 1993. State of the Environment in the Atlantic Region , Environment Canada, Atlantic Region

Ellis, J.H. 1988. Multiobjective mathematical programming models for acid rain control, European J. Operations research, 35:365-377.

Ellis, J. H. 1990. Integrating multiple long-range transport models into optimization methodologies for acid rain policy analysis. European J. Operations research, 46:313-321.

Environment Canada, 1990. Management Plan for Nitrogen Oxides and Volatile organic Compounds, Phase I.

Environment Canada, 1996. Data on VOCs Emissions Forecast., Pollution Data Analysis Division.

SENES, 1995. Canadian Control Technology Costing Study for NOX, VOCs, and SO2.

8. Appendix

Figure 1:

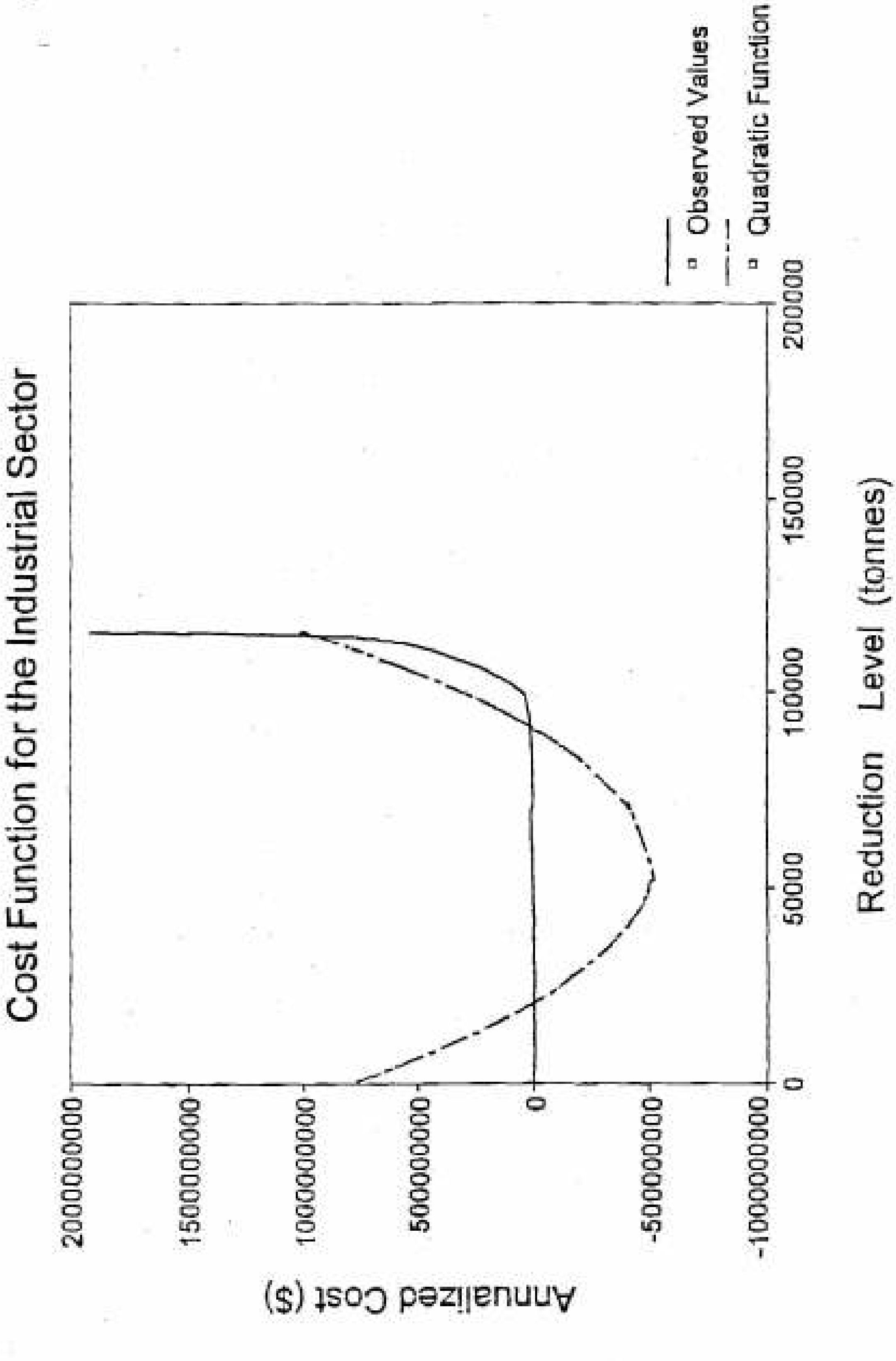

Cost Function for the Industrial Sector
Annualized Cost ($)
2000000000
1500000000
1000000000
500000000
0
-500000000
-1000000000
0
50000
100000
150000
200000
Reduction Level (tonnes)
Observed Values
Quadratic Function

Figure 2:

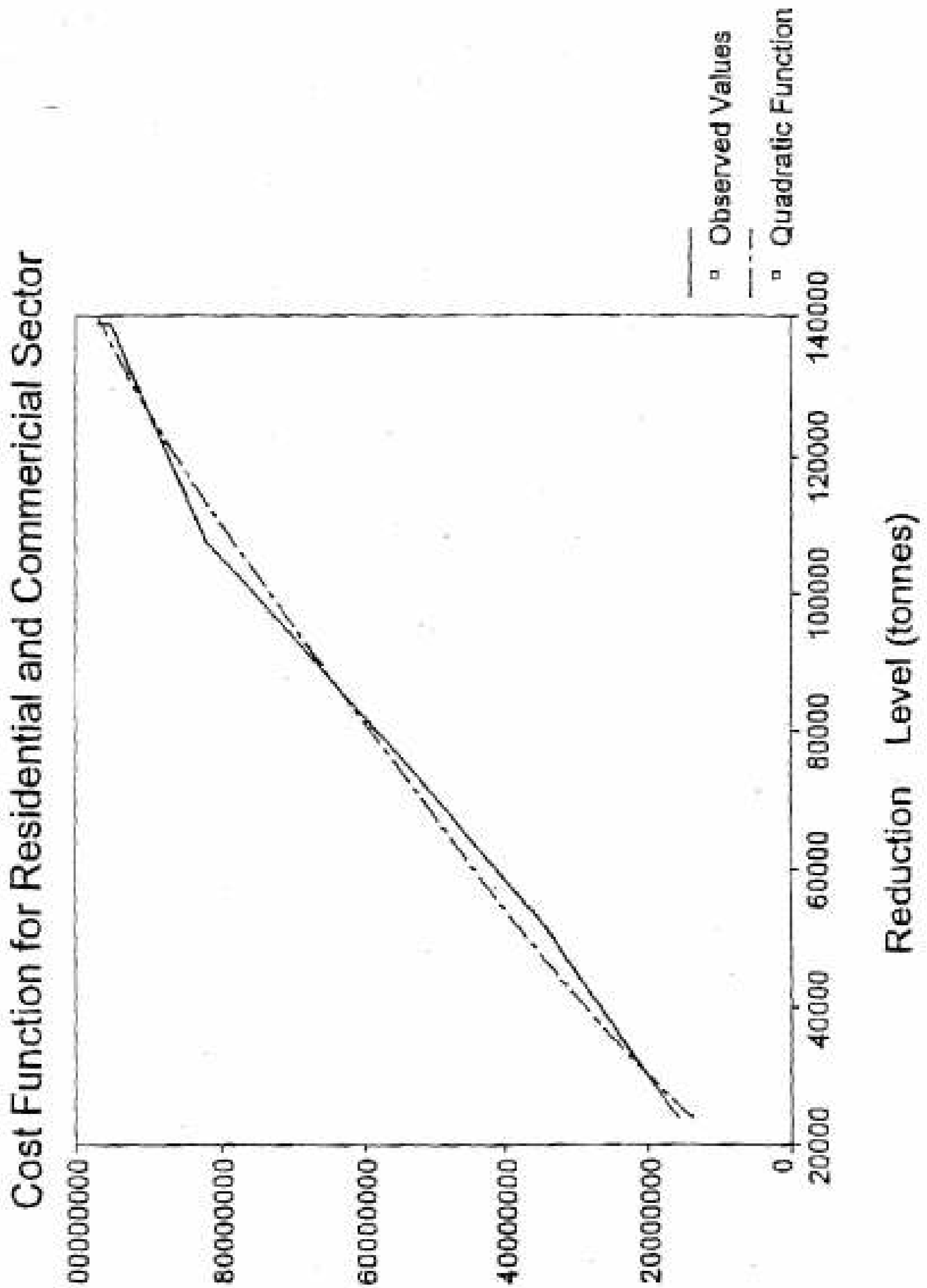

Cost Function for Residential and Commericial Sector
Annualized cost ($)
100000000
80000000
60000000
40000000
20000000
0
20000
40000
60000
80000
100000
120000
140000
Reduction Level (tonnes)
Observed Values
Quadratic Function

Figure 3:

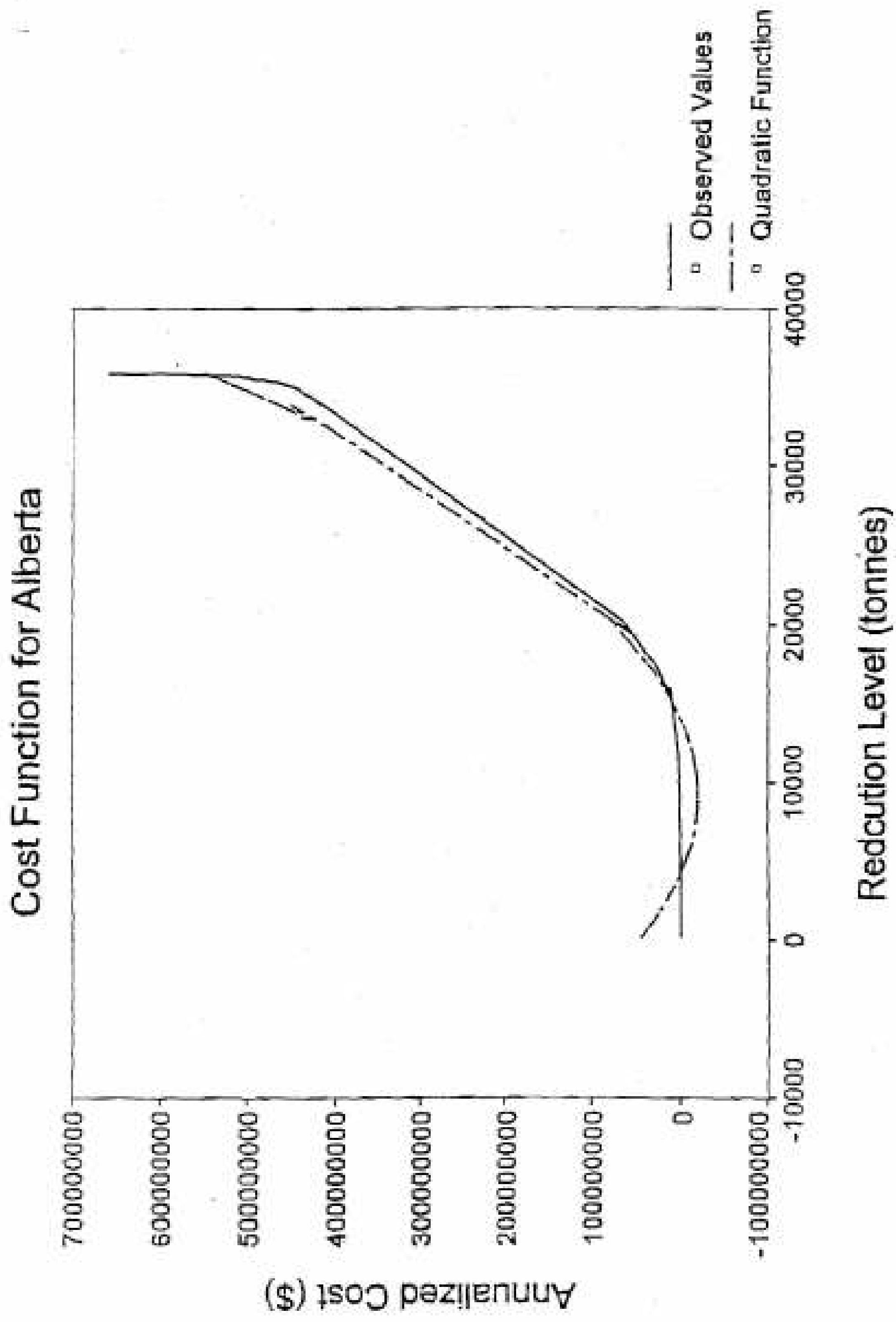

Cost Function for Alberta
Annualized Cost ($)
700000000
600000000
500000000
400000000
300000000
200000000
100000000
0
-100000000
-10000
0
10000
20000
30000
40000
Redcution Level (tonnes)
Observed Values
Quadratic Function

Figure 4:

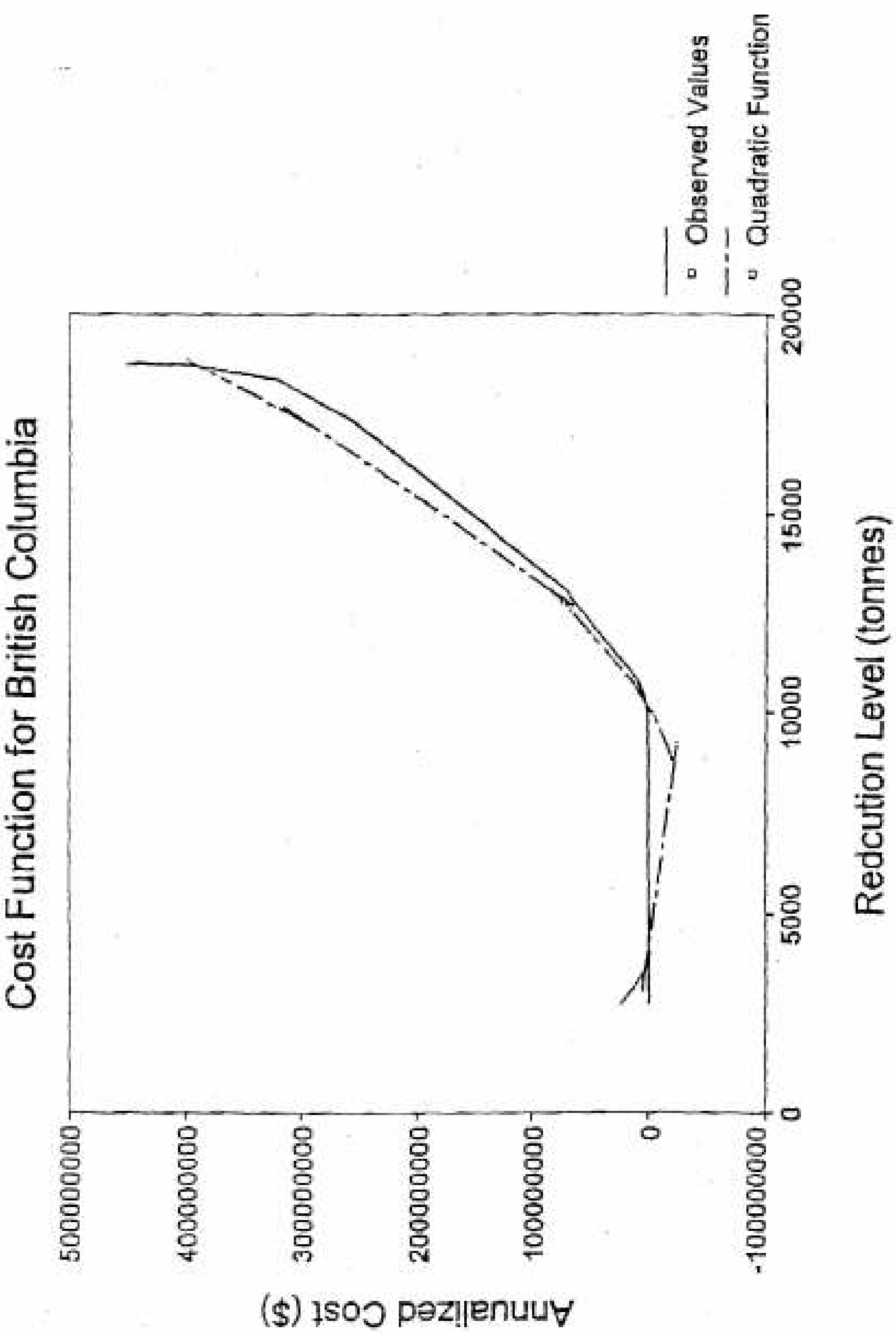

Cost Function for British Columbia
Observed Values
Quadratic Function
Annualized Cost ($)
500000000
400000000
300000000
200000000
100000000
0
-100000000
0
5000
10000
15000
20000
Redcution Level (tonnes)

Figure 5:

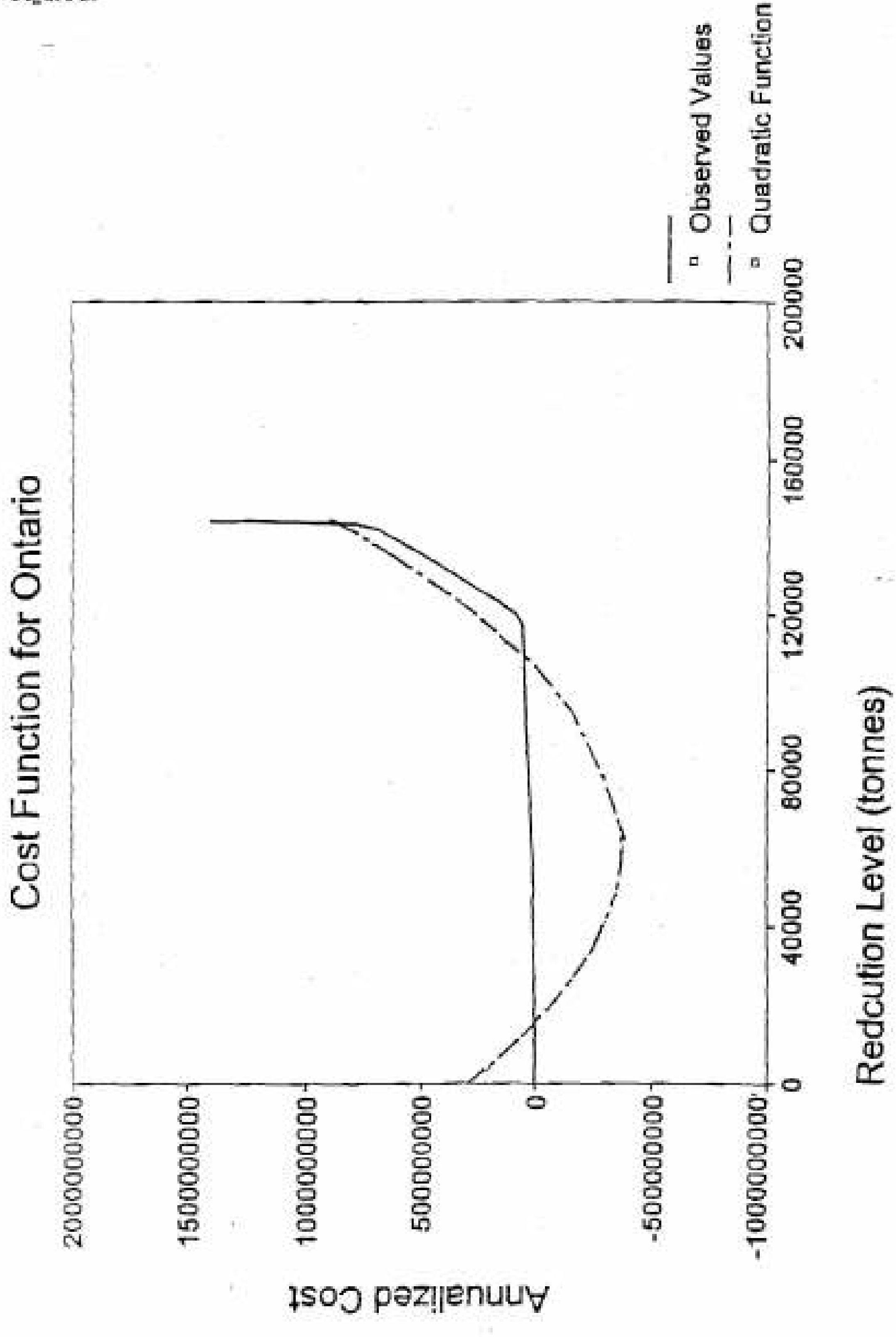

Cost Function for Ontario
Annualized Cost
2000000000
1500000000
1000000000
500000000
0
-500000000
-1000000000
0
40000
80000
120000
160000
200000
Redcution Level (tonnes)
Observed Values
Quadratic Function

Figure 6:

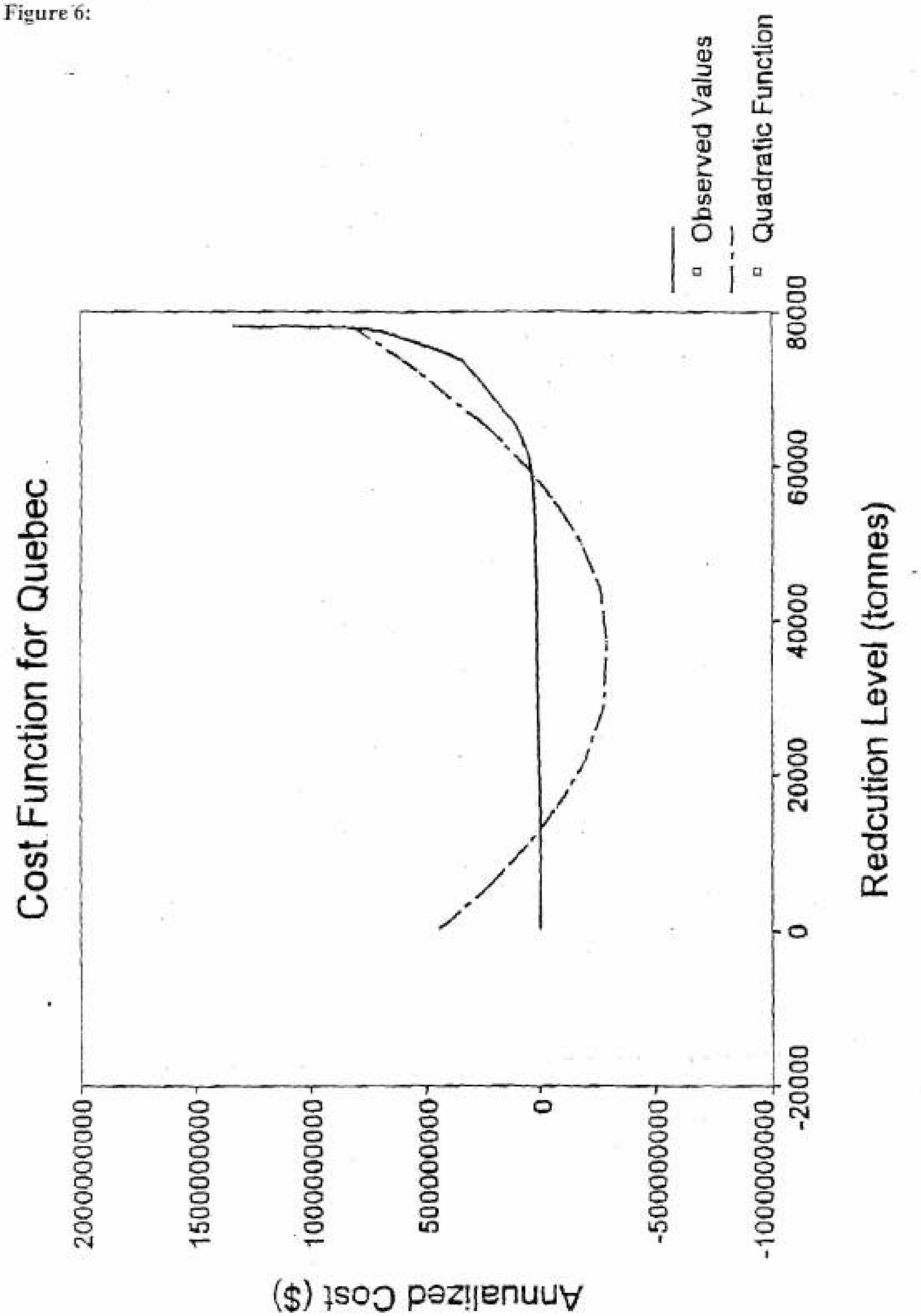
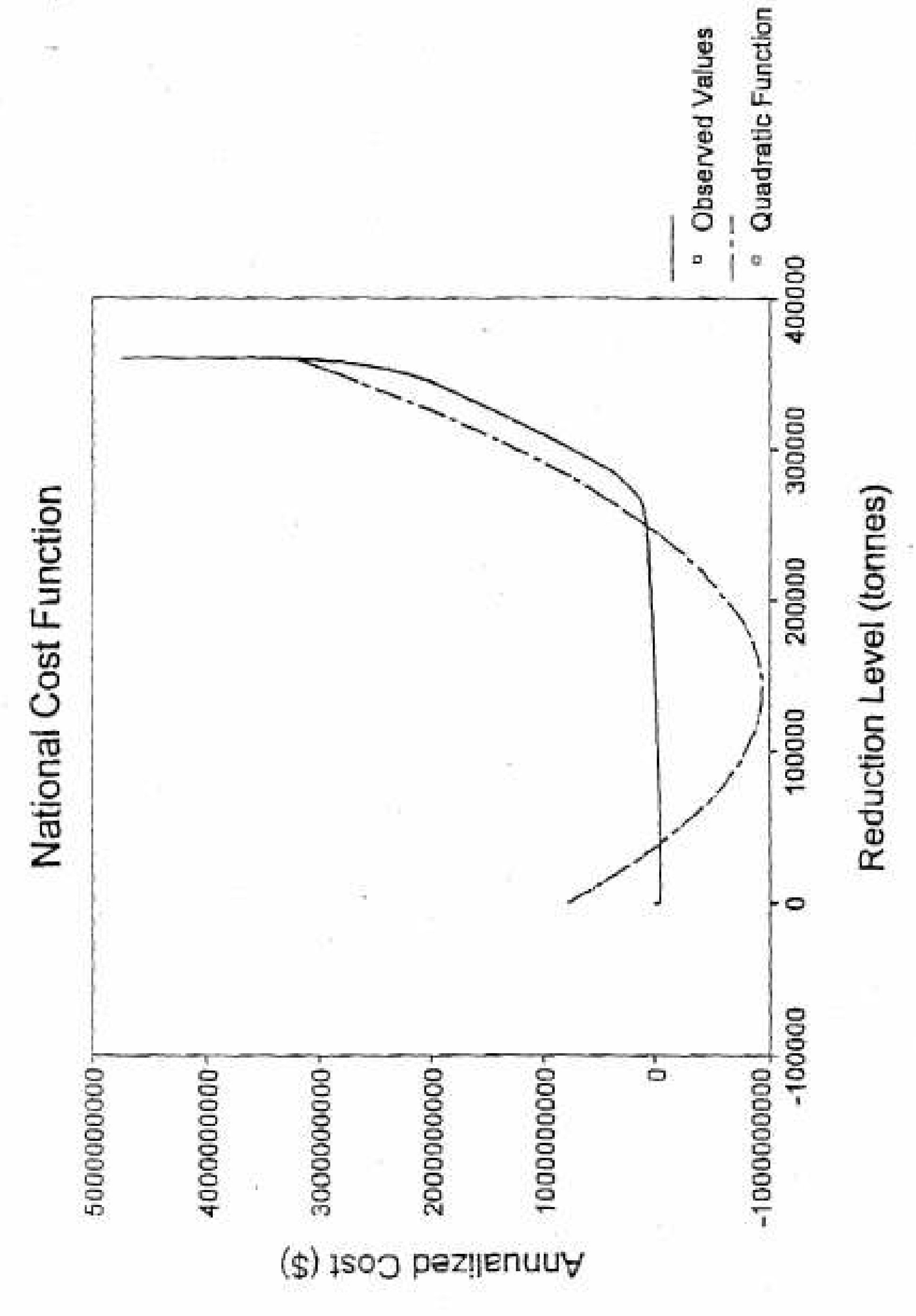

Cost Function for Quebec
Annualized Cost ($)
2000000000
1500000000
1000000000
500000000
0
-500000000
-1000000000
-20000
0
20000
40000
60000
80000
Redcution Level (tonnes)
Observed Values
Quadratic Function

Figure 7:


National Cost Function
Annualized Cost ($)
Reduction Level (tonnes)
5000000000
4000000000
3000000000
2000000000
1000000000
0
-1000000000
-100000
0
100000
200000
300000
400000
Observed Values
Quadratic Function