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ESTIMATION OF COST FUNCTION FOR INDUSTRIAL AIR POLLUTION ABATEMENT IN TAIWAN

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***Key Words*:** Cost function of pollution abatement, regression analysis, dummy variable, Cobb-Douglas production function

ABSTRACT

This study focuses on the estimation of abatement cost functions for air pollution controls in Taiwan. Emission data from stationary sources in 1996 are adopted and analyzed. The pollutants of particulate matters and sulfur oxides among various industry sectors are considered. The major research tasks are therefore the processing of emission data as well as the construction of cost functions. For further discussions, we characterize cost functions into various categories of treatment equipment and industry sectors by adding dummy variables. Among the 3 frequently applied models of cost functions, the Cobb-Douglas function is found to be the best one. The results also shows that, for the removal of particulate matters, the average cost is NT $1.0/kg and the marginal cost is NT $0.27/kg (at the sample mean of 2,080 tons). For the removal of sulfur oxides, the average cost is NT $8.5/kg and the marginal cost is NT $2.2/kg (at the sample mean of 106 tons).

INTRODUCTION

The abatement cost of air pollution control in Taiwanese industry has reached the level of several billion NT dollars per year. The survey and then the establishment of abatement cost databases are, however, still at the stage of preliminary development. The air pollution management strategies used by the Taiwanese agencies include generally both command-and-control and economic approaches. Nevertheless, the promotion and application of economic instruments, such as pollution charges and emission permit trading system to be established, requires the underlying information of abatement cost structure or cost function. This study intends to estimate the cost function of air pollution abatement in industrial sectors. The major research tasks therefore include literature review, data acquisition and analysis, and the estimation of cost function. The paper, in addition to the section, consists of four parts. Literature review on estimation of pollution control cost functions is presented first, followed by the description and screening of the acquired data. Generalized and extended analyses of cost structures are then applied. Lastly, some discussions and summaries conclude this paper.

LITERATURE REVIEW AND THEORETIC DEVELOPMENT

1. Literature Review on Pollution Abatement Cost Functions

Pollution control techniques and thereby the abatement cost functions are commonly divided into categories of solid waste treatment, wastewater treatment, and air pollution control based on the environmental media. Based on the studies reviewed wastewater treatment is the field with relatively fruitful outcomes. Air pollution abatement seems to be less devoted to. In general, Rhyner and Wenger [1], Rigo and Conley [2], and Hegberg [3] estimate the implementation and operation costs of municipal solid waste incinerators

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from the viewpoint of energy and resource recovery. Chang et al. [4] applies coupling analysis on American existing plants to the estimation of construction costs of incinerators. Chang and Wang [5], and Chang et al. [6], with domestic concerns, investigate the cost functions of incineration plants using the fuzzy regression technique. The estimation of cost functions of wastewater treatment, especially domestic investigations in Taiwan, appears to be a better-developed field. Generally summarizing, function forms of translog, Cobb-Douglas (double-log), semi-log, and quadratic models are commonly applied to estimate wastewater treatment costs. Regarding air pollution control, Hartman et al. [7] uses the quadratic model developed originally by Mirman et al. [8] to construct the abatement costs among industrial sectors. Wen et al. [9] applies the Heckman two-step procedure to the estimation of abatement cost function in Taiwan. Particularly, dummy variables are introduced to incorporate the factors of control techniques, regional characteristics, and pollutants on the cost functions.

2. Cost Function of Pollution Control and Methodology

Generally speaking, cost function of pollution control evolves from production function that can be expressed as:

$$Q = f(X) \qquad (1)$$

where X denotes the array of production factors. There exists duality between cost function and production. Suppose that the firm intends to minimize the production cost, the production decision is thus,

$$\text{Minimize } Z = C\ (P_X,\ Q)$$
$$s.\ t.\ Q = f\ (X)\ \text{(constraint on production)} \qquad (2)$$

where the cost $C\ (P_X,\ Q)$ is function of input prices P_X and production quantity Q. The cost function of pollution control is similar to that of production in which the quantity of product is substituted by the amount of pollutant treated. In empirical studies, cross-section data are frequently the only source for the investigations. Under such circumstance, the input prices of pollution control activities can be treated as constants. The (minimum) cost function of pollution control can thus be simplified as:

$$C = f(Q) \qquad (3)$$

The analysis methods for cost function estimation can be generally classified into three categories: (1) econometric regression analysis, (2) mathematical programming, and (3) engineering simulation. In the study the regression analysis approach is adopted because of the availability of fairly comprehensive survey data. Furthermore, the formulation of cost function can also be beneficial to the analysis variable sensitivity and the identification of affecting factors. Based on the studies reviewed previously, three types of function forms are commonly applied in investigating pollution control costs. The following lists the three types of models in which the price variables are omitted due to the merely availability of cross-section data.

- Cobb-Douglas model: $\ln C = \alpha_0 + \alpha_1 \ln Q$ (4)
- Translog model: $\ln C = \alpha_0 + \alpha_1 \ln Q + \alpha_2\ (\ln Q)^2$ (5)
- Quadratic model: $C = \alpha_0 + \alpha_1 Q + \alpha_2 Q^2$ (6)

3. Calculation of Costs

This study applies regression analysis to the estimation of the cost function. The observations of the cost variable can not, however, be the immediate inputs to the models. Some calculation or transformation should be carried out to pursue the analysis. The calculation is generally based on the construction of cash flow diagrams. The annual equivalence of the capital invested for a lifetime of n years can be expressed as the following.

(Annual Eqivalence of the Capital) = (Capital Investment) × (Capital Recovery Factor) (7)

The (Uniform Series) Capital Recovery Factor can be further expressed as:

$$\text{Capital Recovery Factor(CFR)} = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (8)$$

The interest rate ranges commonly from 0 to 6% with that the value of 5% is used here. The lifetime of air pollution control equipment is assumed to be 20 years throughout the study. Furthermore, pollution control costs consist commonly of direct and indirect costs. Capitalized investment and operation expenditures of pollution control equipment are usually classified as direct costs. In contrast, indirect costs consist of, for example, opportunity costs, liability, and compliance fines. This study focuses on direct costs only.

DESCRIPTION AND PREPARATION OF DATA

This study adopts the 1996 survey data of air pollutant emission from stationary sources compiled by the Environmental Protection Administration. The data set consists of totally 87, 894 records of various pollution emissions among numerous industrial sectors. Each record contains entries of, such as, source identification, control device (equipment), pollutant produced, pollutant

Table 1. Descriptive statistics of the 1996 emission survey data and pre-processed results

	Particulate Matter		Sulfur Oxides	
	Original Data Set	Pre-Processed	Original Data Set	Pre-Processed
Number of Emission Sources	19,298	1,346	12,920	278
Number of Manufactures/Plants	7,076	752	5,895	206
Pre-treatment Emission (kg)	4,574,460,379	1,599,166,343	544,142,267	61,805,078
Pollutant Treated (kg)	4,271,452,195	1,558,074,753	43,667,327	29,462,459

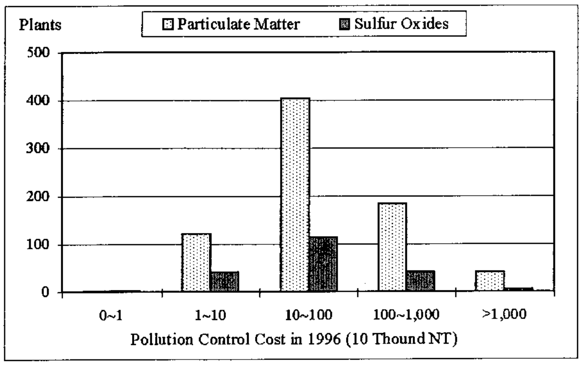


Fig. 1. Illustrative histograms of the samples extracted from 1996 emission data.

treated, pollution emitted, construction cost, operation cost, and other related information. Some of the records, however, contain only partial information and should be delimited. After some pre-processing and screening, particulate matter (PM) and sulfur oxides (SO_X) are the two pollutants bearing the most data records. The following analyses, therefore, focus on the two pollutants only. Consequently, the samples extracted for regression analysis are described as Table 1. The histograms of the samples are illustrated as Fig. 1. Moreover, the study only applies cross-section data of the single year of 1996. The fixed costs (construction costs) are transformed into the annual equivalence using Equations (7) and (8) The variable costs (operation costs) are assumed to be constant throughout the year.

ESTIMATION OF THE COST FUNCTIONS

1. Setting for Regression Analysis

As described in the previous section the pollutants of PM and SO_X bearing the most data records after data screening and pre-processing. The regression analyses focus on the two pollutants only. The models of the cost function considered are Cobb-Douglas, translog, and quadratic. The method of parameter estimation used is the ordinary least squares (OLS) approach. To consider factors of control device categories and industrial sectors, dummy variables are introduced. In the extended analyses, the dummy variables are incorporated in both slope and interception terms.

2. Results form the Generalized Analyses

For both generalized and extended regression analyses we apply the SAS® package to the estimation of parameter values. The results from the generalized analyses, *i.e.*, trying to identify the most suitable function form of the abatement cost, are listed as the following.

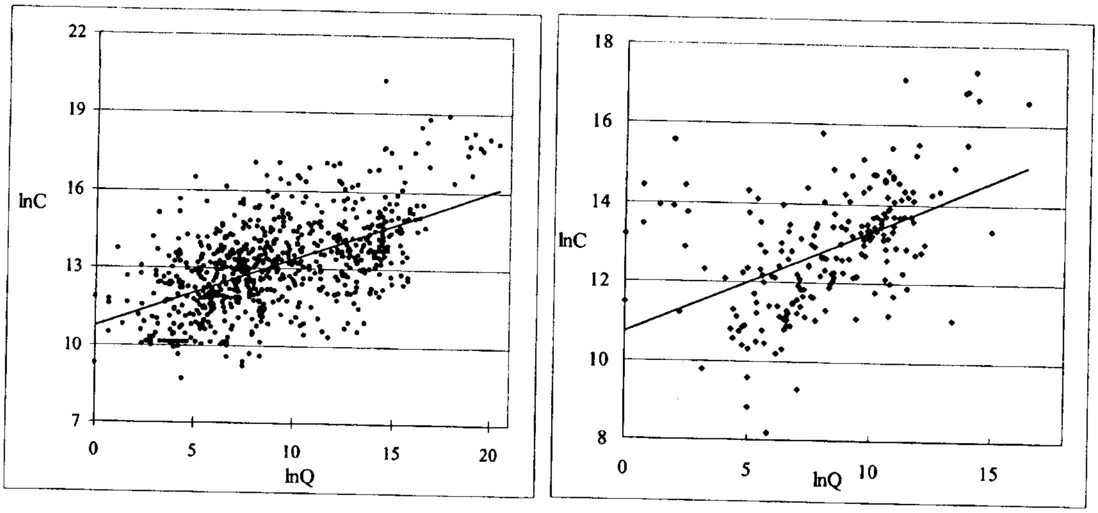
(1) Cobb-Douglas model, $\ln C = \alpha_0 + \alpha_1 \ln Q$, results shown as Table 2 and Fig. 2.

(2) The translog model, $\ln C = \alpha_0 + \alpha_1 \ln Q + \alpha_2 (\ln Q)^2$, results shown as Table 3 and Fig. 3.

(3) The quadratic model, $C = \alpha_0 + \alpha_1 Q + \alpha_2 Q^2$, results shown as Table 4 and Fig. 4.

The discussions on the generalized regression analyses can be generally summarized as follows.

(1) The quadratic model is not suitable for describing the abatement cost function based on the criterion of low goodness of fit (the coefficient of determinant, R^2).
(2) The parameter values of the Cobb-Douglas model are significantly different from zero because the estimated parameters have relatively high t-values.
(3) The translog model, with an additional and relatively nonlinear term of $(\ln Q)^2$, may be less applicable due to its complexity in function form.



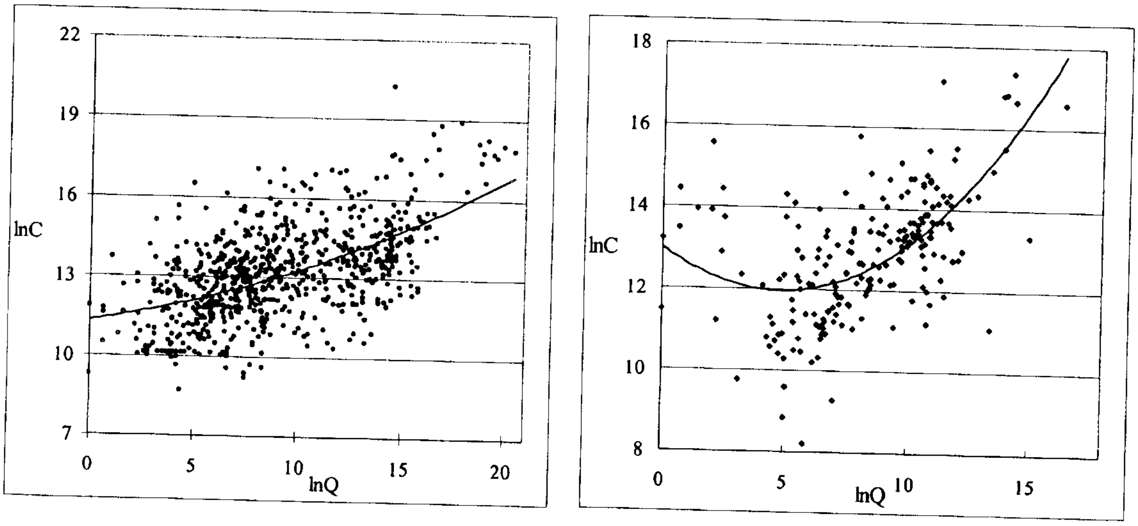
Particulate Matter

Sulfur Oxides

Fig. 2. The scatter plot of the sample and the fitted curve (Cobb-Douglas model).

Table 2. Parameter estimation of the Cobb-Douglas model

		Annual Total Cost			Annual Average Cost		
Pollutant	Parameter	Value	t-value	R^2	Value	t-value	R^2
Particulate Matter	α_0	10.75	82.64	0.34	10.75	82.64	0.80
	α_1	0.26	19.84		-0.74	-55.37	
Sulfur Oxides	α_0	10.73	39.21	0.25	10.73	39.21	0.74
	α_1	0.26	8.28		-0.74	-23.81	



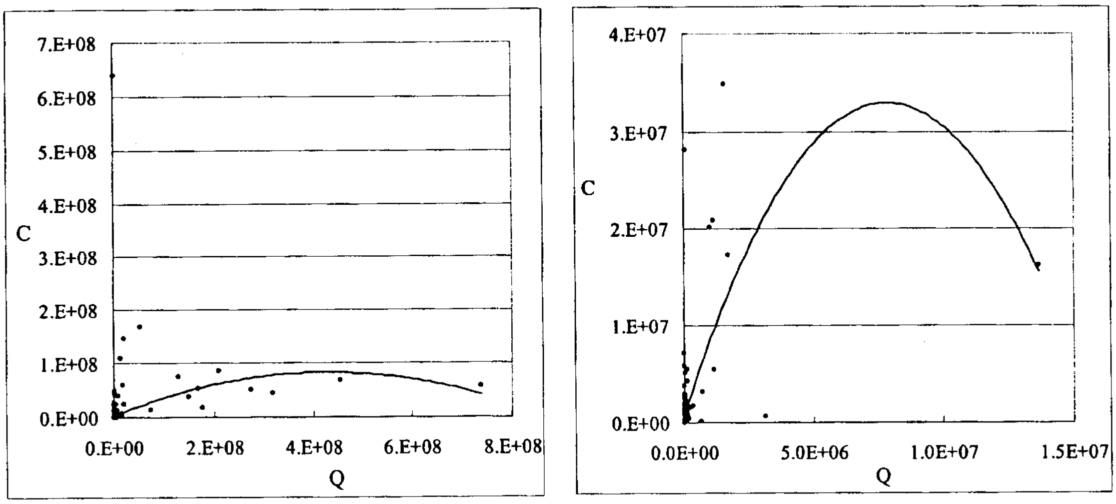
Particulate Matter

Sulfur Oxides

Fig. 3. The scatter plot of the sample and the fitted curve (translog model).

Table 3. Parameter estimation of the translog model

		Annual Total Cost			Annual Average Cost		
Pollutant	Parameter	Value	t-value	R2	Value	t-value	R2
Particulate Matter	α_0	11.33	42.97	0.35	11.33	42.97	0.81
	α_1	0.12	2.07		-0.88	-15.03	
	α_2	0.01	2.51		0.01	2.51	
Sulfur Oxides	α_0	12.99	29.85	0.38	12.99	29.85	0.78
	α_1	-0.42	-3.81		-1.42	-12.86	
	α_2	0.04	6.36		0.04	6.36	



Particulate Matter **Sulfur Oxides**

Fig.4. The scatter plot of the sample and the fitted curve (quadratic model).

Table 4. Parameter estimation of the quadratic model

		Annual Total Cost			Annual Average Cost		
Pollutant	Parameter	Value	t-value	R^2	Value	t-value	R^2
Particulate Matter	α_0	2,875,229	3.09	0.06	2,685	4.61	0.0006
	α_1	0.37	5.92		-2.4×10^{-5}	-0.61	
	α_2	-4.3×10^{-10}	-3.98		3.0×10^{-14}	0.45	
Sulfur Oxides	α_0	753,475	3.17	0.35	18,701	2.56	0.0024
	α_1	8.18	9.23		-0.018	-0.67	
	α_2	-5.2×10^{-7}	-7.67		1.2×10^{-9}	0.59	

Table 5. Estimation of abatement costs based on the Cobb-Douglas model

Statistic Characteristics		Pollutant Treated (kg)	Total Cost (NTD)	Average Cost (NTD/kg)	Marginal Cost (NTD/kg)
Particulate Matter	Q_1	70	143,167	2,045.	540.
	Median	670	259,805	388.	102.
	Q3	13,900	578,215	42.	11.
	Mean	2,080,000	2,167,314	1.0	0.27
Sulfur Oxides	Q_1	270	193,160	715.	185.
	Median	1,570	304,228	194.	50.
	Q_3	15,800	552,016	35.	9.0
	Mean	106,000	902,113	8.5	2.2

Table 6. Estimation of cost function considering device classification

	Dummy Variables	Device Classification	Sample Size	Estimation of the Cost Function
Particulate Matter	D_1	Baghouse	1,006	$\ln C = 11.02 + 0.16 \ln Q$
	D_2	Cyclone	221	$\ln C = 11.07 + 0.07 \ln C$
	D_3	Inertial Collector	42	$\ln C = 10.44 + 0.16 \ln Q$
		ESP	77	$\ln C = 13.19 + 0.17 \ln Q$
Sulfur Oxides	D_1	Wet Scrubber	247	$\ln C = 11.48 + 0.15 \ln Q$
	D_2	FGD	5	$\ln C = 4.95 + 0.83 \ln Q$
		Others	26	$\ln C = 7.61 + 0.59 \ln Q$

Table 7. Estimation of cost function considering categories of industrial sectors

	Dummy Variables	Device Classification	Sample Size	Estimation of the Cost Function
Particulate Matter	D_1	Non-Metal Products	85	$\ln C = 10.23 + 0.30 \ln Q$
	D_2	Metal Products	262	$\ln C = 10.05 + 0.37 \ln Q$
	D_3	Petroleum/Coal	226	$\ln C = 13.40 + 0.03 \ln Q$
		Others	179	$\ln C = 10.87 + 0.26 \ln Q$
Sulfur Oxides	D_1	Metal Products	9	$\ln C = 11.15 + 0.09 \ln Q$
	D_2	Petrochemical	95	$\ln C = 11.26 + 0.39 \ln Q$
	D_3	Non-Metal Products	56	$\ln C = 13.04 + 0.04 \ln Q$
		Others	46	$\ln C = 9.75 + 0.36 \ln Q$

Conclusively, the study generally suggests that the Cobb-Douglas model is relatively more applicable for describing the abatement cost structure based on the analyses of 1996 emission survey data. The following discussions and extended analyses, consequently, apply the function form only. Furthermore, with the determined function form the characteristic values related to the abatement costs can be estimated analytically. Table 5 summarizes the average costs and marginal costs of the four statistical characteristics of the independent variables (the pollutant treated), in which the corresponding costs of the first three quartiles (Q_1, Median, and Q_3) and the arithmetic average (Mean) are evaluated.

3. Results from the Extended Analyses

The preceding generalized analyses consider neither classification of control devices nor categories of industrial sectors. The section, therefore, intends to characterize the qualitative aspects by introducing dummy variables. The setting of the regression analyses on the Cobb-Douglas cost function is listed as the following.

- Classification of control devices: four types of devices for particulate material control devices - baghouse (filter), cyclone, inertial collector, and electrostatic precipitator (ESP) three types of sulfur oxides control devices - wet scrubber, flue gas desulfurization system, and other type (*e.g.*, absorption).
- Industrial sectors considered: four categories of manufactures producing particulate matter - non-metal products, metal products, petroleum/coal, and others; four categories of manufactures producing sulfur oxides - metal products, petrochemical products, non-metal products, and others.

The regression analyses on qualitative (dummy) independent variables consider shifts in both the intercept and slope terms. The results from applying the OLS parameter estimation procedure are summarized as Tables 6 and 7. While considering device classification, the electrostatic precipitator is found to be the most expensive technique among the four control devices for particulate matter. The investigation of the t-values of estimated parameters further depicts that the two dummy variables, introduced for classifying SO_X control devices, are not significantly different from zero. The classification may not be applicable, i.e., the control costs of techniques for SO_X are less differentiated. As the categories of industrial sectors are concerned, no obvious observation can be drawn other than the estimation results shown in Table 7.

SUMMARIES AND RECOMMENDATIONS

This study applies the regression analysis technique to the development of abatement cost function of industrial air pollution control. The

1996 emission survey data of stationary sources compiled by the Environmental Protection Administration is adopted and analyzed. To incorporate the qualitative characteristics of control device classification and industrial sector categories, dummy variables are introduced to perform the extended analyses. The results and discussions can be summarized as the followings.

1. Based on the analyses of the 1996 survey data in Taiwan the Cobb-Douglas model is found to be the most applicable for describing the abatement cost structure among the three commonly applied function forms. The negative slope factors in the (average) cost functions further depict the characteristics of economies-of-scale while controlling particulate matter and sulfur oxides. The marginal cost, with negative slope factor in the functional form, departs from the hypothesis of increasing marginal abatement cost. This may be due to the application of cross-section data (without considering the treatment efficiency) instead of some pilot data incorporating marginal effects of control technique. As a result, the average abatement costs of particulate matter and sulfur oxides are 1.0 NTD/kg and 8.5 NTD/kg (per pollutants treated) respectively. The figures are calculated based on the characteristic statistics of arithmetic average of the sample extracted.
2. An economic instrument of pollution charges is currently imposed on stationary emission of sulfur oxides and nitrogen oxides. The current rate of sulfur oxides emission is 12 NTD/kg. Compared to the 1996 emission data and the determined cost function, the estimated pollutant treatment is found to be 15 tons per year. There are almost 70% of emission sources in the 1996 survey data whose amounts of pollutant treated per year are less 15 tons. That may imply that the pollution charges may not be an incentive to the portion of the emission sources for further pollution reduction.
3. The extended regression analyses on dummy variables considering qualitative aspects depict that the electrostatic precipitator is found to be the most expensive technique among the four control devices for particulate matter. The investigation of the t-values of estimated parameters further depicts that the two dummy variables classifying SO_X control devices are not significantly different from zero. This may imply that the control costs of techniques for SO_X are less differentiated. As the categories of industrial sectors are concerned, no obvious observation can be drawn.

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REFERENCES

1. Rhyner, C. R. and R. B. Wenger, "Capital Costs of Resource Recovery Facilities in USA," *Waste Management Research*, 4, pp31-326 (1986).
2. Rigo, R. G. and A. D. Conley, "Waste To Energy Facility Capital Costs," *Proceedings of National Waste Processing Conference*, pp.23-28 (1988).
3. Hegberg, B. A., "Municipal Solid Waste Incineration with Energy Recovery: Technologies, Facilities, and Vendors for Less Than 550 Tons per Day," Office of Technology Transfer, University of Illinois, Center of Solid Waste Management and Research (1990).
4. Chang, N. B., T. D. Nount and R. E. Schuler, "Econometric Analysis of Construction and Operating Costs of Municipal Solid Waste Incinerators," *Journal of Environmental Software*, 8, pp.173-186 (1993).
5. Chang, N. B. and S. F. Wang, "The Development of Material Recovery Facilities in The United States: Status and Cost Structure Analysis," *Resources Conservation and Recycling*, 13(2), pp.115-128 (1995).
6. Chang, N. B., Y. L. Cheng and H. H. Yong, "A Fuzzy Goal Regression Model for the Construction Cost Estimation of Municipal Waste Incinerators," *International Journal of Systems Science*, 27(5), pp.433-445 (1996).
7. Hartman, R. S., D. Wheeler and M. Singh, "The Cost of Air Pollution Abatement," The Industrial Pollution Projection System, World Bank policy research working paper #1398 (1994).
8. Mirman, L. J, D. Samet and Y. Tauman, "An Axiomatic Approach to the Allocation of a Fixed Cost Through Prices," *The Bell Journal of Economics*, 14(1) (1983).
9. Wen, L.-C., Y.-C. Bor, D.-N. Liu, Y.-L. Chien, K.-M. Wang, *Study on Imposing Framework and Impact Assessment of the Second-Stage Air Pollution Charge Sys-*

tems, technical report, Environmental Protection Administration, the Republic of China (1997). (in Chinese)

Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-chief within six months.

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台灣地區固定污染源空氣污染防治成本函數之研究

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關鍵詞： 污染防治成本函數、迴歸分析、虛擬變數

摘要

污染防治爲一極爲耗用經費之行爲，然而由於基本資料之不足，各部門在預算編列或成本推估上，常有成本動態資訊掌握不易，或工程效益評價不易推動等問題。再者，政府部門亦逐漸引用經濟工具以推動具經濟誘因之管制手段，有鑑於此，分析探討污染防治成本結構，已成爲近年來一個重要的課題。本研究以空氣污染固定污染源爲研究對象，利用民國85年固定污染源操作許可申請資料，進行成本函數迴歸分析，以推估空氣污染防治成本。此外，爲考量不同污染防治設備、行業別及污染規模等因素，本研究再以加入虛擬變數的方式，延伸探討不同特徵的污染防治成本函數。研究結果顯示，在本研究選用之三種成本模型中，以 Cobb-Douglas 函數型較佳；防治成本推估方面，粒狀污染物在污染去除量爲2,080噸時（樣本平均數），年防治平均成本爲每公斤1.0元，邊際防治成本爲每公斤0.27元；硫氧化物在樣本平均去除量106噸時，年防治平均成本每公斤8.5元，邊際防治成本爲每公斤2.2元。