Environmental Kuznets Curve Hypothesis Revisited: With Approaches of Growth Theory and Statistical Analysis

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Abstract

As an economy develops and incomes rise, people become more concerned about issues such as public health and environmental quality. In 1955, Kuznets proposed an "Inverted U" hypothesis referring to a relationship between income inequality and per capita income. In the 1990s, many researchers introduced the terminology "Environmental Kuznets Curve" (EKC) to hypothesize the relationship between environmental improvement or degradation and economic development, and to speculate the turning point where environmental quality begins to improve with increase in per capita income. Using growth theory and statistical methods, this thesis focuses on examining the validity of the EKC hypothesis – whether the relationship between environmental quality and economic growth follows the trajectory of an inverted U curve, or commonly termed EKC.

There are mainly two tasks that are undertaken in this research. One is to develop theoretical models, in which economic growth theory is adopted to analyze the path of such an environment-growth relationship. In developing the theoretical models, this research differentiates pollution as a stock or as a flow depending on the depreciation rate of the studied pollutant. Particularly, two environmental growth models are formulated for pollution treated as a flow or stock. In the pollution as a stock case, besides the equation of motion of capital stock in the production sector, another equation of motion of pollution stock is also formed as a constraint to decide the optimal utility. As a result, optimal solutions to the environmental growth models are evaluated and transitional dynamics are analyzed. Besides, conditions on the existence of EKC and income levels of the environmental turning point (ETP) are analyzed theoretically.

The second task of this research is to verify the EKC relationship between economic growth and environmental quality using empirical datasets, for which three level studies, global, regional, and individual country, are conducted. In the empirical research, statistical methods are extensively employed, and a general econometric model is developed on the base of theoretical results from the environmental growth models. This econometric model is used to estimate the income levels of ETP, and the underlying causes that determine the existence of EKC for the three geographical levels of the study. Emissions of six major air pollutants are applied to represent environmental quality. The income level, represented by GDP per capita, indicates the impact of economic scale on the environment, from which ETP can be derived and thus the existence of EKC can be evaluated. Furthermore, economic structural impacts of both compositional and decompositional effects on environmental quality are analyzed, among which impacts of technological innovation, inter-sectoral and intra-sectoral changes, and environmental policy response, are particularly focused.

Keywords: Economic Development, Economic Structure, Growth Model, Environmental Quality, Environmental Kuznets Curve, Inverted U Curve, Environmental Turning Point, Air Pollution.

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This thesis is the result of my several years' researches through the entire Ph.D. program at the Applied Economics Department in the University of Minnesota. The idea of investigating the relationship between the two conflict perspectives of life, environment and economic growth, first came when I was doing a research project for Prof. Sandra Archibald and Dr. Zbigniew Bochniarz at the Center of Nation in Transition, Humphrey Institute of Public Affairs, during my first year of the Ph.D. program, even though at the time the research methodology on how to approach the problem was not clear.

Courses taken in later years taught by professors in the Economics Department including Leonid Hurwicz, Marcel K. Richter, Jan Werner, Timothy Kehoe, Edward Prescott, Edward Foster, and V. V. Chari, by professors in the Applied Economics Department including Terry Roe, Vernon Ruttan, Jay Coggins, K. William Easter, Stephen Polasky, C. Ford Runge, Francis Homans, Steven Taff, Vernon Eidman, Robert King, Jeffrey Apland, Glenn Pederson, Paul Glewwe, Terrance Hurley, Jean Kinsey, Donald Liu, Rodney Smith, Claudia Parliament, and Elizabeth Davis, by professors from the Statistics Department including R. Dennis Cook, James Dickey, and Peihua Qiu, and by professors in the Humphrey Institute of Public Affairs with Edward Schuh, Sandra Archibald, John Brandl, Robert Kudrle, Morris Kleiner, Deborah Levison, Stephen Hoenack, and Samuel Myers Jr. provide useful methodological tools and knowledge-based structures that enable me to combine these topics systematically and to analyze the question in an in-depth manner. I would like to express my thanks here to all these people mentioned above and many others not mentioned that I have been benefitted from.

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Contents

Introduction

The Environmental Kuznets Curve (EKC) hypothesis has been used to describe the relationship between environmental improvement or degradation and economic development. It states that pollution levels are increased as a country develops up to a certain point, but then begin to be decreased with further increases in per capita income. This is reflected as an inverted U curve, the relationship between pollution level and income on the base of per capita term. This hypothesis was first proposed by Grossman and Krueger in 1992, and restated by them in 1995[1].

A number of studies in the 1990s verified this hypothesis empirically by estimating a reduced-form relationship between indicators of environmental quality and income. These authors include Grossman and Krueger [1991, 1995], Shafik and Bandyopadhyay [1992], Hettige *et al.* [1992], Shafik [1994], Selden and Song [1994], Lucas [1994], Holtz-Eakin and Selden [1995], and Suri and Chapman [1996], who explored empirical evidence of the Kuznets curve relationship for a variety of air and water pollutants by employing either cross-country or time-series data, or both. Two journals, *Environment and Development Economics* and *Ecological Economics,* issued their special editions in 1997 and 1998, respectively, that extensively discussed the EKC-related subjects and explored the existence of an income level of the environmental turning point (ETP).

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[1] Although many scholars have proposed the similar relationship between income and environment early in the 70s, e.g. Vernon Ruttan [Antle & Heidebrink, 1995], the first use of the term, Environmental Kuznets Curve, can be traced to a paper by Panayotou [1993] written for the World Employment Programme Research Working Paper series. The first use of it in an academic journal was by Selden and Song [1994]. The original Kuznets "Inverted U" hypothesis refers to the relationship between income inequality and per capita income, that is, in an early stage of economic growth the distribution of income worsens, while at later stages it improves (Kuznets [1955]).

In general, their results show that for several pollutants, such as sulphur dioxide, there exists an inverted U-shaped relationship between pollution emissions or concentrations and income. But some empirical findings suggest that there is no such relationship for some other pollutants. A cross-country development report conducted by the World Bank [1992] found that the relationship between economic development and environmental quality for pollutants can be characterized into three groups. Though a group of environmental indicators experience an “inverted U” pattern (*e.g.*, sulphur dioxide and air particulate matter), it appears that some indicators of environmental quality continue to worsen with higher levels of per capita income (*e.g.*, municipal waste) and some others experience an improvement on any level of income (e.g., public sanitation and sewer).

Besides empirical work, there is an extensive literature on environmental quality in association with growth theory. Research papers of this category include Keeler *et al.* [1971], D’arge and Kogiku [1973], Forster [1973], Gruver [1976], Heal [1982], Ploeg [1991], Tahvonen and Kuuluvainen [1993], Selden and Song [1995], Michel and Rotillon [1995], Elbasha and Roe [1996], Mohtadi [1996], as well as recent work by Stokey [1998], Qi and Coggins [1999], Andreoni and Levinson [2000], and Hauer and Runge [2000]. Most of the above literature demonstrates that there is a certain relationship between pollution and growth along an optimal growth path. Models introduced by these authors can be further extended to develop a theoretical base that can be served to investigate the validity of the EKC hypothesis. This is exactly one of the tasks this study is going to undertake.

Since there are strong intertemporal aspects of pollution problems in interaction with economic growth, the research conducted in this study intends to extend the earlier theoretical studies to establish theoretical supports to the EKC hypothesis by adopting a growth model incorporating environmental quality.

In developing the theoretical models, the paper emphasizes that pollution, as a variable, enters people's utility function, along with consumption, to determine a representative agent's preference over time. Two growth models are formulated in the theoretical part of the analysis characterizing the nature of pollutants. In a one-state-variable environmental growth model, pollution is treated as a flow, while in a two-state-variable environmental growth model, pollution is a stock that affects people's preference. Moreover, along with the equation of motion of capital stock in the production sector for the classical growth model, another equation of motion of pollution stock is also formed as a constraint to decide the optimal utility in the two-state-variable model. The optimal steady-state solutions to the one-state-variable growth model, along with the optimal growth paths of consumption, capital investment and pollution emission, as solutions to the two-state-variable environmental growth model, will be evaluated. These analyses provide guidance for social planners on how to allocate restricted natural resources and stipulate regulative policies optimally.

The principle contribution of this study is to develop the theoretical EKC relationship between economic growth and environmental quality, which serves as a basis for testing the EKC hypothesis empirically. In the later part of this study, some statistical methods will also be used to examine the validity of the EKC hypothesis by applying the global panel data with six major air pollution indicators, such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter (PM) and volatile organic compounds (VOC). If the EKC assertion is correct, then the income level of the environmental turning points (ETP) should also be true by the estimated evidence using these six air pollution indicators. In this case, the pollution levels of them should be observed to decrease with further increase in per capita income beyond the peak of their turning points.

The organization of the dissertation is as follows. Theoretical growth models incorporating environmental quality are formulated in Chapter One. In this chapter, it will start from some assumptions for the basic growth model and the general form of the one-state-variable and two-state-variable environmental growth models, then to evaluate the steady-state equilibrium and optimal growth path of the two models, respectively. Thirdly, the transitional dynamics towards the steady-state equilibrium and the optimal growth path for the one-state-variable and two-state-variable growth models will be analyzed, separately. Finally, conditions under which the EKC relationship between economic growth and environmental quality exist and whether they determine the income level of the EKC relationship are investigated in the context of the two model formulations. The theoretical results will be summarized in the last section of Chapter One. In Chapter Two, the EKC hypothesis is empirically examined in which six major air pollutants are included to represent environmental quality. The panel data of these indicators cover the period of 1986 to 1998 for over 100 countries in this empirical study. In particular, an econometric model supported by the underlying theorem is presented in this chapter, where the data are analyzed, and the regression results regarding the ETP values and determinants of the EKC shape are interpreted and compared among different air pollutants within three different geographical levels for national, regional and global studies, respectively. Results of the empirical studies are summarized in the last section of Chapter Two. Finally, Chapter Three summarizes the paper and provides extended discussion for future research.

Chapter 1
Theoretical Models

1.1 Review of Growth Models Incorporating Environmental Quality

Growth theory has experienced a boom in the late 1980s through the entire 1990s. However, most of growth models, in general, overlook the interaction between economic growth and environment. Actually environmental pollution has both direct and indirect welfare effects. The omission of environment implies that no pollution is produced during the process of economic activities or, alternatively, that if pollution is generated it has no effects on social welfare. However, an increase in pollution reduces social utilities and impairs the objective of economic growth. Accordingly, any theory of optimal economic growth that does not account for the externality effects such as pollution can not claim to be complete.

There are strong intertemporal characteristics of the pollution problem. These reinforce the relevance of a dynamic approach using optimal control theory. Even if pollution is not actively controlled, it is possible that the economy will reach an equilibrium, that is, move to a steady-state in terms of the pollution level as well as the capital stock[2]. In general, this steady state will not be optimal. By devoting resources to pollution control, the economy may need to seek a different equilibrium in order to maximize society's welfare

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[2] Forster [1972] and Tahvonen and Kuuluvainen [1993] proved that there exists a sub-optimal equilibrium when pollution is not optimally controlled.

over time. In this sense, optimal control theory may be called for in dealing with resource allocation when pollution is involved. Traditionally, a growth model under the neoclassical framework is used to study the optimal intertemporal allocation of resources associated with economic growth. From this perspective, environmental externalities should be considered when we study the development course of an economy.

The earlier dynamic growth models introducing environmental quality when using an optimal control theory include those in Keeler *et al.* [1971], Forster [1973], Gruver [1976], Heal [1982], Selden and Song [1995], Elbasha and Roe [1996], and Mohtadi [1996]. Models by Keeler *et al.* and Gruver are under the framework of that by Solow with a fixed saving rate. Models formulated by the other authors, such as, Forster, Heal, Selden and Song, Elbasha and Roe, and Mohtadi, study the interaction between economic growth and pollution control based on a one-state-variable model. That is, only the accumulation of capital stock but not the movement of pollution stock is included in their studies. Pollution emissions, the flow variables determining the change of pollution stock, are assumed to enter the utility function in the models of Forster, and of Selden and Song. In addition, Keeler *et al.* assume that emissions are generated in a fixed proportion to the rate of production, while emissions are generated in a fixed proportion to consumption in Heal's model. All of these authors have studied pollution problems in the context of the neoclassical growth model. In particular, both Keeler et al. and Forster conclude that, when the pollution problems are considered and some resources are devoted to pollution control, the optimal steady-state endpoints for consumption and capital stock are lower than those from the neoclassical model when the pollution is ignored.

Ploeg [1991], Tahvonen and Kuuluvainen [1993] and Stokey [1998] have formally derived two-state-variable growth models regarding both production capital and pollution stock, in which they study a long-run consequence of economic growth and pollution control. However, Ploeg assumes that emissions are generated in a fixed proportion of output, Tahvonen and Kuuluvainen treat emission as an input in production, and both emissions and emission standard are included in the production process as inputs in Stokey's model. These approaches have been criticized because in many cases other inputs cannot be varied independently from emissions and the pollution abatement costs can not be distinguished from the capital investment for production. Since the investment is not separable between commodity production and pollution abatement, the effects of capital investment on production and expenditures on pollution control cannot be analyzed separately.

Moreover, some other approaches have been used to investigate the pollution effects on economic growth. John and Pecchenino [1994], and Jones and Manuelli [1995] posit an overlapping generations model in which economic growth is determined by market interactions, and pollution regulations are set through collective decision-making by the younger generation. The young collectively tax themselves to make investments that improve the environment when they are old. This approach is not widely used because there may be multiple equilibria that are Pareto inefficient, and there could be overinvestment in the environment. Andreoni and Levinson [2000] lay out a simple static model of the microfoundations of the pollution and economic growth relationship. Although their result is consistent with a Pareto efficient policy and a competitive market economy, the authors do not consider the optimal policy issues in allocating resources between pollution control and production investment, and disregard the characteristics of pollution problem, such as pollution spillover and intertemporal issues. Hauer and Runge [2000] present a game theoretical approach in studying the pollution problem in the perspective of public goods in a global commons, which focuses on collective actions among different jurisdictions.

Listed in the above is some of the major theoretical literature on the subject of pollution and growth. Although the Environmental Kuznets Curve (EKC), or inverted U-shaped curve, is implicitly embedded in most of these studies, only few focus explicitly on the transitional paths for the pollution and growth. However, Selden and Song [1995], and Stokey [1998] are the first who use the neoclassical environmental growth model to examine the inverted U curves for pollution. Both of them assume that there is a predetermined critical level when people's tastes come into play and pollution abatement efforts become greater to offset the dirty effects from growth. The theoretical results of their work confirm that environmental pollution displays an inverted U-shaped pattern over time, growing in the early stages of development and declining as the economy approaches the optimal equilibrium. Though Andreoni and Levinson [2000] analyze a static model in the microfoundation framework on the pollution and growth relationship, they also observed an Environmental Kuznets Curve relationship for economic growth and pollution that can be derived directly from the technological links between consumption and abatement activities. In the context of a game theory, Hauer and Runge confirm an Environmental Kuznets Curve in the global commons describing a response of high income countries to the environmental externalities.

According to different characteristics of pollution as a flow or as a stock, this study formulates two separate environmental growth models involving pollution control in the framework of a neoclassical Ramsey setting. In these models, production and pollution abatement are simultaneously employed to determine the optimal solutions for consumption, capital stock and pollution level. And resources are disaggregated among consumption, investment in production, and expenditure on pollution abatement. The pollution problem is investigated in the context of this model setting, indicating that the production process emits pollutants, and the activity of pollution abatement reduces these emissions. Similar to the simplest models of those by Forster [1973] and Selden and Song [1995], the one-state-variable model of this study assumes that pollutants are dissolved by the environment immediately after they are emitted. While in the two-state-variable model, a combining effect of pollution emissions and their different natural decay rates is assumed. Thus, the equation of motion in pollution stock is constructed additively to that of the capital stock. Both differential equations are considered constraint conditions in the welfare optimization problem in the two-state-variable model. However, it will be shown that the difference in the theoretical implications for the Environmental Kuznets Curve hypothesis from the two models is slight.

In this study, the two-state-variable growth model includes the movement of pollution stock which represents the change of environmental quality, differing from the simplest one-state-variable growth model, where pollutants are flow emissions. However, both models introduce the variable of expenditure on pollution abatement which is helpful to analyze the effect from the pollution control activity, differing from those prior environmental growth models proposed by Tahvonen and Kuuluvainen, and by Stokey. Most importantly, both models investigate a transitional growth path for the relationship between pollution and economic growth. Seeking for a theoretical basis supporting for the existence of the Environmental Kuznets Curve relationship for pollution and economic growth is the main focus of this research, which differs from most of the previous researches in the area.

The framework of control theory provides with insights into the use of mechanisms to direct patterns of consumption, production and pollution control. Besides, there are strong intertemporal aspects of the pollution problem. The optimal steady state equilibrium and optimal growth path, as solutions to the maximization problem with the environmental consideration over time, can be obtained using a dynamic approach that draws upon the optimal control theory. Similar to most of the previous environmental growth model in the neoclassical framework, this study will also apply the dynamic approach of optimal control theory in obtaining the optimal solutions.

1.2 Assumptions of Environmental Growth Model

Some assumptions are required to make before the theoretical work is formally proceeded.

(1) Pollution is a pervasive phenomenon. Keeler et al. [1971], one of the pioneering researchers dealing with the pollution problem, define pollution to be any stock or flow of physical substances, which impairs man's capacity to enjoy life. The question may be raised whether pollution can be considered only as a flow or whether as a stock. Obviously, it depends to what extent pollution tends to accumulate, which is, in turn, determined by its

own natural decay rate. If a pollutant has very high rate of depreciation or decay, the stock may lose its significance in this perspective. Noise pollution is a good example of such cases. Some types of air pollution and organic water pollution can be reasonably regarded as a flow variable in this context. It is worth pointing out that the effect of pollution may last long after the pollution itself is gone. The distinction that has been emphasized between the stock and flow relates directly to the distinction of the two model settings. In the simplified one-state-variable model of this study, it is assumed that pollution can be characterized as a flow, in which pollution is considered to have a negative effect on aggregate utility, to be an increasing function of production output, and to be negatively related to the stock of pollution control capital.

However, some other types of environmental degradation, such as heavy metals, deforestation and depletion of the ozone layer, are cumulative and self-decaying very slowly. In these cases, it is more reasonable to assume that disutility is related to the accumulated stock of pollutants. To capture this idea, a two-state-variable environmental growth model is also constructed in this study to assume that pollution accumulates as a stock which affects utility, and decays away at a fixed rate. Besides, same as in the one-state-variable model, the factor that the flow of pollutants increases with the production and decreases with the pollution control capital is additionally considered in the two-state-variable model[3].

(2) Pollution is a public goods and usually cannot be allocated on an individual basis. In the theoretical model, we assume that the utility function, production function, and emis-

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[3] More extensive discussion on pollution as a flow or as a stock can be referred to the work by Keeler et al [1971], Gruver [1976], and Stokey [1998].

sion function are all in aggregate forms in relating to a whole society, and the growth rate of the population is not considered in this model setting. Therefore, the general forms of the utility function, production function, and emission function for a social optimal problem can be defined as $U(C, P)$, $F(K, X)$, and $G(K, X)$, respectively. Where the society's consumption level (or utility function), $U(C, P)$, depends on the composite commodity consumption C and the environmental pollution P. The production function, $F(K, X)$, and the emission function, $G(K, X)$, reflect two opposite outputs in the process of production; one is a good output and the other is a bad output, and both of them are functions of the capital stock K and the pollution abatement expenditure X in aggregate terms. In addition, as a source of pollution emission during the production process, capital stock (K) has two-sided effects that affect the magnitude of pollution emission. The major effect is that pollution emissions are produced as by-products simultaneously with the output during the production process. On the other hand, with an increase in production, or more efficient use of input factors, less emission will be generated with further increase of production scale. This point of views will be illustrated fully by the properties of the emission function in Assumption (6) as follows.

(3) For the sake of simplicity, it is further assumed that utility is additively separable, increasing at a nonincreasing rate in consumption C, and decreasing at a nondecreasing rate in pollution P. Namely, the separable utility function takes the form of $U(C, P) = U_1(C) - U_2(P)$, with $U_1'(C) > 0$, $U_1''(C) \leq 0$, $U_2'(P) > 0$, and $U_2''(P) \geq 0$. This implies that utility is concave in C and disutility is convex in P. We realize that it has been common to assume $U_{CP} \leq 0$, implying that an increase in consumption may increase

the marginal disutility for pollution. In this study, the separable utility form, i.e., $U(C, P) = U_1(C) - U_2(P)$, is assumed for simplicity, which implies $U_{CP} = 0$[4].

(4) As stated above, the processes of production and pollution abatement exist simultaneously in economic activities. Besides the common factor of capital[5], the expenditure on pollution control, or the costs of pollution abatement, as an input enters the processes to produce two outputs. One is a good output - the composite commodity; and the another is a bad output - the pollution emission. Therefore, the evolution of the economy can be defined by the movement of capital stock $K(t)$ for both one-state-variable and two-state-variable models, and additionally that of pollution stock $P(t)$ for the two-state-variable model in the following differential equations in terms of a social planner's problem[6]:

$$\begin{aligned} \dot{K}(t) &= F(K,\, X) - \pi K(t) - C(t), \\ \dot{P}(t) &= G(K,\, X) - \delta P(t), \end{aligned}$$

where π and δ are the depreciation rate of production capital and the decay rate of pollution stock, respectively.

Both processes of production and pollution abatement improve social welfare by increasing people's utilities. Higher production level provides more commodities, while pollution abatement offers better amenities. Allotment between the capital investment

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[4] Michel and Rotillon [1995] have proved that, for the social optimum problem, both separable utility functional form ($U_{CP} = 0$), and the "distaste" effect utility form ($U_{CP} < 0$) conclude with the same results that admit a stationary optimal solution with finite levels of consumption, capital stock and pollution. In their study, they also show that when the pollution abatement is efficient enough, the optimal solution will lead the economy to unlimited growth, whatever the form of utility function the problem has.

[5] Note that the factor of labor is not considered separately in the functional form of production.

[6] Note that, unlike an individual producer, a social planner recognizes each firm's increase in its capital stock and adds to the aggregate capital stock and, hence, contributes to the productivity of all other firms in the economy. Therefore, a planner's problem is to maximize the utility function subject to the accumulation constraints.

on production and the expenditure on pollution abatement implies that there is a welfare trade-off. The strategy of optimal allotment may provide a possibility that the environmental quality is improved with economic growth, what is referred to as a "win-win" outcome, the situation of EKC along the downward sloping portion of the curve after the peak of the turning point is reached. However, since resources being used in one process will inevitably reduce the availability that can be used in another process, such a "win-win" outcome seems less likely to be achieved if the total amount of available resources is much limited, especially for a country whose economic level is very low.

(5) The public goods nature of pollution reflects the fact that the effect of pollution, no matter what source it comes from, has influence on the whole society. In obtaining the explicit solutions of the theoretical results, it may be convenient to specify the functional forms. For this purpose, a particular functional form for production output at a society's aggregate level can be assumed as follows:

$$Y = AK^{\alpha},$$

where Y is an aggregate output level, K is the aggregate capital stock, A is technological coefficient, and α is a capital return rate (or, conventionally capital-share coefficient), in which $A > 0$, $\frac{1}{2} < \alpha < 1$. Here, the aggregate capital stock (K) can be defined as a broad concept of capital that encompasses components of physical capital, human capital, knowledge, and public infrastructure, and whatever can bring returns to the investments.

Note that we restrict the conventional capital-share coefficient (α) to fall in the range between $\frac{1}{2}$ and 1 in this study, which is consistent with the empirical facts derived from the neoclassical model in the existing literatures that require a much higher capital-share coefficient. As we know, in the Solow-Swan model, the rate of convergence depends inversely on the capital share, because a smaller capital share means that diminishing returns set in more rapidly. To accord with an observed rate of convergence of about two percent per year, it requires the value of α to around 0.75. This relatively high capital share is even reasonable for an expanded measure of the capital stock that also includes human capital. Thus, with a broad concept of capital, the Solow-Swan model can generate the rates of convergence that have been observed empirically, whereas the capital share should be relatively high. A relatively high value of α also fits the pattern of the Ramsey model. In the Ramsey growth model, the transitional pattern for the saving rate depends on whether the saving rate at the steady state (s^*) is greater than, equal to, or less than $\frac{1}{\theta}$, the elasticity of substitution for the utility, which is in turn associated with the capital-share coefficient, α. The intertemporal-substitution effect requires that the saving rate is not falling during the transition to the steady state, which implies that the rate of saving (s^*) to be greater than or equal to $\frac{1}{\theta}$. And the condition, $\theta > \frac{1}{\alpha}$, ensures that $s^* \geq \frac{1}{\theta}$ is satisfied[7]. Values of α in the neighborhood of 0.75 accord better with the empirical evidence, followed with $\theta = 1.75$ that generates the constant saving rate. In contrast, if $\alpha = 0.3$ is assumed, then the value of θ that generates a constant saving rate is 17. In the sense, $s^* < \frac{1}{\theta}$ applies and the saving rate falls, which is counterfactual to the reality as the economy develops[8]. However, we

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[7] For a detailed proof of the behavior of the saving rate, readers may refer to the book, "Economic Growth" by Barro & Sala-i-Martin [1995] on page 89-90.

[8] The steady-state saving rate, s^*, is given by

$$s^* = \alpha \cdot (x + n + \delta)/(\rho + \theta x + \delta),$$

where, x is the steady-state growth rate, n is the population growth rate, ρ is the rate of time preference, and δ is the capital depreciation rate. For the derivation, please refer to Barro & Sala-i-Martin [1995].

may reduce the required value of α to 0.5-0.6 if we assume very high values of θ (in excess of 10) along with a value of δ close to 0.

(6) Note that, in general, the emission function, $G(K, X)$, has the following properties[9]:

$$\begin{aligned} \frac{\partial G}{\partial K} &> 0, \ \frac{\partial G}{\partial X} < 0, \\ \frac{\partial^2 G}{\partial K^2} &\leq 0, \ \frac{\partial^2 G}{\partial X^2} \geq 0, \text{ and } \frac{\partial^2 G}{\partial K \partial X} = \frac{\partial^2 G}{\partial X \partial K} \leq 0. \end{aligned}$$

The first derivative terms, $\frac{\partial G}{\partial K} > 0$ and $\frac{\partial G}{\partial X} < 0$, imply that emissions increase with production capital, and decrease with abatement expenditure. For the second derivatives, this term $\frac{\partial^2 G}{\partial K^2} \leq 0$ implies that the marginal emission from capital is nonincreasing as K increases. If we have this term $\frac{\partial^2 G}{\partial X^2} \geq 0$, then the marginal decrease of emission is at a nonincreasing rate with the increase of unit abatement cost X. And the non-positive sign of the cross partial derivative term, $\frac{\partial^2 G}{\partial K \partial X} = \frac{\partial^2 G}{\partial X \partial K}$, reflects the fact that the marginal increase of emissions, $\frac{\partial G}{\partial K}$, is at a nonincreasing rate with the increase of abatement cost or, alternatively, the marginal decrease of emission, $\frac{\partial G}{\partial X}$, is nondecreasing when production scale becomes larger, *i.e.*, K becomes larger.

For convenience, an explicit functional form for pollution emission at the aggregate level can also be specified as follows, which satisfies the above properties:

$$G = \frac{BK^{\alpha}}{K^{1-\alpha}} - \phi X = BK^{2\alpha-1} - \phi X,$$

where G is an aggregate level of pollution emission, X is an abatement expenditure, and B and ϕ are intensity parameters of emission and abatement expenditure, respectively, in

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[9] The emission function exhibits concavity, i.e., $G_K > 0$, and $G_{KK} < 0$, as has been suggested by some authors including Tahvonen & Kuuluvainen [1993].

which, $B, \phi > 0$. Note that there are several ways to define the emission function as that of production, capital stock, and pollution control expenditure in the present literature. The emission function defined above assumes that pollution occurs at the time of production. That is, pollution is in general caused by production. With this form, the emission function, $G(K, X)$, is positively related to the aggregate output, negatively related to the pollution control expenditure. BK^{α} in the emission function results from the assumption of fixed proportion of output ($Y = AK^{\alpha}$) that generates the externality output, and the denominator of the first term, $K^{1-\alpha}$, captures the substitution effect between the capital stock and emissions. Because only one input factor, K, is considered to generate the output. When the effect of technological change is introduced in the production, besides that in the control of pollution process, more efficient use of energy inputs, for example, may cause the emission generation to decline with the increase of using these input factors. Thus, in the production process with simply one input factor, $K^{1-\alpha}$ is introduced to reflect such effect of technological change, as a result, to reduce the emission generating speed.

1.3 One-State-Variable Environmental Growth Model

Pollution as a stock or flow of physical substances impairs man's capacity to enjoy life. As a flow, pollution has a positive marginal product in the production function, and a negative effect on people's utilities. However, the stock of a pollutant confers a negative marginal utility and impairs production directly. Pollution can be considered as a flow or stock, depending on the natural decay rate of the pollutant.

Noticely, pollutants are treated as both flow and stock types in the work of many recent researchers, such as Ploeg (1991) and Stokey (1998). Both of them show that there is not much difference in affecting the optimal solutions when considering pollutants either as flows or stocks. In this study, pollution is first treated as the flow of a pollutant emitted as an inevitable by-product of production. People's utilities are affected by pollutants when they are dissolved by the environment immediately after being emitted. That is, the decay rate is high enough to assume total depreciation of a pollutant. However, during the process of production there is an amount of investment devoted to clean-up activities. Hence, a one-state-variable growth model can illustrate explicitly the situation of pollution problems in this context. Consider an optimal growth problem $[P_1]$ of a social planner as follows:

$[P_1]$

$$\max_{C,\,P,\,K,\,X\geq 0} \int_0^\infty U(C,\ P(K,\ X))e^{-\rho t}dt$$

subject to

$$\begin{aligned} \dot{K}(t) &= F(K,\ X) - \pi K(t) - C(t), \qquad (1.1) \\ P(t) &= G(K,\ X), \\ \rho &> 0, \end{aligned}$$

where,

$C(t)$ is the consumption level of composite commodity,

$P(t)$ is the pollution emission,

$K(t)$ is the capital stock for production,

$X(t)$ is the expenditure for pollution abatement,

$F(K, X)$ is the production function of output,

$G(K, X)$ is the function of pollution emissions,

ρ is the discount rate of time preference, and

π is the depreciation rate of the capital stock.

All the above variables are functions of time t. The parameter ρ is exogenously given.

1.3.1 Optimal Steady-State Equilibrium

To characterize the transitional growth path and the optimal solutions of the above problem, some assumptions on the utility function, production function and pollution emission function are necessary to make. For simplicity, a separable utility function and the AK^α production function are assumed. Moreover, we assume that the abatement effort is separable from the investment in production. Pollution emission is a by-product of the production process, increasing at a nonincreasing rate with capital investment. Rather, pollution abatement expenditure plays a role in restraining the magnitude of pollutants emitted during this process. Specifically, the utility function, production function and pollution emission function take the following particular forms:

$$U(C,\ P(K,\ X)) = \ln C - \beta P(t) \tag{1.2}$$

$$F(K,\ X) = AK^\alpha - X(t) \tag{1.3}$$

$$P(K,\ X) = BK^{2\alpha-1} - \phi X(t) \tag{1.4}$$

where, α, β, ϕ, A, and B are parameters for utility, production, and pollution emission functions, which satisfy β, ϕ, A, $B > 0$ and $\frac{1}{2} < \alpha < 1$.

Then, optimal control theory can be used to derive the optimal growth path. The current-value Hamiltonian of the problem can be written as:

$$H = \ln C - \beta\left(BK^{2\alpha-1} - \phi X(t)\right) + \lambda\left(AK^{\alpha} - X(t) - \pi K(t) - C(t)\right),$$

where λ is the co-state variable with respect to capital stock $K(t)$. Consumption, $C(t)$, expenditure on pollution abatement, $X(t)$, and thus pollution emission, $P(t)$, are control variables. The first-order necessary and transversality conditions can be obtained as follows:

FONC:

$$\begin{aligned} \frac{1}{C} - \lambda &= 0 && (1.5) \\ \beta\phi - \lambda &= 0 && (1.6) \\ \frac{\dot{\lambda}}{\lambda} &= (\rho + \pi) - \alpha A K^{\alpha-1} + \frac{B}{\phi}(2\alpha - 1)K^{2(\alpha-1)} && (1.7) \end{aligned}$$

TVC:

$$\lim_{t\to\infty} \lambda(t)K(t)e^{-\rho t} = 0, \tag{1.8}$$

By (1.5) and (1.6), we obtain, $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{C}}{C} = 0$, and $C^* = \frac{1}{\beta\phi}$. Combining with (1.7), the steady-state solution for the capital stock can be obtained. That is, $\frac{\dot{K}}{K} = 0$ and $K^* = \Phi^{\frac{1}{\alpha-1}}$, where $\Phi = \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\rho+\pi)}}{2B(2\alpha-1)}\right]$, a constant[10].

---

[10] $\alpha \neq \frac{1}{2}$ is provided by the assumption.

Reconsidering (1.1), (1.3), and (1.4), the steady-state solutions for the pollution abatement and emission levels are, therefore, the following equalities:

$$\begin{aligned} X^* &= A\Phi^{\frac{\alpha}{\alpha-1}} - \pi\Phi^{\frac{1}{\alpha-1}} - \frac{1}{\beta\phi} \\ P^* &= B\Phi^{\alpha} - \phi\left(A\Phi^{\frac{\alpha}{\alpha-1}} - \pi\Phi^{\frac{1}{\alpha-1}} - \frac{1}{\beta\phi}\right). \end{aligned}$$

Now, we turn to check the stability characteristics around the steady-state solutions. The general dynamic system of this problem can be defined by these two equations:

$$\begin{aligned} \dot{K} &= AK^{\alpha} - \pi K - X - C \\ \dot{\lambda} &= (\rho - \alpha AK^{\alpha-1} + \pi)\lambda + (2\alpha - 1)\beta BK^{2(\alpha-1)}. \end{aligned}$$

Then, the Jacobian matrix of this linearized system evaluated at the steady state is shown to be as this matrix,

$$J = \begin{bmatrix} \alpha AK^{\alpha-1} - \pi & 0 \\ 2(2\alpha-1)(\alpha-1)\beta BK^{2\alpha-3} - \alpha(\alpha-1)AK^{\alpha-2}\lambda & \rho - (\alpha AK^{\alpha-1} - \pi) \end{bmatrix}. \quad (1.9)$$

The characteristic roots $R_i (i = 1, 2)$ are the solutions of the characteristic equation

$$R^2 - (trJ)R + \Delta J = 0,$$

where trJ is the trace of J, and ΔJ is the determinant of J. Therefore, by assumption, we have,

$$trJ = \rho > 0. \quad (1.10)$$

From (1.7), at the steady state, we get,

$$\begin{aligned}(\rho+\pi)-(\alpha A-\frac{\alpha B}{\phi})K^{\alpha-1} &= 0,\\ &\quad or\\ \alpha AK^{\alpha-1}-\pi &= \rho+\frac{\alpha B}{\phi}K^{\alpha-1}. \qquad (1.11)\end{aligned}$$

That is,

$$\alpha AK^{\alpha-1}-\pi>\rho>0. \qquad (1.12)$$

From the Jacobian Matrix (1.9), we can obtain its determinant. Combining with (1.12), the following conditions can be achieved,

$$\begin{aligned}\Delta J &= [\rho(\alpha AK^{\alpha-1}-\pi)-(\alpha AK^{\alpha-1}-\pi)^2]<0, \qquad (1.13)\\ [tr(J)]^2-4(\Delta J) &= [\rho^2-4\rho(\alpha AK^{\alpha-1}-\pi)+4(\alpha AK^{\alpha-1}-\pi)^2]>0. \quad (1.14)\end{aligned}$$

From (1.10), (1.13), and (1.14), it can be seen that one root is positive, one is negative, and $[tr(J)]^2-4(\Delta J)\geq 0$, so the steady state we have obtained above is a stable saddle-point. This implies that the unique path converging to the steady state is optimal.

As a result, the optimal steady-state solution to the one-state-variable growth model incorporating environmental degradation can be summarized in Proposition 1.

Proposition 1 *Under a one-state-variable growth model with economic growth and pollution abatement [P_1], the optimal steady-state solution is* $\{C^*, K^*, X^*, P^*\}$, *such that it satisfies the first-order necessary conditions (*1.5*), (*1.6*), and (*1.7*), and the transversality* *condition (*1.8*). That is,*

$$
\begin{aligned}
C^* &= \frac{1}{\beta\phi} && (1.15)\\
K^* &= \Phi^{\frac{1}{\alpha-1}} && (1.16)\\
X^* &= A\Phi^{\frac{\alpha}{\alpha-1}} - \pi\Phi^{\frac{1}{\alpha-1}} - \frac{1}{\beta\phi} && (1.17)\\
P^* &= B\Phi^{\alpha} - \phi\left(A\Phi^{\frac{\alpha}{\alpha-1}} - \pi\Phi^{\frac{1}{\alpha-1}} - \frac{1}{\beta\phi}\right), && (1.18)
\end{aligned}
$$

where $\Phi = \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\rho+\pi)}}{2B(2\alpha-1)}\right]$, *a constant provided* $\alpha \neq \frac{1}{2}$, *and the growth rates,* $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{C}}{C} = \frac{\dot{K}}{K} = 0$, *at the steady state.*

1.3.2 Analysis of Transitional Dynamics

Equations (1.15) - (1.18) are the optimal solutions at the steady-state equilibrium to Problem [P$_1$]. The equations of motion for this problem can be described by the following equations, which satisfy the first-order necessary conditions and the capital stock constraint condition,

$$
\begin{aligned}
\dot{K}(t) &= F(K,\, X) - \pi K(t) - \frac{1}{\beta\phi}, && (1.19)\\
P &= G(K,\, X) = BK^{2\alpha-1} - \phi X. && (1.20)
\end{aligned}
$$

The evolution of the two equations can be depicted with phase diagrams as in Figure 2 of Appendix I, from which we can investigate the behavior of the system in the $(K,\, P)$ space.

Consider first the locus of stationary capital stock, $\dot{K} = 0$, then the slope of stationary capital stock is evaluated via Equation (1.19) as:

$$\frac{dP}{dK}\Big|_{\dot{K}=0} = \frac{F_K - \pi}{-F_X \cdot \frac{\partial X}{\partial P}} \gtreqless 0, \text{ as } K \lesseqgtr K^*, \tag{1.21}$$

where, K^* is the capital stock at the steady state with pollution emission for Problem [P$_1$][11]. According to the properties for production and pollution emission functions in the previous section, marginal productivity of abatement effort, F_X, is nonpositive, while abatement effort is increasing with pollution level. That is, $\frac{\partial X}{\partial P} > 0$. Thus, the denominator of Equation (1.21) is greater than zero. The slope, $\frac{dP}{dK}$, for line $\dot{K} = 0$, depends absolutely on the numerator, which reflects the marginal productivity of production less the capital natural depreciation rate. The capital natural depreciation rate is always less than the marginal productivity; otherwise, there will be no production activity. As conventionally believed, the marginal productivity of production increases at a decreasing rate. Therefore, the slope, $\frac{dP}{dK}$, is concave, turning to decline at the optimal level of the capital stock.

---

[11] Denote that $\hat{K}$ and $\hat{P}$ are the values of capital and pollution for which $\dot{K} = 0$ and $\dot{P} = 0$ simultaneously, i.e. the steady state values of K and P for the neoclassical growth model when pollution is ignored. Usually, this is called "Golden Age Equilibrium". In contrast, the steady-state solution is $\{K^*, P^*\}$ for Problem [P$_1$] of this study when the pollution problem is considered. Sometimes it is called "Murky Age Equilibrium" or "Polluted Golden Age Equilibrium". Keeler et al [1971], Forster [1972, 1973], Ploeg [1991], Tahvonen and Kuuluvainen [1993], have all concluded that the polluted steady state is less than the neoclassical steady state. That is,

$$K^* < \hat{K}, \text{ and } P^* < \hat{P},$$

which can be seen in Figure 2 in the appendix.

The behavior of pollution emission in the (K, P) phase plane can also be derived by Equation (1.20),

$$\frac{dP}{dK}|_{\dot{P}=0} = \frac{B(2\alpha - 1)K^{2(\alpha-1)}}{\phi\frac{\partial X}{\partial P} + 1} > 0, \text{ for all } K \in [0, \infty], \text{ since } \alpha > \frac{1}{2} \text{ is assumed.} \tag{1.22}$$

These results are shown in Figure 2 of Appendix I for $\alpha > \frac{1}{2}$. The $\dot{P} = 0$ and $\dot{K} = 0$ loci divide the space into four regions, and the arrows show the directions of motion in each region. The steady-state values for $\dot{P}$ and $\dot{K}$ are solved in the preceding section when the growth rate of the capital stock becomes zero. It also has been proved that there exists a saddle-point stability around the steady state. It is depicted in Figure 2 that the (K, P) system exhibits saddle-path stability. The stable arm is an upward-sloping curve that goes through the origin and the steady state. Along the transitional path, P^* and K^* converge toward their steady-state values.

The existence of a steady state implies that there is an optimal trajectory since it satisfies the sufficient conditions of optimality. We show that the steady state is a saddle-point in the sense that the unique path converging to the steady state is optimal. The analysis of transitional dynamics is useful for a social planner in searching for the optimal trajectories for $K(t)$, $C(t)$, $X(t)$, and implicitly $P(t)$ towards the steady-state equilibrium solution.

1.3.3 Implication of the Environmental Kuznets Curve

As for this study, the optimal trajectory of the interaction between pollution emission, $P(t)$, and capital stock, $K(t)$, is of most interest to us, because together they determine the optimal growth path of environmental quality. More importantly, the steady-state analysis and transitional dynamics of the above one-state-variable environmental growth problem [P$_1$] provide guidelines in obtaining the optimal environmental growth paths with interaction between $K(t)$ and $P(t)$ towards the steady-state equilibrium. Moreover, it can be demonstrated that the Environmental Kuznets Curve, i.e., the inverted U-shaped curve, is embedded within this simplest one-state-variable environmental growth model.

Existence of EKC

Reconsider problem [P$_1$]. For the sake of simplicity, specific functional forms for utility, production and pollution emission (1.2) - (1.4), and the first-order necessary conditions (1.5) and (1.6) are used to substitute into the constraint condition for the capital stock (1.1). This yields

$$P = \phi\dot{K} + BK^{2\alpha-1} - \phi AK^{\alpha} + \phi\pi K + \frac{1}{\beta}. \tag{1.23}$$

Considering that pollution emission (P) and capital stock (K) are invariant with time t, by definition, $\dot{K}$ can be approximately written as, $\dot{K} = \frac{K_t - K_0}{t}$, where K_0 is the initial value of the capital stock. Substituting into the above equation (1.23), we have

$$P_t = BK_t^{2\alpha-1} - \phi AK_t^{\alpha} + \phi(\frac{1}{t} + \pi)K_t - \frac{\phi}{t}K_0 + \frac{1}{\beta}. \tag{1.24}$$

For any time period t, Equation (1.24) can be differentiated with respect to capital stock, K_t, to get the expression as follows,

$$\frac{\partial P_t}{\partial K_t} = (2\alpha - 1)BK^{2(\alpha-1)} - \alpha\phi AK_t^{\alpha-1} + \phi(\frac{1}{t} + \pi). \tag{1.25}$$

From (1.25), the second derivative of pollution emission with respect to capital stock can also be obtained, that is,

$$\frac{\partial^2 P_t}{\partial K_t^2} = 2(2\alpha - 1)(\alpha - 1)BK^{2\alpha-3} - \alpha(\alpha - 1)\phi A K_t^{\alpha-2}. \tag{1.26}$$

As we know, the existence of the Environmental Kuznets Curve implies that the first derivative of pollution with respect to the capital stock is initially increasing, i.e., $\frac{\partial P_t}{\partial K_t} \geq 0$. After reaching a certain maximum point, $\tilde{K}_t > 0$, it turns down, i.e., $\frac{\partial P_t}{\partial K_t} \leq 0$. To rule out the possibility of discontinuity, it is reasonable to assume that the pollution function (1.24) with respect to K_t is concave. That is,

$$\frac{\partial^2 P_t}{\partial K_t^2} \leq 0, \;\; for \, \forall \, K_t \, , \tag{1.27}$$

which will be sufficient for EKC to exist in the environmental growth model. Therefore, the necessary and sufficient conditions for the existence of the inverted U-shaped Environmental Kuznets Curve can be defined as follows.

Definition 1: *An Environmental Kuznets Curve (EKC) exists if and only if the following necessary and sufficient conditions are satisfied.*

A) Necessary Conditions:

$$\begin{array}{rcl} For \; some \; \tilde{K}_t & > & 0, \\ (I) \, \dfrac{\partial P_t}{\partial K_t} & \geq & 0, \; when \; K_t \leq \tilde{K}_t \, , \;\; and \\ (II) \, \dfrac{\partial P_t}{\partial K_t} & \leq & 0, \; when \; K_t \geq \tilde{K}_t \, ; \end{array} \tag{1.28}$$

*B) Sufficient Condition: Condition (*1.28*) plus*

$$\frac{\partial^2 P_t}{\partial K_t^2} \leq 0, \; for \, \forall \, K_t \, . \tag{1.29}$$

Deriving Conditions for $\frac{\partial P_t}{\partial K_t} \geq 0$.

By (1.25), to ensure $\frac{\partial P_t}{\partial K_t} \geq 0$, it is required that the following condition be satisfied, that is,

$$(2\alpha - 1)BK^{2(\alpha-1)} - \alpha\phi A K_t^{\alpha-1} + \phi(\frac{1}{t} + \pi) \geq 0. \tag{1.30}$$

Based on the sign of this term $(2\alpha - 1)$, we may obtain the alternative conditions for $\frac{\partial P_t}{\partial K_t} \geq 0$, namely,

$$(A.I.1) \; If \; (2\alpha - 1) \; > \; 0, then \; K_t \leq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha - 1)(\frac{1}{t} + \pi)}}{2B(2\alpha - 1)} \right]^{\frac{1}{\alpha-1}} \tag{1.31}$$

$$(A.I.2) \; If \; (2\alpha - 1) \; < \; 0, then \; K_t \geq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha - 1)(\frac{1}{t} + \pi)}}{2B(2\alpha - 1)} \right]^{\frac{1}{\alpha-1}} \tag{1.32}$$

Deriving Conditions for $\frac{\partial P_t}{\partial K_t} \leq 0$.

On the other hand, from Equation (1.25), we see that the following inequality is required in order to satisfy $\frac{\partial P_t}{\partial K_t} \leq 0$. That is,

$$(2\alpha - 1)BK^{2(\alpha-1)} - \alpha\phi A K_t^{\alpha-1} + \phi(\frac{1}{t} + \pi) \leq 0. \tag{1.33}$$

This implies that the conditions for $\frac{\partial P_t}{\partial K_t} \leq 0$ satisfy

$$(A.II.1)\ If\ (2\alpha - 1)\ >\ 0, then\ K_t \geq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha - 1)(\frac{1}{t} + \pi)}}{2B(2\alpha - 1)} \right]^{\frac{1}{\alpha - 1}} \quad (1.34)$$

$$(A.II.2)\ If\ (2\alpha - 1)\ <\ 0, then\ K_t \leq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha - 1)(\frac{1}{t} + \pi)}}{2B(2\alpha - 1)} \right]^{\frac{1}{\alpha - 1}} \quad (1.35)$$

Deriving Conditions for $\frac{\partial^2 P_t}{\partial K_t^2} \leq 0$.

As we know, the concavity condition for the pollution function, along with the necessary conditions, suffices to guarantee that the Environmental Kuznets Curve exists. In other words, the second derivative of pollution emission in terms of the capital stock, $\frac{\partial^2 P_t}{\partial K_t^2}$, must be non-positive. By (1.26), it should satisfy this statement,

$$(B)\ \frac{\partial^2 P_t}{\partial K_t^2} \leq 0,\ only\ if\ \frac{1}{2} < \alpha < 1, \quad (1.36)$$

which is virtually the condition ensuring the existence of EKC.

Combining (1.31) - (1.32) for the first derivative $\frac{\partial P_t}{\partial K_t} \geq 0$, (1.34) - (1.35) for the first derivative $\frac{\partial P_t}{\partial K_t} \leq 0$, and (1.36) for the second derivative $\frac{\partial^2 P_t}{\partial K_t^2} \leq 0$, and then cancelling out the contradicting parts, we may obtain the following necessary conditions (1.37) and (1.38) for the existence of EKC, such as,

$$\begin{aligned} \frac{\partial P_t}{\partial K_t} &\geq 0,\ iff\ \phi A^2 \geq 4\frac{(2\alpha - 1)}{\alpha^2} B(\frac{1}{t} + \pi),\ and\ \frac{1}{2} < \alpha < 1, \\ when\ K_t &\leq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha - 1)(\frac{1}{t} + \pi)}}{2B(2\alpha - 1)} \right]^{\frac{1}{\alpha - 1}}; \end{aligned} \quad (1.37)$$

and

$$
\begin{aligned}
\frac{\partial P_t}{\partial K_t} &\leq 0,\ iff\ \phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi),\ \ and\, \frac{1}{2} < \alpha < 1, \\
when\ K_t &\geq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}}. \qquad (1.38)
\end{aligned}
$$

Since (1.37) and (1.38) satisfy the second derivative $\frac{\partial^2 P_t}{\partial K_t^2} \leq 0$ for EKC, reconsidering the definition of the existence of EKC in (1.28), we can summarize the existence of EKC into the following statements,

$$
\begin{aligned}
& To\ satisfy\ (1)\ and\ (2), \\
(1)\ If\ K_t &\leq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}},\ then\ \frac{\partial P_t}{\partial K_t} \geq 0; \\
(2)\ If\ K_t &\geq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}},\ then\ \frac{\partial P_t}{\partial K_t} \leq 0, \\
& if\ and\ only\ if\ the\ conditions, \qquad (1.39) \\
\phi A^2 &\geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi),\ \ and\, \frac{1}{2} < \alpha < 1, \\
& are\ satisfied, where\ the\ switching\ point, \\
\tilde{K}_t &= \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}}.
\end{aligned}
$$

As a result, it is essential to have $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)\ and\ \alpha > \frac{1}{2}$ (the latter condition is actually provided by the assumption) in order to ensure EKC to exist in this one-state-variable environmental growth model. Alternatively, EKC is embedded in the one-state-variable environmental growth model, based on the above conditions being satisfied. Here, B is an intensity parameter of pollution emission, ϕ is a parameter of abatement technology, and A, α are commonly production parameters for technological change and the capital return rate, respectively. Thus, the existence of the Environmental Kuznets Curve depends on the combining effects of the intensity of pollution emission, production and pollution abatement technologies, and the return rate of capital stock.

Turning Point of EKC

Now, we need to explore the turning point for the Environmental Kuznets Curve. Further considering Equations (1.19) and (1.20), and differentiating with respect to time t, this yields

$$\dot{P} = \left[(2\alpha - 1)BK^{2(\alpha-1)} - \alpha\phi AK^{\alpha-1} + \phi\pi)\right]\dot{K} + \phi\ddot{K}, \tag{1.40}$$

the sign of which depends on the accumulating rate of capital stock over time.

- Case 1: when the capital stock accumulates at a constant rate, that is, a constant return to scale economy over time[12], then $\ddot{K} = 0$ and the turning point of capital stock, $\widetilde{K^C}$, is

$$\widetilde{K^C} = \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi\pi B(2\alpha - 1)}}{2B(2\alpha - 1)}\right]^{\frac{1}{\alpha-1}}, \tag{1.41}$$

  whereby the pollution emission turns to decline.

---

[12] Slightly different from the definition for "economy of scale" as the size of an economic body, i.e., larger firms tend to enjoy economies of scale advantages over their smaller competitors in profiting more and losing less facing the same market situation, we define the "economy of scale", alternatively, "increasing returns to scale", in the context of this research as "reduction in cost per unit resulting from increased production", or "increasing in the return rate of per unit input factor", realized through the production process. Economies of scale can be accomplished because as production increases, the cost of producing each additional unit falls and the operational efficiency increases.

Similarly, the constant return to scale (or the economy of scale is constant return to scale), and the decreasing return to scale (or the economy of scale is decreasing return to scale), can be defined accordingly in the above context.

- Case 2: when the capital stock accumulates at an increasing rate for the economy, that is, an increasing return to scale economy over time, then $\ddot{K} > 0$ and the turning point of capital stock, $\widetilde{K^I}$, will be

$$0 < \widetilde{K^C} < \widetilde{K^I} < K^*,$$

where K^* is the optimal capital stock at the steady state.

- Case 3: when the capital stock accumulates at a decreasing rate for an economy, that is, a decreasing return to scale economy over time, then $\ddot{K} < 0$ and the turning point of capital stock, $\widetilde{K^D}$, will be

$$0 < \widetilde{K^D} < \widetilde{K^C}.$$

Therefore, the turning point levels of the capital stock, $\widetilde{K}(\widetilde{K^D}, \widetilde{K^C}, \widetilde{K^I})$, for the Environmental Kuznets Curve, which represent the income levels of an economy, vary depending on different scale of economy over time, as can be depicted in Figure 2.

1.4 Two-State-Variable Environmental Growth Model

As pointed out in the assumption section of Chapter One, some environmental degradation, such as heavy metals, deforestation and depletion of the ozone layer, is more reasonable to assume as a stock, because these pollutants are cumulative and self-decaying very slowly. More importantly, the distinction we made between a stock and flow relates directly to the control problem. As a social problem, we are frequently incapable of exercising direct control over the undesired quantity of the flow of pollutants. For planning purposes, then, it is more desirable to control the stock of pollutants. In this sense, studying of a pollution problem in the context of stock control theory is of an extremely importance. In addition, as indicated by some authors, such as Ploeg [1991], the marginal social damage from the stock of pollutants is lower than that from the flow of pollutants, due to the self-decaying effect of the pollution stock.

To illustrate the problem thoroughly, pollutants are treated as a stock in this section, where a two-state-variable environmental growth model may be more appropriately applied in this context. In this model setting, it is assumed that the pollution stock decays at a fixed rate given exogenously. Since the stock of pollutants confers a negative marginal utility, it enters the utility function as a flow, reflecting an increase of disutility when the stock of it is increasing. Moreover, the pollution stock is positively related to the flow of pollutants, while it is a direct increasing function with production investment. The latter part of the assumption implies another movement of a state variable, i.e., the movement of pollution stock, in addition to that of capital stock.

Formally, we can write the optimal growth problem [P_2] of the two-state-variable model for a social planner as follows:

[P_2]

$$\max_{C,\,P,\,K,\,X\geq 0} \int_0^\infty U\left(C,\ P\right) e^{-\rho t} dt$$

subject to

$$\dot{K}(t) = F(K,\ X) - \pi K(t) - C(t), \tag{1.42}$$

$$\dot{P}(t) = G(K,\ X) - \delta P(t), \tag{1.43}$$

$$\rho > 0,\ and\, 0 < \pi,\ \delta < 1.$$

where,

$C(t)$ is the consumption of composite commodity,

$P(t)$ is the pollution stock,

$K(t)$ is the capital stock for production,

$X(t)$ is the expenditure for pollution abatement,

$F(K, X)$ is the production function for output level,

$G(K, X)$ is the function of pollution emissions,

α is the capital share parameter for production function,

ρ is the discount rate of time preference,

π is the depreciation rate for capital stock K, and

δ is the decay rate of pollution stock P.

All of the above variables are functions of time t. The parameters, α, ρ, π, and δ are exogenously given.

1.4.1 Balanced Growth Path and Optimal Solutions

In this section, an optimal control theory is used to derive the optimal growth path. First we consider that the utility for consumption and disutility for pollution take the constant elasticity form. That is,

$$U_1(C) = \frac{C^{1-\sigma_1}}{1-\sigma_1}, \text{ and } U_2(C) = \beta\frac{P^{1+\sigma_2}}{1+\sigma_2}, \text{ with } \beta > 0,$$

where σ_1 and $-\sigma_2$ are called constant coefficients of intertemporal elasticity of substitution, or coefficients of relative risk aversion[13], for consumption C and pollution P with $\sigma_1, \sigma_2 \geq 0$.

Then, the current value Hamiltonian of the problem can be written as follows:

$$H = \frac{C^{1-\sigma_1}}{1-\sigma_1} - \beta\frac{P^{1+\sigma_2}}{1+\sigma_2} + \lambda_1\left[F(K,\,X) - \pi K(t) - C(t)\right] + \lambda_2\left[G(K,\,X) - \delta P(t)\right],$$

where λ_1, λ_2 are the co-state variables with respect to capital stock $K(t)$ and pollution stock $P(t)$, respectively. Consumption, $C(t)$, and expenditures on pollution abatement, $X(t)$, are control variables. The necessary and transversality conditions are thus obtained as follows:

---

[13] The risk aversion coefficients are defined as follows:
$-\frac{\dot{(\log U_1'(C))}}{\dot{(\log C)}} = -\frac{U_1''(C)}{U_1'(C)}C = \sigma_1$, and $-\frac{\dot{(\log U_2'(P))}}{\dot{(\log P)}} = -\frac{U_2''(P)}{U_2'(P)}P = -\sigma_2$.

FONC:

$$
\begin{aligned}
C^{-\sigma_1} - \lambda_1 &= 0, & (1.44)\\
\frac{\lambda_2}{\lambda_1} &= -\frac{F_X}{G_X}, & (1.45)\\
\frac{\dot{\lambda}_1}{\lambda_1} &= \rho + \pi - F_K - \frac{\lambda_2}{\lambda_1} G_K, & (1.46)\\
\frac{\dot{\lambda}_2}{\lambda_2} &= \rho + \delta + \frac{\beta P^{\sigma_2}}{\lambda_2}. & (1.47)
\end{aligned}
$$

TVC:

$$
\begin{aligned}
\lim_{t\to\infty} \lambda_1(t) K(t) e^{-\rho t} &= 0, & (1.48)\\
\lim_{t\to\infty} \lambda_2(t) P(t) e^{-\rho t} &= 0. & (1.49)
\end{aligned}
$$

Taking logarithms on both sides of (1.44), and differentiating it with respect to time t, it yields

$$\frac{\dot{\lambda}_1}{\lambda_1} = -\sigma_1 \frac{\dot{C}}{C}, \text{ or } \frac{\dot{C}}{C} = -\frac{1}{\sigma_1}\frac{\dot{\lambda}_1}{\lambda_1}.$$

We know that, along the balanced-growth path for the two-state-variable growth model, the growth rates are $\frac{\dot{C}}{C} = \frac{\dot{K}}{K} = \frac{\dot{X}}{X}$, which grow at a common constant rate. Marginal products of F_K, F_X, G_K, and G_X are all constant. Thus, from (1.45), $\frac{\lambda_2}{\lambda_1}$ is constant, so that

$$\frac{\dot{\lambda}_1}{\lambda_1} = \frac{\dot{\lambda}_2}{\lambda_2} = \rho + \pi - F_K + \frac{F_X \cdot G_K}{G_X}.$$

Therefore,

$$\frac{\dot{C}}{C} = \frac{\dot{K}}{K} = \frac{\dot{X}}{X} = -\frac{1}{\sigma_1}(\rho + \pi - F_K + \frac{F_X \cdot G_K}{G_X}).$$

By (1.47), $\frac{P^{\sigma_2}}{\lambda_2}$ is constant, and thus we have

$$\frac{\dot{P}}{P}=\frac{1}{\sigma_2}\frac{\dot{\lambda}_2}{\lambda_2}=\frac{1}{\sigma_2}(\rho+\pi-F_K+\frac{F_X\cdot G_K}{G_X}),$$

which is also a constant.

Conclusively, the optimal balanced-growth path, as a solution to the two-state-variable growth model incorporating the environment, can be summarized in the following Proposition 2.

Proposition 2 *Under the two-state-variable growth model with economic growth and pollution control [P_2], the optimal balanced-growth path is* $\{C(t), X(t), K(t), P(t), \lambda_1(t), \lambda_2(t)\}_0^\infty$ *such that it satisfies (1.44) - (1.47) and the transversality conditions (1.48) - (1.49). That is, the optimal growth rates at the balanced path satisfy the following conditions:*

$$\frac{\dot{\lambda}_1}{\lambda_1} = \frac{\dot{\lambda}_2}{\lambda_2}=\rho+\pi-F_K+\frac{F_X\cdot G_K}{G_X}, \tag{1.50}$$

$$\frac{\dot{C}}{C} = \frac{\dot{K}}{K}=\frac{\dot{X}}{X}=-\frac{1}{\sigma_1}(\rho+\pi-F_K+\frac{F_X\cdot G_K}{G_X}), \tag{1.51}$$

$$\frac{\dot{P}}{P} = \frac{1}{\sigma_2}\frac{\dot{\lambda}_2}{\lambda_2}=\frac{1}{\sigma_2}(\rho+\pi-F_K+\frac{F_X\cdot G_K}{G_X}). \tag{1.52}$$

To characterize the optimal solutions at the balanced-growth path explicitly, specific functional forms for production and pollution emission may be assumed. The production and pollution emission functions take the same specific forms as in the one-state-variable model. Besides, the more simplified log-utility functional form is replaced in the later study hereafter. Following the same procedure as above, we can derive the explicit expressions of the first-order necessary conditions using these specific functional forms, that is,

$$\begin{aligned}
\frac{1}{C}-\lambda_1 &= 0,\text{ or }\frac{\dot{C}}{C}=-\frac{\dot{\lambda}_1}{\lambda_1}, && (1.53)\\
\frac{\lambda_2}{\lambda_1} &= -\frac{1}{\phi},\text{ or }\frac{\dot{\lambda}_1}{\lambda_1}=\frac{\dot{\lambda}_2}{\lambda_2}, && (1.54)\\
\frac{\dot{\lambda}_1}{\lambda_1} &= \rho+\pi-\alpha A K^{\alpha-1}-\frac{\lambda_2}{\lambda_1}(2\alpha-1)BK^{2(\alpha-1)}, && (1.55)\\
\frac{\dot{\lambda}_2}{\lambda_2} &= \rho+\delta+\frac{\beta}{\lambda_2}. && (1.56)
\end{aligned}$$

Denote the constant growth rates at the balanced-growth path as

$$\begin{aligned}
\frac{\dot{C}}{C} &= \frac{\dot{X}}{X}=\frac{\dot{K}}{K}=v,\\
\frac{\dot{P}}{P} &= v_p.
\end{aligned}$$

Combining with the constraint conditions for the capital stock and pollution stock, (1.42) and (1.43), the optimal solutions at the balanced-growth path for the two-state-variable environmental growth model [P$_2$] can be achieved as below:

$$\begin{aligned}
C^* &= \frac{\rho+\delta+v}{\beta\phi}, && (1.57)\\
K^* &= \Psi^{\frac{1}{\alpha-1}}, && (1.58)\\
X^* &= A\Psi^{\frac{\alpha}{\alpha-1}}-(\pi+v)\Psi^{\frac{1}{\alpha-1}}-\frac{\rho+\delta+v}{\beta\phi}, && (1.59)\\
P^* &= \frac{1}{\delta+v_p}\left[B\Psi^{\frac{\alpha}{\alpha-1}}-\phi\left(A\Psi^{\frac{\alpha}{\alpha-1}}-(\pi+v)\Psi^{\frac{1}{\alpha-1}}-\frac{\rho+\delta+v}{\beta\phi}\right)\right]. && (1.60)
\end{aligned}$$

where $\Psi = \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\rho+\pi+v)}}{2B(2\alpha-1)}\right]$, a constant[14]. The growth rates are $\frac{\dot{C}}{C} = \frac{\dot{X}}{X} = \frac{\dot{K}}{K} = v$, $\frac{\dot{P}}{P} = v_p$, and $\frac{\dot{\lambda}_1}{\lambda_1} = \frac{\dot{\lambda}_2}{\lambda_2} = -v$, which are all constant at the balanced-growth path.

As in the one-state-variable model, we can check for the stability characteristics in the neighborhood of the balanced path by the following dynamic system of four equations for this problem:

$$\begin{aligned}
\dot{K} &= AK^{\alpha} - \pi K - X - C \\
\dot{P} &= BK^{2\alpha-1} - \phi X - \delta P \\
\dot{\lambda}_1 &= \rho\lambda_1 - (\alpha AK^{\alpha-1} - \pi)\lambda_1 - (2\alpha-1)BK^{2(\alpha-1)}\lambda_2 \\
\dot{\lambda}_2 &= (\rho+\delta)\lambda_2 + \beta.
\end{aligned}$$

Then, the Jacobian matrix of the system is

$$J = \begin{bmatrix} \alpha AK^{\alpha-1} - \pi & 0 & 0 & 0 \\ (2\alpha-1)BK^{2(\alpha-1)} & -\delta & 0 & 0 \\ Q & 0 & \rho - (\alpha AK^{\alpha-1} - \pi) & -(2\alpha-1)BK^{2(\alpha-1)} \\ 0 & 0 & 0 & \rho+\delta \end{bmatrix},$$

where $Q = -\alpha(\alpha-1)AK^{\alpha-2}\lambda_1 - 2(2\alpha-1)(\alpha-1)BK^{2(\alpha-1)}\lambda_2$. In turn, the characteristic equation can be written out as:

$$R^4 - (trJ)R^3 + (\Omega J)R^2 - (\Pi J)R + \Delta J = 0,$$

where $R_i (i = 1, ..., 4)$ are the characteristic roots to the above equation, ΩJ and ΠJ are the sum of all diagonal second and third order minors of J, respectively, and ΔJ is the determinant of J.

---

[14] Actually, there are two roots for $\Psi = K^{(\alpha-1)}$. Because the other root contradicts the condition that $\frac{1}{2} < \alpha < 1$, thus is discarded.

By some mathematical manipulations, it can be shown that this equation has real solutions with two being negative and two being positive, which implies that the balanced-growth path is indeed asymptotically stable with saddle-point properties. Therefore, the unique path converging to the balanced-growth path is optimal.

Proposition 3 *Under a two-state-variable growth model with economic growth and pollution abatement [P_2], the optimal solution at the balanced-growth path is* $\{C^*, K^*, X^*, P^*\}$ *in (1.57) - (1.60), such that it satisfies the first-order necessary conditions (1.53) - (1.56), and the transversality conditions (1.48) - (1.49).*

1.4.2 Analysis of Transitional Dynamics

Proposition Two concludes the existence of the balanced-growth path for the two-state-variable environmental growth model, while Proposition Three summarizes the optimal solutions at the balanced-growth path. The equations of motion for this problem, which describe the paths of transitional dynamics towards the optimal growth path, can be written out by the following equations. As before, these equations satisfy the first-order necessary conditions and the constraint conditions for the capital stock and pollution stock.

$$\begin{aligned}
\dot{K} &= F(K, X) - \pi K - C = AK^{\alpha} - X(P) - \pi K - \frac{\rho + \delta + v}{\phi\beta} \qquad (1.61)\\
\dot{P} &= G(K, X) - \delta P = BK^{2\alpha - 1} - \phi X(P) - \delta P. \qquad (1.62)
\end{aligned}$$

The evolution of the two equations may be depicted in a phase diagram similarly shown in Figure 2, from which we may investigate the behavior of the system for only the

(K, P) phase plane. Consider first the behavior of capital stock. From (1.61), we obtain

$$\frac{dP}{dK}\Big|_{\dot{K}=0} = \frac{F_K - \pi}{\frac{\partial X}{\partial P}} \gtreqless 0, \text{ as } K \lesseqgtr K^*. \tag{1.63}$$

According to the properties of the production and emission functions, the derivative of $\frac{dX}{dP}$ in the denominator is positive. And the numerator reflects the marginal productivity of production[15], which is increasing at decreasing rate. Therefore, the sign of the slope, $\frac{dP}{dK}$, will switch from initially positive to negative after the capital stock reaches the optimal level.

Similarly, we look at the slope of $\frac{dP}{dK}|_{\dot{P}=0}$ for (1.62) in the (K, P) space. It shows that

$$\frac{dP}{dK}\Big|_{\dot{P}=0} = \frac{B(2\alpha - 1)K^{2(\alpha-1)}}{\phi\frac{\partial X}{\partial P} + \delta} \geq 0, \text{ for } \alpha > \frac{1}{2}. \tag{1.64}$$

Since the numerator is the marginal pollution emission level with respect to the capital stock, as we know from the previous section that its sign depends on the magnitude of the parameter α, and $\frac{dX}{dP}$ in the denominator is positive. And by assumption, ϕ and δ are positive parameters. Thus, the slope, $\frac{dP}{dK}$, for the line $\dot{P} = 0$, will be increasing in the (K, P) phase plane. The phase diagram which illustrates the behavior of only the (K, P) space can be similarly shown in Figure 2. As in the one-state-variable growth model, the (K, P) system exhibits a saddle-path stability. The stable arm is an upward-sloping curve that goes through the origin and the optimal balanced path solution. Along the transitional path, P^* and K^* converge toward their optimal values at the balanced-growth path.

---

[15] Since the rate of marginal productivity will be greater than the capital natural depreciation rate, otherwise, there will be no production activity, the two terms in the numerator will be finally determined by the first one, the marginal productivity of capital stock.

1.4.3 Implication of the Environmental Kuznets Curve

Understanding of the optimal trajectory of the interaction between pollution emission, $P(t)$, and capital stock, $K(t)$, is of particular importance, as it implies the optimal path of environmental quality. As in the one-state-variable environmental growth model, the Environmental Kuznets Curve, or inverted U-shaped curve, can also be derived from the two-state-variable environmental growth model.

Existence of EKC

Reconsidering the constraint conditions for capital stock and pollution stock in (1.61) and (1.62), substituting (1.61) into (1.62) for X, this yields

$$\dot{P} = BK^{2\alpha-1} - \phi AK^{\alpha} + \phi\pi K + \phi\dot{K} + \frac{\rho+\delta+v}{\beta} - \delta P. \tag{1.65}$$

Considering that P and K are invariant in time t, $\dot{K}$ can be approximately written as $\dot{K} = \frac{K_t - K_0}{t}$. Substituting $\dot{K} = \frac{K_t - K_0}{t}$ into Equation (1.65), we get this expression,

$$\dot{P} = BK^{2\alpha-1} - \phi AK^{\alpha} + \phi\pi K + \phi\frac{K_t - K_0}{t} + \frac{\rho+\delta+v}{\beta} - \delta P. \tag{1.66}$$

Solving the above differentiation equation for P, we get

$$P_t = \frac{B}{\delta}K_t^{2\alpha-1} - \frac{\phi A}{\delta}K_t^{\alpha} + \frac{\phi}{\delta}(\frac{1}{t} + \pi)K_t - \frac{\phi}{\delta t}K_0 + e^{-\delta t}D\ , \tag{1.67}$$

where D is an arbitrary constant from the differentiation equation.

For any time period t, the first-order derivative of the pollution stock in terms of the capital stock can be obtained in the following expression,

$$\frac{\partial P_t}{\partial K_t} = \frac{B}{\delta}(2\alpha - 1)K^{2(\alpha-1)} - \frac{\phi A}{\delta}K_t^{\alpha-1} + \frac{\phi}{\delta}(\frac{1}{t} + \pi). \tag{1.68}$$

And the second derivative of pollution emission with respect to capital stock can be obtained accordingly, that is,

$$\frac{\partial^2 P_t}{\partial K_t^2} = \frac{2B}{\delta}(2\alpha - 1)(\alpha - 1)K^{2\alpha-3} - \frac{\alpha\phi A}{\delta}(\alpha - 1)K_t^{\alpha-2}. \tag{1.69}$$

As in the one-state-variable model, the following part verifies the existence of the Environmental Kuznets Curve for the two-state-variable model.

Since α, δ, B are all positive parameters in (1.68), to ensure $\frac{\partial P_t}{\partial K_t} \geq 0$, it is necessary that the following condition be satisfied:

$$\frac{B}{\delta}(2\alpha - 1)K^{2(\alpha-1)} - \frac{\phi A}{\delta}K_t^{\alpha-1} + \frac{\phi}{\delta}(\frac{1}{t} + \pi) \geq 0. \tag{1.70}$$

Since δ is positive, it can be cancelled out from the inequality (1.70). It turns out that the condition for $\frac{\partial P_t}{\partial K_t} \geq 0$ is exactly the same as that in the one-state-variable model, that is,

$$B(2\alpha - 1)K^{2(\alpha-1)} - \phi A K_t^{\alpha-1} + \phi(\frac{1}{t} + \pi) \geq 0, \tag{1.71}$$

where (1.71) is the same as (1.30) in the one-state-variable model for $\frac{\partial P_t}{\partial K_t} \geq 0$.

Correspondingly, after the positive δ term has been cancelled out from both sides of the inequality, the condition for $\frac{\partial P_t}{\partial K_t} \leq 0$ in the two-state-variable model is also the same as that for the one-state-variable model, that is,

$$B(2\alpha - 1)K^{2(\alpha-1)} - \phi A K_t^{\alpha-1} + \phi(\frac{1}{t} + \pi) \leq 0. \tag{1.72}$$

By comparison, we see that Equation (1.72) is same as Equation (1.33) in the one-state-variable model for $\frac{\partial P_t}{\partial K_t} \leq 0$.

Similarly, to ensure that the above necessary condition is sufficient, the pollution emission function of the two-state-variable model (1.67) must be concave in capital stock.

In other words, the second derivative of pollution emission in terms of capital stock must be non-positive, which can be evaluated from (1.69) as,

$$(B)\ \frac{\partial^2 P_t}{\partial K_t^2} \leq 0,\ only\ if\ \frac{1}{2} < \alpha < 1. \tag{1.73}$$

As a result, this condition for the two-state-variable model is the same as that for the one-state-variable model. Therefore, it can be concluded that the necessary and sufficient conditions for both models will be exactly the same. By written out, the necessary conditions for the existence of EKC for the two-state-variable model can be expressed as follows:

$$\begin{aligned} \frac{\partial P_t}{\partial K_t} &\geq 0,\ iff\ \phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi),\ \ and\ \frac{1}{2} < \alpha < 1, \\ when\ K_t &\leq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}}; \end{aligned} \tag{1.74}$$

and

$$\begin{aligned} \frac{\partial P_t}{\partial K_t} &\leq 0,\ iff\ \phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi),\ \ and\ \frac{1}{2} < \alpha < 1, \\ when\ K_t &\geq \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}}. \end{aligned} \tag{1.75}$$

By the definition of the existence of EKC in (1.28) and (1.29), combining (1.74), (1.75), and (1.73), the necessary and sufficient conditions of EKC for the two-state-variable model can be finally summarized in the following statements,

$$
\begin{aligned}
& To\ satisfy\ (1)\ and\ (2), \\
(1)\ If\ K_t &\leq \left[\frac{\phi(\frac{1}{t}+\pi)}{\alpha(\phi A - B)}\right]^{\frac{1}{\alpha-1}},\ then\ \frac{\partial P_t}{\partial K_t} \geq 0; \\
(2)\ If\ K_t &\geq \left[\frac{\phi(\frac{1}{t}+\pi)}{\alpha(\phi A - B)}\right]^{\frac{1}{\alpha-1}},\ then\ \frac{\partial P_t}{\partial K_t} \leq 0, \\
& if\ and\ only\ if\ the\ conditions, \\
\phi A^2 &\geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi),\ and\ \frac{1}{2} < \alpha < 1, \\
& are\ satisfied,\ where\ the\ switching\ point\ is \\
\tilde{K}_t &= \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi B(2\alpha-1)(\frac{1}{t}+\pi)}}{2B(2\alpha-1)}\right]^{\frac{1}{\alpha-1}}.
\end{aligned}
\tag{1.76}
$$

This result is exactly what we get for the one-state-variable model in the statement of (1.39). Therefore, until now, we have proved that the existence of the Environmental Kuznets Curve (EKC), namely inverted U-shaped curve, is embedded in both environmental growth models developed for this research.

In sum, the Environmental Kuznets Curve (EKC) being an inverted U-shaped only depends on the relational conditions of relevant parameters for the production and emission functions, that is, $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)\ and\ \alpha > \frac{1}{2}$, being satisfied, although $\alpha > \frac{1}{2}$ is guaranteed by the assumption. This implies that the existence of EKC requires that the intensity of pollution emission (B) due to production being outweighed by the combined effects of pollution abatement technology (ϕ) and capital production technology (A), along with a relatively high return rate of the capital stock.

Turning Point of EKC

Let us also investigate the turning point of income level for this problem. Reconsidering the constraint conditions (1.61) and (1.62) for Problem [P$_2$], solving the differentiation equation (1.62) for P, we have,

$$P\left(t\right)=\frac{BK^{2\alpha-1}-\phi X+e^{-\delta t}D\delta}{\delta}, \tag{1.77}$$

where D is an arbitrary constant.

Combining equations (1.61) and (1.77), and moving terms, we obtain the following equation,

$$P_t=\frac{B}{\delta}K_t^{2\alpha-1}-\frac{\phi A}{\delta}K_t^{\alpha}+\frac{\phi\pi}{\delta}K_t+\frac{\phi}{\delta}\dot{K}+e^{-\delta t}D+\frac{\rho+\delta+v}{\beta\delta}\,. \tag{1.78}$$

Differentiating (1.78) with respect to time t, we obtain the following equation of motion for pollution stock with respect to that for capital stock,

$$\dot{P}=\left(\frac{(2\alpha-1)B}{\delta}K^{2(\alpha-1)}-\frac{\alpha\phi A}{\delta}K^{\alpha-1}+\frac{\phi\pi}{\delta}\right)\dot{K}+\frac{\phi}{\delta}\ddot{K}-\delta De^{-\delta t}. \tag{1.79}$$

This equation of motion is similar to the one we obtain for the one-state-variable model, differing only in the last term, which reflects the decaying factor of the pollution stock. In the one-state-variable model, pollutants are treated as flows, whereby the decay rate of pollutants is ignored. As a result, there is no effect of pollution depreciation in the movement of the pollution stock.

Similar as in the one-state-variable model, it can be evaluated from Equation (1.79) that the turning point of capital stock, which represents the turning point of income level for an economy, depends on the economy of scale over time. For the constant return to scale economy when $\ddot{K} = 0$, the turning point is

$$\widetilde{K^C} = \left[\frac{\alpha\phi A - \sqrt{(\alpha\phi A)^2 - 4\phi\pi B(2\alpha - 1)}}{2B(2\alpha - 1)}\right]^{\frac{1}{\alpha-1}}. \tag{1.80}$$

Define $\widetilde{K^I}$, $\widetilde{K^D}$ as the turning points for an increasing return to scale economy, i.e. $\ddot{K} > 0$, and an decreasing return to scale economy, i.e. $\ddot{K} < 0$, respectively. Then from (1.79), it can be evaluated that,

$$0 < \widetilde{K^D} < \widetilde{K^C} < \widetilde{K^I} < K^*,$$

where, K^* is the optimal capital stock level at the balanced-growth path. This is exactly the same relational result of turning point levels as we obtain for the one-state-variable model. In comparison, the pollution stock of the two-state-variable model will be lower by a parallel decaying factor, $\delta De^{-\delta t}$, over the entire range of the capital stock, which is independent of the scale of economy. Therefore, the result of the two-state-variable model can be similarly illustrated by Figure 2 in the appendix.

1.5 Simulation of Theoretical Outcomes

In the previous sections, two theoretical models, the one-state-variable and two-state-variable models, have been developed to evaluate the hypothesis of the Environmental Kuznets Curve. It concludes that the existence of the Environmental Kuznets Curve depends on the intensity of pollution emission, the production and abatement technologies, and the return rate of capital stock, while the environmental turning point level in terms of income depends on the scale effect of an economy over time. In this section, some simulation methods will be used to verify the above theoretical results.

Conditions of the existence of EKC for both one-state-variable model (Equation 1.39) and two-state-variable model (Equation 1.76) imply that, when the effect of emission intensity outweighs the effect of technological improvement, then pollution emission tends to increase with income but at decreasing rate. This situation is likely to occur when an economy experiences an initial boom, and the capital return rate is relatively low. Eventually, it will turn to decline at certain level when the capital stock accumulates to the peak. On the other hand, when the technological effect dominates the emission intensity effect, which is likely when an economy is at the ripening stage, and the capital return rate is very high, then the pollution emission tends to reach the peak of the inverted U-shaped curve at a relatively fast speed. The Environmental Turning Point (ETP) is usually observed under this situation. By simulating the emission functions (1.24) and (1.67) at the optimality, the Environmental Kuznets Curve relationship can be depicted both numerically and graphically.

For the case when $\phi A^2 \leq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$, given the parameter values, $\alpha = 0.8$, $\beta = 0.01$, $\phi = 0.9$, $A_1 = 0.1$ (for Model 1), $A_2 = 1$ (for Model 2), $B = 10$, $\pi = 0.1$, $\delta = 0.9$, $K_0 = 0$, and $D = 100$, which satisfy the required assumptions, the optimal pollution emission functions (1.24) and (1.67) can be shown in Figure 3 and Figure 4 in Appendix J, separately, where $t = 1, 2, 3, 4, \textit{and } 5$ are represented by black, blue, green, red, and yellow-colored lines, respectively. As expected, pollution emissions are increasing with the increase of capital stocks for any fixed time period, but at a decreasing rate with the variation of both capital stock and time. However, the turning point is asymptotically approaching some level far from the simulation range, but hard to reach the exact value. For the two-state-variable model, there is a parallel decline in the intercepts with an increase of time t, which can be seen in Figure 4. This is because there exists an effect of the decay rate in the two-state-variable model that drives the environment to be self-improved, controlling for all the other factors.

In contrast, for the case when $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$ and $\alpha > \frac{1}{2}$, given the parameter values of $\alpha = 0.8$, $\beta = 0.01$, $\phi_1 = 0.9$ (for Model 1), $\phi_2 = 0.1$ (for Model 2), $A_1 = 10$ (for Model 1), $A_2 = 50$ (for Model 2), $B = 10$, $\pi = 0.1$, $\delta = 0.9$, $K_0 = 0$, and $D = 100$, the optimal emission functions (1.24) and (1.67) can be graphically displayed in Figure 5 for $t = 1, 2, 3, 4, \textit{and } 5$, and Figure 6 and Figure 7 for $t = 1$. Not surprisingly, the turning points of EKC, as expected, occur under such conditions, when the negative impacts of a dirty environment are offset fast by technological enhancement. In reality, the declining trend of environmental degradation is likely observed in those economies having relatively high growth rate along with also relatively high investments on pollution abatement efforts.

At the same time, under such conditions, the declining effect of environmental negativity (or improvement of environmental quality) is moving even faster with the increase of time t, controlling for all other factors. Figure 6 and Figure 7 show the relationship between capital stock and pollution emissions for a fixed time period, where the inverted U-shaped EKC is even more obvious.

Accordingly, Table 1.1-3.2 in Appendix B display the simulation results in numerical figures by using optimal conditions (1.24) and (1.67). The inverted U-shaped Environmental Kuznets Curve describing the relationship between capital stock and pollution emissions can also be examined by these tables.

In Table 1.1 and Table 1.2, for any fixed time period, pollution emissions are increasing with the capital stock, while such increasing rate is declining but at a very slow pace, as shown in the columns of the change of pollution emissions that becomes smaller with the increase of capital stocks. This pattern of the movement of pollution emissions applies to both one-state-variable and two-state-variable models in the case when the negative impacts of the pollution emissions are dominant, but the capital return rate is relatively low. However, the pollution emissions tend to be declining with time t for any fixed capital stock value, which can be observed horizontally across different time periods in Table 1.1 and 1.2. But, this fashion of the changing pattern can be observed even more clearly in Table 2.1 and 2.2, where pollution emissions are evaluated with the variation of time t for any fixed capital stock value.

Similarly as illustrated in the above graphical results, the switching points of the inverted U-shaped EKC are mostly observed in Table 3, the case when technology plays a leading role over the negative effect of the environmental degradation, along with a higher return rate of the capital stock, that is, $\alpha > \frac{1}{2}$. It can be shown that, in any time period of Table 3.1 and 3.2, pollution emissions are firstly increasing with capital stock, then decreasing for both one-state-variable and two-state-variable models. Examining each column of both tables, the signs of the change of pollution emissions are shifting from positive to negative at certain point when their values are declining all the way along with the increase of capital stock. This switching point is usually termed the turning point of the Environmental Kuznets Curve. Furthermore, the negative values of the change of pollution emissions start earlier when the time period increases to a higher level, which explains that the Environmental Kuznets Curve tends to be lower in terms of income level and with the increase of time whenever the time effect is our only consideration.

In sum, the above simulation results are consistent with those theoretical conclusions derived in the previous sections that EKC exists only when the interaction effect of the pollution abatement and production technology outweighs the effect of emission intensity due to production, and the capital stock experiences a higher return rate. Figures 3-7 and Tables 1.1-3.2 in Appendix J & B, respectively, summarize these simulation outcomes.

1.6 Theoretical Conclusions

Environmental pollution has long been regarded as a problem of externalities, one of the major factor that causes the market failure of a competitive economy. Traditional remedies, such as internalizing the externalities, for the market failure seems inadequate to achieve the desirable outcomes where the pollution problem is involved, since in many situations pollution and environmental problems are characterized by the problem of the commons. To deal with these matters may require some form of centralized coordination and control. Moreover, there are strong intertemporal aspects of the pollution problem, since pollution can accumulate or decay over time, in the sense that today's pollution can be a result of past investment and consumption decisions. These concerns for the environment give us the incentives of using the dynamic approach of control theory in tackling the pollution problem. Accordingly, the growth theory in the framework of neoclassical Ramsey model with care for the environment can be served as an appropriate model setting to analyze these problems. It has been found, however, there is a drawback of traditional growth models which focus only on the movement of the capital and consumption without considering environmental issues. Following the early studies, such as Keeler et al. [1971], Forster [1972], and more recently Ploeg [1991], Tahvonen and Kuuluvinen [1993], Seldon and Song [1995], Michel and Rotillon [1995], and Stokey [1998], this research uses the dynamic approach of control theory to analyze the pollution problem in the context of a neoclassical growth model, especially the growth path of environmental degradation.

Pollution is a pervasive phenomenon, which damages the environment either as a flow or as a stock. This paper distinguishes between stock and flow externalities arising from pollution. The distinction depends on the extent to which pollution tends to accumulate, which is, in turn, determined by the natural decay rate of pollutants. According to the different characteristics of pollution as a flow or as a stock, two separate environmental growth models involving pollution control are formulated in the preceding theoretical analysis. In the simple one-state-variable model, it is assumed that pollution can be characterized as a flow, in which pollutants are considered to be dissolved by the environment immediately after they are emitted. To reflect the characteristics of some other types of pollutants that are cumulative and self-decaying very slowly, a two-state-variable environmental growth model is also constructed where a combined effect of pollution emissions and their natural decay rate is assumed. In both models, production and pollution abatement are simultaneously employed to determine the optimal solutions for consumption, capital stock and pollution level. Resources are disaggregated among consumption, investment in production, and expenditure on pollution abatement. In the one-state-variable model, the pollution as flow emissions affects utility in a negative way, while in the two-state-variable model, the pollution accumulates as a stock that impairs people's welfare, and decays away at a fixed rate. Accordingly, the two-state-variable growth model includes additionally the movement of pollution stock which represents the change of environmental quality, differing from the simplest one-state-variable growth model, where only the movement of the capital stock is required to be involved. The purpose of developing the environmental growth models is to discover the optimal growth paths for the relationship between pollution and economic growth, which is helpful to verify the existence of the EKC hypothesis. It has been found that the theoretical outcomes of the two models are surprisingly similar in implying the existence of the EKC relationship between environmental degradation and economic growth, which is dependent on the combined effects of the intensity of pollution emission (B), abatement technology of pollution emission (ϕ), production technology (A), and the return rate of capital stock (α). However, the inverted U-shaped EKC is independent of whether pollution is a flow or a stock.

Both models in the theoretical analysis are under the setting of social optimum. In this sense, firms devote some resources to abate pollution in order to meet the emission standard during the production process. For the one-state-variable model with specific functional forms, there exists a unique steady state, implying that it is an optimal trajectory steady state, since it satisfies the necessary and sufficient conditions of the optimality. We have shown that the steady state is a saddle-point stability. Alternatively to say, in the one-state-variable model, the unique saddle-path converging to the steady state is optimal. For the two-state-variable model, there is a unique balanced growth path along which consumption, investment capital, and pollution abatement expenditure grow at a common constant rate. At the optimum, pollution stock accumulates at a constant rate, even though environmental degradation has been improved at a relatively low level. This encourages further efforts to abate the pollution, which is made possible by a positive growth rate of the capital stock. In this case, the dynamics is a little more complicated. However, the transitional path to the balanced-growth path is similar to the one-state-variable model, which is characterized as a saddle-path stability. Accordingly, for the two-state-variable model, the unique balanced-growth path with a saddle-path stability is optimal. Henceforth, with specific functional forms, the unique solutions obtained at the balanced-growth path are also the optimal solutions. In both models, the utility for consumption and disutility for pollution are assumed separable. Thereby, the result that there exists a unique optimal solution with saddle-point stability for both models with separable utility functional forms is consistent with those proved by Tahvonen and Kuuluvainen [1993] and Michel and Rotillon [1995][16].

Some conclusions may be drawn by comparing the optimal solutions of the two theoretical models. First, the optimal capital stock for the two-state-variable model when pollution is considered as a stock, is generally less than that for the one-state-variable model when pollution is treated as a flow. Second, the optimal consumption level is lower in the two-state-variable model than in the one-state-variable model, if $\rho + \delta + v < 1$ is satisfied. Vice versa, if $\rho + \delta + v > 1$, then the optimal consumption level of the two-state-variable model is higher than that of the one-state-variable model. The equality holds when $\rho + \delta + v = 1$. Third, the pollution abatement expenditure at the optimum differs in the two models depending on the combining effects of the differences of the optimal consumption and capital stock plus the constant growth rate of abatement expenditure. Finally, the difference of optimal pollution level for the two models is associated with the difference of abatement effort and additionally with the growth rate of pollution stock, which is in turn linked with the consumption and capital stock at the optimum.

The Environmental Kuznets Curve relationship for pollution and growth have been derived from the two growth models studied here. During the transition to a steady state (or balanced-growth path), the optimal pollution path displays an inverted U-shaped pattern, growing in the early stages of development and declining as the economy approaches the steady state. This optimal pollution-income relationship is the consequence of the dy-

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[16] Tahvonen and Kuuluvainen [1993], and Michel and Rotillon [1995] proved that, if $U_{CP} \leq 0$, i.e., separable utility or distaste effect utility forms are assumed, then the social optimal problem admits a stationary state, which is a unique saddle-point.

namic approach of the optimal control outcome for the neoclassical environmental growth models, which does not depend on the elasticity parameter of preferences. This is different from the result by Stokey [1998] in which pollution exhibits an inverted U shape if and only if the elasticity of marginal utility exceeds one. However, similar to that of Andreoni and Levinson [2000], in which the inverse U shape for pollution requires that the capital investment technology admits a higher return rate[17]. Besides, both the theoretical and simulation results of this study conclude that the Environmental Kuznets Curve (or inverted U-shaped curve) occurs only if the negative pollution effects due to production are outweighed by the production and abatement technologies, in addition that the investment return for capital is relatively high ($\alpha > \frac{1}{2}$). But different from this study of using growth theory and dynamic approach, their results (Andreoni and Levinson [2000]) are derived from a static model of the microfoundations of pollution-income relationship.

Furthermore, this paper concludes that the peak of the inverted U curve may occur differently with various income levels, depending on the scale of economy, alternatively to say, on the accumulating rate of capital stock. With fast accumulating rate of the capital stock, the turning point of the inverted U curve tends to peak at a higher income level. Vice versa, the turning point of the Environmental Kuznets Curve tends to occur at a lower income level when the economy develops at a relatively slow pace. This fashion of the change of income level for the environmental turning point (ETP) happens to both models in this study, which is independent of whether pollution is treated as a flow or as a stock. The only difference is that the pollution level (or environmental degradation condition) for

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[17] Slightly different from this study, Andreoni and Levinson [2001] emphasize that the inverted U-shaped curve for pollution requires that the capital investment on abatement technology is increasing return to scale.

the two-state-variable model when pollution is considered as a stock, will be lower (or improved) than that for the one-state-variable model when pollution is treated as a flow over the entire range of the income level, no matter what the economy of scale is. This is because that the decaying factor of the pollution stock is additionally taken into account in the two-state-variable growth model, but not in the one-state-variable model. These theoretical results are graphically illustrated in Figure 2.

It is worth pointing out that, in order to make the theoretical models simple in illustrating the EKC phenomenon, there nevertheless exist some limitations to the above theoretical study, such as the conclusions are drawn under a series of assumptions, and the model itself is derived in a closed economy in the sense that trade is not allowed.

Chapter 2
Empirical Studies

In the previous chapter, growth models incorporating environmental quality have been formulated and the theoretical results on the existence of the Environmental Kuznets Curve (EKC) and its peak turning point have been derived. In this chapter that follows, statistical and econometric methods will be used to further verify the existence of EKC and its turning point level empirically for some environmental indicators. In particular, attention will be focused on six major air pollutants, carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), suspended particulate matter (SPM), and volatile organic compound (VOC), using global panel data with 131 countries over 19 years. In addition, this empirical study will also examine the underlying causes that determine the EKC relationship.

2.1 Review of Previous Empirical Work

There are a large amount of the empirical EKC studies[18]. The approaches of these studies can be generally categorized into three groups.

The most conventional method of the first group is to use reduced-form models applying on a wide range of environmental indicators for either cross-country or individual country studies. The functional forms in the most general cases are linear, quadratic, and

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[18] Need to mention that research papers by Stern et. al [1996], Barbier [1997], and Stern [1998] provide a quite complete review on the empirical studies of the EKC relationship. However, the review hereafter provides a different perspective of views.

cubic, which can be in levels or logs. Different combinations of included independent variables provide various interpretations on the EKC theme. The most influential studies of this group include those by Shafik and Bandyopadhyay [1992], Panayotou [1993, 1995], Seldon and Song [1994], Grossman and Krueger [1991, 1995], Holtz-Eakin and Selden [1995], Cole et. al [1997], Carson et. al [1997], Vincent [1997], Stern and Common [2001], and Roca et. al [2001]. The first empirical study is given by Grossman and Krueger [1991] estimating the environmental impact of NAFTA for SO_2 and SPM using the GEMs data source[19]. Shafik and Bandyopadhyay's study is particularly influential that is used as a background study for the World Bank Development Report [1992]. They estimated EKCs for ten different indicators including air-quality, water-quality and deforestation studies[20]. Selden and Song estimated EKCs for four aggregate air emission indicators using data series from World Resource Institute. The environmental turning points estimated by them are higher than those of ambient concentration ETPs. Holtz-Eakin and Seldon adopt CO_2 emissions data by Oak Ridge National Laboratory (ORNL) to estimate the reduced-form relationship between per capita income and emissions, and then to forecast aggregate emissions and their distribution among countries. Panayotou estimated EKCs for SO_2, NO_x, SPM and deforestation, only employing cross-sectional data and using GDP in nominal

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[19] GEMs is a joint project of the World Health Organization and the UN Environmental Program. For almost two decades GEMs has monitored air and water quality in a cross-section of countries. The air quality data is obtained by monitoring the ambient concentration level at the observatory sites, mostly located in the urban areas of different countries.

[20] According to their report, air pollutants can be divided into three categories in terms of the shapes of the curves relating to the observed logarithmic GDP and air pollutant emissions. Firstly, some indicators display very strong inverted U curves in the full range such as CO, NO_x, and SO_2. That is, emission rises on the low-income levels until it reaches a peak, then it becomes to fall with an increase of GDP per capita. The second category of pollutants show monotonically increasing trends with income and the non-existence of the peak levels of emissions. CO_2 and VOC belong to these indicators. The other indicator, PM, has a declining trend of emissions as income rises (World Bank Report [1992]).

US dollars. The other studies use similar methodologies to examine EKC for some specific regions or individual countries. Cole et. al and Stern and Common investigated a wide range of environmental indicators particularly for OECD. Carson et. al studied seven types of air emission indicators across 50 US states, and Roca et. al estimated the EKC trends of six air pollutants in Spain. However, Vincent analyzed the EKC relationship for a single developing country, Malaysia. In general, their results show that for several pollutants, such as sulphur dioxide, there exists an inverted U-shaped relationship between pollution emissions or concentrations and income. But some empirical findings suggest that there is no such relationship for some other pollutants.

Although most of these studies use advanced statistical tools to correct for econometric problems, such as FGLS for heteroscedasticity and fixed-effects estimations for a random shock, they nevertheless tend to fall into some major problems with basic EKC estimates and their interpretations. Because these studies assume unidirectional causality between growth and environmental quality, they are likely to neglect some of the other determinants, such as structural change, technological improvement, associated with the course of development which also have effects on the change of environmental quality. As pointed out by Grossman and Krueger [1995], the disadvantage of a reduced-form model is that it is not clear why the estimated relationship exists and especially what kind of the interpretation should be given to the estimated coefficients of the polynomial.

In contrast to the reduced-form model, the second group of empirical studies deals with structural models. These studies have attempted to decompose the EKC relationship into a number of more fundamental underlying components such as structural change, scale effect and some other causes. Empirical work in this group include those by Ekins [1997], Moomaw and Unruh [1997], De Bruyn et. al [1998], Torras and Boyce [1998], Kaufmann et. al [1998], and Magnani [2001]. In Ekins' study, the environment-income relationship is expressed in terms of the economic sector. Therefore, his structural model states that the percentage change of environmental effects equals the percentage change of outputs plus two terms incorporating the change rates of technology and sectoral composition in outputs. In this sense, the increase in environmental effect due to the increase of output could be reduced by introducing an environmental improvement technology or by the sectoral composition shifting away from relatively pollution intensive sectors.

Using a similar derivation, the study of De Bruyn et. al resulted in a structural model stating that changes in emissions over time can be explained by changes in economic growth, plus changes in emission intensity of outputs and changes in the price of input related factors. The impacts of the technological and structural changes, as well as those of environmental policies, are supposed to be captured by the respective coefficients of these variables. When he interprets his structural model, Magnani decomposes the actual pollution into two quantities, incipient pollution which reflects the level and composition of production and policy induced abatement. He argues that the relationship between pollution emissions and development depends on how growth changes both components of pollution emissions. The downward sloping EKC will emerge if pollution abatement grows with per capita income enough to offset the high incipient pollution rates, characteristic of medium-income and high-income countries. Compared to the above studies, the other empirical work with structural models is more practical in nature. Moomaw and Unruh use a two-time-period model to test for the structural shift of per capita CO_2 emissions and per capita income due to historic events related to the oil price shocks of the 1970s and the policies that followed them. Torras and Boyce straightforwardly test the determinants of environmental policies, while Kaufmann et. al are concerned about rising population that they attempt to identify how changes in the level and spatial intensity of economic activity affects the atmospheric concentration of SO_2.

The advantage of dealing with a structural model is that the estimated coefficients are more conveniently interpreted as they are closely related to the underlying causes that determine the EKC relationship. It avoids some of the fundamental problems, such as simultaneity, or unidirectional causality, that commonly occurred in the reduced-form models. However, the analysis using a pure structural model is likely to deviate from the basic EKC theme and the linear coefficient of income term does not tell much stories of the true relationship between economic level and environmental quality. Besides, it seems difficult to carry out a rigorous and systematic decomposition of economic structure relating to the EKC relationship. This sort of analysis has, however, not been conducted yet. Although the limitations of the reduced-form model are obvious, the influence of income on environmental pressure is directly estimated under such a functional form.

In addition to the conventional reduced-form study of the EKC relationship, it has been recognized that understanding the determinants of EKC, such as structural change, technological progress, is of importance. The third group of empirical studies of the EKC relationship uses a combination of reduced-form and structural model approaches. Studies of this category include those by Panayotou [1997], Suri and Chapman [1998], and

Agras and Chapman [1999]. Panayotou claims that estimation of a reduced-form EKC should only be a first step to understand the environment-development relationship, not the endpoint. The improvement of the environment with income growth, however, is not automatic but depends on economic growth, pollution abatement effort, policies and institutions. In his study, Panayotou adjusted a cubic functional form that additionally includes GDP per square kilometer and the industrial share in GDP; both are in cubic and their interaction terms. According to his study on the global ambient SO_2 level, the turning point is around $5,000. Suri and Chapman focus on the impact of growth, international trade and structural change on the turning point of pollutants through their influence on the sources of emissions. In particular, they analyzed the impact of international trade explicitly on commercial energy consumption. They found that the introduction of a trade variable substantially raised the turning point of the curve for energy consumption to about $224,000. Agras and Chapman thus reformulate the traditional EKC model by including energy prices in a dynamic EKC relationship. They conclude that energy prices strongly influence EKCs for energy and CO_2, and trade is an important structural aspect of EKC. This group of empirical works attempts to make the EKC studies more realistic and thorough. However, it is likely that these studies retain the same shortcomings that exist in both of the above two groups, since it is unlikely to have consensus on which structural indicators should be included and what functional form the regression model should take without an underlying theoretical theme. Besides, in practice, there is little research work having taken into account both sides of the empirical studies focusing on the EKC relationship.

Since little work has been done to effectively combine a theory-based reduced-form with structural models to approach the EKC study, the empirical study of this research intends to make some contributions to the area and attempts to avoid some of the pitfalls existing in the prior work.

2.2 Econometric Model

In Chapter One, two environmental growth models have been formulated and analyzed, from which the relationship between economic growth and environmental quality has been theoretically derived. It appears that there exists the Kuznets (or inverted U-shaped) curve pattern between income and pollution. This chapter will, by employing global panel data, examine the impact on the movement of pollution as an economy grows empirically. Before formally proceeding to the econometric model, several points relating to the setup of the econometric model need to be clarified.

(1) From the theoretical results in Chapter One, there exists the EKC relationship between economic growth and pollution control, which depends on the marginal productivity of production and the scale of an economy that is in turn represented by the accumulation level of capital stocks, or income level of the economy. In fact, by using econometric methods, we can test for the existence of the EKC relationship and obtain the income level of the turning point where there is a change of state on pollution from deterioration to improvement. Specifically, a quadratic reduced-form can be used to verify the above theoretical result, where the signs and significance levels of coefficients for the linear and quadratic income terms are of great importance, which signaling whether an EKC or inverted U rela-

tionship between income and environment exists for certain indicator. If such relationship turns out to be true, we can also estimate the income value of its turning point.

(2) The theoretical model in Chapter One is formulated as a social optimum problem, in the sense that a social planner allocates natural resources between the capital investment on production and expenditure on pollution abatement efforts. This implies that the strategy of optimal allotment may provide a possibility that the environmental quality is improved with economic growth. In reality, government policies, including regulatory standards, pollution taxes and the creation of tradable emission permits, have been one of the most potent spurs to the pollution reducing efforts.

(3) The theoretical model is dynamic in nature, from which a dynamic optimal control theory is applied in obtaining the optimal solutions. However, as in so far, there is not much empirical literature on the EKC relationship taking this issue into consideration yet. Only Agras and Chapman [1999] analyze the impact of the lagged emission level on current emission level, which shows of little importance because the emission level depends on many other determinants, such as income level, policy stringency, economic structure, rather than its own historical information. In our econometric model, lagged income level and lagged gasoline price, which is the retail price at the pump after environmental tax, will be introduced in the model formulation to reflect the lagged effect of these determinants on the current pollution level.

(4) As has been pointed out in the above, there is a limitation of the theoretical model that conclusions are drawn under the assumption that the economy is closed. However, there is an increasing consensus that the empirical EKC relationship depends on some de-

terminants other than the income level, of which structural change, technological improvement, and environmental regulation are the most important and significant factors. As Panayotou [1993], Ekins [1997] and Stern [1998] argue, at low levels of development environmental degradation is limited. As economic development accelerates with the intensification of resource extraction, though, both the economy and environmental degradation undergo dramatic structural change from rural to urban, from agricultural to industrial. A second transformation begins at higher levels of development, structural change towards services and information-technology-intensive industries, coupled with increased environmental awareness and enforcement of environmental regulations, which result in a gradual decline of environmental degradation. Openness and international trade reflect structural change within economies and structural differences between economies. These arguments undoubtedly reinforce the EKC or inverted U hypothesis of the income-environmental relationship. In formulating the econometric model, variables reflecting sectoral structural change will be considered in addition to the quadratic reduced-form structure.

Based on the formulation of the above theoretical models, adjusting for the structural formation, and using a quadratic functional form as indicated by the theoretical model, the econometric model for this empirical study can be derived as follows. For any economic sector, k, the income-environmental relationship can be expressed as:

$$E_k = a_k y_k, \tag{2.81}$$

where E is the environmental emission level, y is the output of the sector, and a is a technical coefficient of the sector's emission intensity.

Then the aggregate emission level of total production for an economy can be expressed as:

$$E = \sum_k E_k = \sum_k a_k y_k = Y \sum_k A \frac{y_k}{Y} = AY \sum_k s_k, \tag{2.82}$$

where s_k is the share of sector k in total output, Y is the total income, or the level of GDP, and A is the technical coefficient of emission intensity for the economy.

Taking logarithms on both sides of equation (2.82), we obtain the following expression:

$$\ln E = \ln A + \ln Y + \ln \sum s_k. \tag{2.83}$$

The left-hand-side term in equation (2.83) is the effect of emission level of the economy, the first term of the right-hand-side of the equation is the effect of emission intensity due to technical change, which can be termed the technique effect[21]. The second term is the effect of output that can be called the scale effect. And the third term incorporates the structural transformation among sectors that can be termed the structural transformation effect and the aggregate change of sectoral shares in GDP within a sector due to the effect of economic development on the environment.

Notably, energy prices have played a role, through government regulation, in lowering the level of emission via more rational use of resources and technical innovation of pollution abatement. Combining different sources of determinants that affect the emission level for a single pollutant, an extended generalized econometric model used in this study

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[21] Conventionally, A is called total factor productivity (TFP). When the pollution problem is studied in this analysis, we may conveniently regard it to be the productivity effect on the pollution intensity due to technique change. In abbreviation, A is considered to be the effect of the technical change on the pollution emission hereafter.

can be written out as follows:

$$\ln(E_{it}) = \beta_0 + \beta_1 \ln(Y_{it}) + \beta_2 \left(\ln(Y_{it})\right)^2 + \beta_3 \ln(Y_{it-1}) + \beta_4 \ln S_{it} + \beta_5 \ln(P_{it-1}) + \varepsilon_{it}, \tag{2.84}$$

where,

E_{it} is environmental indicators,

β_0 is constant term, which reflects the technological change,

Y_{it} is GDP per capita in international PPP dollars[22],

S_{it} represents structural share variables, or sectoral shares in GDP,

P_{it} is retail oil price at the pump after the environmental taxes,

i denotes countries,

t indicates time,

it_{-1} in the subscript represents the first-order time lag of the relevant variables,

$\beta\prime s$ are coefficients of respective variables, and

ε_{it} is error term.

The econometric model (2.84) takes the logarithm of both dependent and independent variables to capture the idea that the change rate of economic level has impacts on the change rate of environmental quality, which is consistent with the theoretical conclusions.

Since there are strong intertemporal interacting effects between pollution and economic growth, a dynamic characteristic has been incorporated in the setup of the econometric model. In reality, the impact of lagged emission level on current emission level

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[22] We are assuming here, that within each economy, people are more homogenous, therefore, it is more convenient to use per capita GDP and pollution on both sides of the equation to do regression analysis. Besides, the regression results are more comparable across nations in terms of per capita terms.

shows of little importance. Therefore, only lagged income and lagged environmental price are introduced to capture the effect of time response.

To obtain the estimated coefficients of the above econometric model, information about environmental quality, economic level, structural share variables and environmental price are required. Specifically, data of pollution emission indicators and GDP in constant 1995 PPP international dollars will be used in the estimation, which are both in per capita terms to adjust for the different population size across countries. Structural share variables are sectoral shares of value added in GDP measured in percentage, and the environmental policy variable is represented by the retail gasoline price per gallon at the pump after environmental taxes have been incorporated, which is measured in constant 1995 US dollars.

GDP, lagged GDP, and GDPSQ terms are income effect variables, where the linear GDP variables represent the scale of economic activity or income. Other things remaining equal, the larger the scale of economic activity, the greater the generation of pollution. The GDPSQ term, on the other hand, is acting as an indicator, such as structural transformation effect due to the increase of income, together with technique effect represented by the constant term to some extent counteracting the scale effect. The structural composition of GDP first moves in favor of pollution-intensive industrial sector while the share of agriculture declines. At higher stages of development the share of industry begins to fall while that of the non-pollution-intensive service sector rises (Suri and Chapman [1998]). Overall, pollution emission increases at a decreasing rate with the increase of GDP. In this sense, GDPSQ term is expected to have a negative sign. Besides, the structural share variables representing the existing structure and composition of economic activity, along with the price variable representing the increase of environmental awareness and policy regulation, are also considered in the study. Note that one would expect that some past environmental-related energy price rather than the current price would have an influence on emission levels. Hence, the lagged environmental price variable rather than the current term is included in the econometric model.

Empirically, the existence of an EKC relationship and its turning point between income and environmental quality are determined by the combination of all the above impacts. If such a relationship exists in reality, it is useful to derive the income level where such an EKC turning point lies. For this purpose, the signs and magnitudes of β_1 and β_2 in Model (2.84) are of particular importance. The emission level can be said to exhibit a meaningful Kuznets relationship with per capita GDP only if $\beta_1 > 0$ and $\beta_2 < 0$, and the turning points can be calculated as the value of $Y(TP) = e^{-\frac{\beta_1}{2\beta_2}}$, where the change of pollution emissions turns from positive to negative.

In estimating the econometric model, the panel data set of various countries with different years is used in the analysis. However, variations of technological, political and economic conditions exist from time to time for the reason of several occurring historical events. For instance, due to an oil price shock and policy changes that followed, 16 developed countries underwent a dramatic transition of carbon uses in the 1970s[23]. To control for such time impacts, year dummy variables can be included to capture the time effect.

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[23] The 16 developed countries include Austria, Belgium, Canada, Denmark, Finland, France, West Germany, Iceland, Italy, Japan, Luxemboug, Netherlands, Sweden, Switzerland, United Kingdom, and United States (Moomaw and Unruh [1997]).

On the other hand, variations are likely to be large due to the divergence of country specific factors, such as resource endowment, climate, geographical location and culture. A country-specific fixed-effects estimation is used to remedy the problem which may occur due to these localized variations. Besides, estimation technique, such as feasible generalized least square ($FGLS$) method, is also used to obtain the estimated results in correcting for heteroscedasticity that may exist in both time-series and cross-sectional datasets. These issues will be discussed in more detail in the later sections.

The dependent variables in the econometric model are six major air pollutants: CO_2, CO, NO_x, SO_2, PM and VOC, which are of great public concern. The emissions of these air pollutants suggests a change of environmental quality. Since there are huge differences in country size which have heterogeneous impacts on the aggregate data, per capita emission data rather than the aggregate concentration data are used. A reasonable assumption that the population are homogeneous within each economy makes the rescaling into per capita measure more convenient in interpreting and comparing the results across countries. Realizing that people usually measure environmental quality by referring to pollution stock, note that emission as a flow accumulates to a stock of a pollutant, while this stock decays away naturally. Note that some pollutants, like noise pollution, decay instantly, or say, their decay rate is very high. For these pollutants, their stocks are equivalent to emissions. The six air pollutants studied here have the nature of high decay rates, so that their emission flows and stocks can be considered equivalent. Another reason to use emission data is that only these emission data are collected at the country level by official sources. Thus, a complete and reliable dataset associated with emissions of the six studied air pollutants by country is relatively easy to obtain, whereas data on the concentration of these air pollutants (as the concept of pollution stock), however only collected by the monitoring stations, and the number of these observatories is very limited.

Structural variables are sectoral shares of value added in GDP, which represent the structure or composition of economic activity in the econometric model. And they include services/GDP, energy use/GDP, manufacture/GDP, chemical industry/GDP, basic industry/GDP, industry/GDP, agriculture/GDP, and food/GDP for the study. All of these variables are in percentage terms, calculated by converting the sectoral value added into constant 1995 US dollars and then divided by GDP, respectively.

2.3 Data Sources

The CO_2 emission data are provided by the Carbon Dioxide Information Analysis Center (CDIAC). The data include emissions from aggregate fossil fuel consumption and other industrial uses. They include contributions to the carbon dioxide flux from solid fuels, liquid fuels, gas fuels, and gas flaring. The other emissions data (NO_x, SO_2, CO, PM and VOC) are from OECD and the U.N. Economic Commission's Co-Operative Project for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants, which are country-wide aggregate data. To convert into per capita terms, annual total population data by United Nation Population Division have been used. A complete dataset for this study spans a time period of 1985 to 1995 for PM and 1980 to 1998 for the rest of the pollutants, and it includes 131 countries for CO_2, and 23, 26, 25, 29 and 23 countries for CO, NO_x, SO_2, PM and VOC, respectively.

When employing panel data, GDP per capita is defined in purchasing power parity (PPP) in international dollars. PPP is calculated using the World Bank Atlas method. Some of the estimates are based on regressions, others are extrapolated from the latest international comparison program of the benchmark estimates[24].

The GDP per capita data (in PPP standard) are drawn from the World Bank World Development Indicator Database, which combines the Penn World Table data available from 1950 to 1992 with its own data starting from 1992 up to date by using a converting technique. Such construction of the data allows us to compare across countries and over time.

The sectoral share data, which reflect the economic structures, are also drawn from the World Bank World Development Database. They are all in percentage terms, which are calculated by dividing the absolute value by the GDP indicator. In consistent with the World Bank converting technique, all the current values are transformed into the constant 1995 US dollars before the percentage ratios are taken. The data range is consistent with those of the environmental indicators in use for the regression process.

The indicator of oil gasoline price is measured in terms of US dollars per gallon, which is combined from different sources. Most of them are from World Bank Indicators 2001, and Energy Information Administration in the United States Department of Energy, especially for years 1991, 1993, 1995, and 1998. Some of others are drawn from Interna-

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[24] GDP PPP is gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar in the United States. GDP measures the total output of goods and services for final use occurring within the domestic territory of a given country, regardless of the allocation to domestic and foreign claims (WRI [2001]). Appendix A lists international comparison of 1997 GDP per capita index between Atlas method in US dollars and Purchasing Power Parity (PPP) in international dollars.

tional Energy Agency, Organization for Economic Cooperation and Development (OECD) quarterly reports. The price indicator is collected as the oil retail price at the pump after the environmental taxes have been taken into consideration, which is a nationwide average value. Detailed information about the panel datasets used in the study is listed in Table 4.

Table 4: Data Sources

Variables	Years Covered	Countries Covered	Sample Size	Sources
CO_2	1980-1998	131	2489	Oak Ridge Lab, WRI
CO	1980-1998	23	437	OECD & UN
NO_x	1980-1998	26	494	OECD & UN
SO_2	1980-1998	25	475	OECD & UN
PM	1985-1995	29	551	OECD & UN
VOC	1980-1998	23	437	OECD & UN
GDP per capita in int'l $	1980-1998	vary with emission indicators	~	WB
Sectoral value added	1980-1998	vary with emission indicators	~	WB
Gasoline Price	1980-1998	vary with emission indicators	~	WB, USEIA, IEA
Total Population	1980-1998	vary with emission indicator	~	UN

2.4 Statistical Analysis

According to statistical theory, the six indicators of air pollution are dependent variables y and income and other influential factors are independent variables x. The statistical model

$$y = E(y \mid x) + \varepsilon$$

is used to analyze the relationship between economic growth and the environment, where $E(y \mid x)$ is the mean of y conditioned on x, and ε is stochastic errors with zero mean.

The statistical work contains two research tasks. Since the goal of a regression model is to find the specific function which matches the mean curve $E(y \mid x)$ the best, thus the first task is to analyze the $E(y \mid x)$ curves for different pollutants from real data. The second task is the regression analysis, that is, estimating the coefficients of the regression model. If the regression model is realistic, the two approaches should conclude with consistent results.

2.4.1 Analysis of $E(y \mid x)$ Curves

The curve estimations of the relationship between GDP per capita in international dollars and the emissions of air pollutants at global level are displayed in Figures 8 - 9 of Appendix K. For ease of comparison, both mean curve and lowess curve results are presented in the series of figures. The mean curves describe $E(y \mid x)$ relating income and air pollution emissions, while the lowess curves describe the relationship for the observed data using a locally weighted smoothing technique due to Cleveland, 1979[25]. The time range of datasets are from 1980 to 1998 for five pollutants, CO_2, CO, SO_2, NO_x, and VOC, and from 1985 to 1995 for only PM. Although all the six pollutants show some evidence of the inverted U-shaped relationship with income under the panel settings, such income-pollution relationship without control for either time or country is hard to give meaningful interpretations because of its following certain time path, or due to different levels of economic development. To rule out the unexplained time effect in the global analysis, results from a single year (1990) are presented in a panel of six graphical figures, each of them representing one of the six air pollutants. Since the mean curve is the regression result of a binary relationship over the entire observed range, the relationship between air pollutant and income level shows an inverted U-shaped EKC curve more obviously in this setting

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[25] Same as the mean curve to examine the binary relationship between the two variables, LOWESS curve, however, is more precise in following the raw data.

than those in the lowess curve which uses a locally smoothing technique. However, both lowess curves and mean curves are shown to be more reasonable in describing the true relationship in a single year of the cross-sectional data than in the panel dataset spanning a period of time.

For further comparison, sets of graphs of mean curves and lowess curves of the income-pollution relationship for individual countries within the time period of 1980 to1998 for CO_2, CO, SO_2, NO_x, and VOC, and 1985 to 1995 for PM are displayed in Figures 10 - 15 of Appendix K. Even though mean curves, in most cases, are more obvious than those of lowess curves, both types of curves exhibit strong evidence of an EKC (or inverted U-shaped) relationship between income and pollution for almost all countries in the appendix. Therefore, compared to the global panel data and to the cross-sectional country data, the graphical result of time-series data for each individual country reflects the best consistency with the EKC theme. This result suggests that the EKC relationship between environmental quality and economic growth is more reasonable to describe the environmental growth path within an economy in linking to the change of economic levels spanning over certain time period, or called "horizontal" path, rather than cross-country environmental path in terms of different stages of economic development at certain fixed point of time, or called "vertical" path. However, since the global economy, overall, develops in the same direction, though the speed of development diverges across nations, the EKC relationship should also be true to a great extent in the global context, but less obvious as compared to that in terms of an individual country developing at different economic stages.

Graphically, the natural logarithmic values for the environmental turning points range from 9 to 10 emission levels for almost all countries in the appendix with five pollutants except CO_2, corresponding to the range from 8,100 to 22,000 income levels in terms of 1995 constant PPP international dollars. For CO_2, the environmental turning points span a wider range, from the logarithmic values of 6 to 10 emission levels, corresponding to the range from about 400 to 22,000 income levels in PPP dollars. In general, the environmental turning points for less developed countries, mostly in Sub-Saharan Africa[26], are at the lowest income level, since there is no obvious evidence showing that these economies have ever started developing within the observed range. It is less likely to see their environmental situation degraded without the sources of polluting activities, which are in close linkage to the economic development. On the other extreme, the environmental turning points for countries experiencing early stage of economic boom, mostly for Far East and Pacific region, show the highest turning points at the income level, since the fast speed of growth at the early stage of development predicts a higher increasing rate of pollution emission, which in turn implies a higher environmental turning point with respect to the income level. This phenomenon is underlying the theoretical support to the EKC hypothesis. Notice from the graphical analysis, for some high income OECD countries that maintain relative high growth rate also exhibit relatively high income level of the environmental turning point (ETP). This evidence further confirms the previous theoretical result that the economy of scale matters to the income level of ETP, while whether the environ-

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[26] There is no graphical analysis on the individual country for South Asia region, due to lacking enough observations.

mental turning point can be observed (or EKC exists in reality) additionally depends on the level of production technology, abatement effort and capital return rate of the economy.

2.4.2 Regression Analysis

In this study, six airborne pollutants are examined to signify the change of environmental quality over the studying period, which are treated as dependent variables. As suggested in the econometric model (2.84), the independent variables that explain the change of environmental quality over time include GDP per capita, representing a country's income level, country's sectoral share variables examining within structural change effect, and the retail gasoline price after environmental tax, standing for the environmental policy impact. The statistical summary of these variables is reported in Table 5 below.

Table 5: Summary Statistics of the Variables

Variable	Observation	Mean	Std. Dev.	Min	Max
CO_2	2489	4066.493	5600.458	10.573	39138.5
CO	399	148.3385	91.30548	23.8854	465.9347
SO_2	418	55.76472	49.82533	3.6682	269.7581
NO_x	437	43.33372	28.80595	8.2111	149.6052
PM	143	17.08797	16.43497	2.699	56.962
VOC	399	45792.16	38434.55	7517	292710
PPP	2489	7225.468	7216.285	421.275	44163.5
Oil Price	371	2.4166	1.063789	.0726	5.4069
Energy	1691	2.799176	1.878908	.7503	13.145
Manufact	1967	14.84137	7.314053	.3641	40.5754
Service	2199	51.89842	12.88604	17.1827	85.1872
Chemical	854	1.768022	1.062567	.0697	5.6315
Industry	2188	28.7357	10.90014	4.4863	80.522
Basic Industry	924	6.591059	3.200976	.5895	19.2631
Agriculture	2211	19.30297	14.58403	.1187	72.029
Food & Beverage	924	4.70325	2.391329	.5756	15.7267

The global panel data including environmental, economic and policy indicators are used in the empirical study for a comparison at the global, regional and country levels, respectively. For cross-sectional datasets, it is likely that some econometric problems, especially heteroscedasticity in the regression analysis, will be encountered. Usually, there are two ways to correct it. One is to use a fixed-effects model including a country-specific dummy variable α_i and a year-specific dummy variable α_t. And another method is to use generalized least square (GLS) instead of ordinary least square (OLS) estimation in the random-effects model. From a practical point of view, the fixed-effects approach is costly in terms of degrees of freedom loss. In this study, both methods are adopted to explore appropriate methods to get rid of the heteroscedasticity problem.

By setting the minimum tolerance level as low as $(1e-6)$ in the regression analysis[27], some variables below such minimum value will be excluded in the regressions. This technique, which excludes the possibility of extreme multicollinearity problems, is applied to both fixed-effects and random-effects regression estimations. The regression results are listed in the tables of Appendix C through Appendix H.

Table 6.1 through Table 6.6 report the regression statistics for CO_2, CO, NOx, SO_2, PM, and VOC, respectively. The analysis is conducted for each of the six air pollutants separately, because it is reasonable to assume that the emission levels, and thus the stocks, of the six pollutants are independent from each other. For each pollutant, both

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[27] Some econometric software, such as SPSS, ET, set 0.001 as a default for minimum tolerance value. Stata, which was used in this study, however, set $(1e-6)$ as default, so that any variable has its coefficient's significance level lower than this value will be eliminated by the program automatically. The tolerance level $= 1 - R^2$. Extremely low tolerance value implies that this variable is highly multicolinear with other variables, and it may not contribute much impact on the dependent variable, and thus can be dropped in the model.

fixed-effects and random-effects models are run on the basic form (without sectoral share variables), and on the complete form (with one sectoral share variable for each run). For most cases, the fixed-effects models show better overall goodness of fit and more significant t-values, although in the random-effects estimations the heteroscedasticity problem has been corrected by using $FGLS$ (since variance-and-covariance matrix Ω is unknown). However, the differences between the two models in general are minor. Therefore, results from both approaches are included in order for a detailed comparison in the remaining sections. In the random-effects models, besides the log-likelihood ratio which is an alternative measure for overall fitness, Hausman's Wald criterion result is also reported in the tables, which is asymptotically distributed as a chi-squared value with K degree of freedom.

Hausman's Wald criterion is used to test the hypothesis that an individual effect is uncorrelated with the log-dependent variable using the estimated covariance matrices of the slope estimator in the least square dummy variable ($LSDV$) model and the random-effects model. In all cases examined in this study, the chi-squared statistics are significantly high, which suggests that the hypothesis that the individual effects are uncorrelated with the dependant variables should be rejected. However, not all of the log-likelihood ratios are significant at a 95% confidence level after correcting for heteroscedasticity using $FGLS$ in the random-effects estimation, especially for CO. This implies that, although the $FGLS$ approach remedies some of the pitfalls existing in the random-effects estimation, particularly that of heteroscedasticity, it cannot capture all the individual characteristics including geographical and time trend effects, particularly for CO pollutant. As a result, the random-effects estimations for CO pollutant are not included in the analysis.

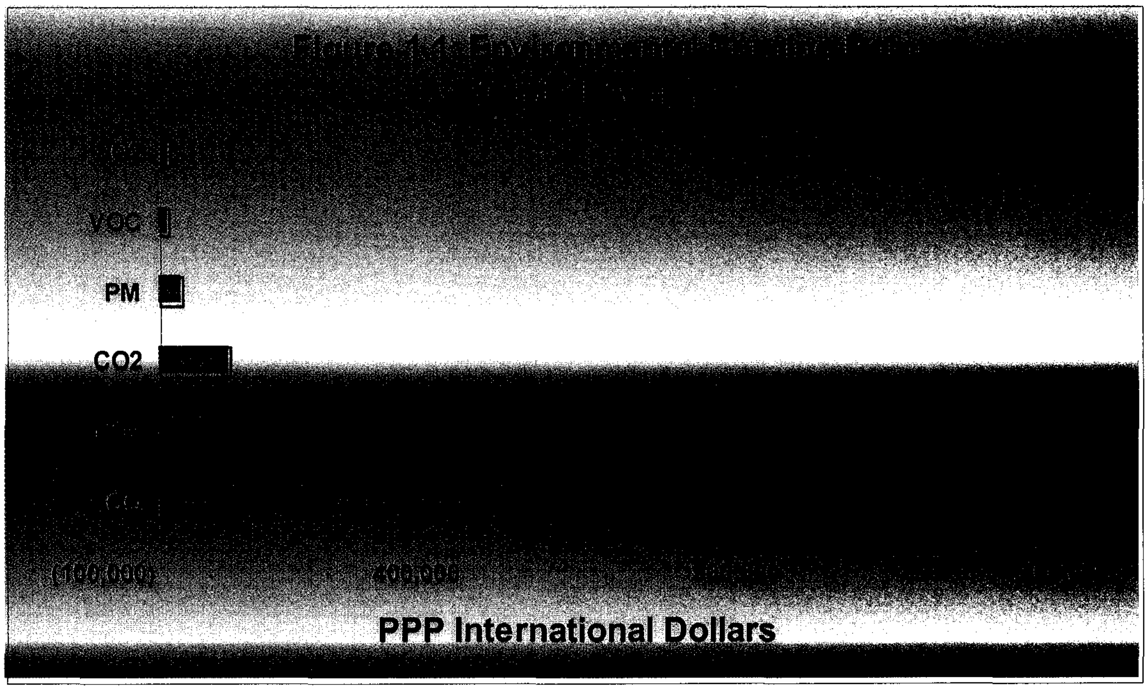
All the estimated coefficients have got the expected signs in both fixed- and random-effects models. This result is consistent with the binary relationship between income and pollution using mean curve and lowess curve in the previous graphical analysis. The t-value of each estimator, F-statistic and its significance level of the overall fitness for the fixed-effects model, and the z-value, likelihood ratio statistic for the random-effects model are both reported in the tables of the appendix.

In sum, based on the econometric model (2.84), the fixed-effects regression provides the best results, including expected signs and satisfied coefficients, although it sacrifices the number of degrees of freedom. The random-effects approach after using $FGLS$ to correct for heteroscedasticity, nevertheless, provides alternative best-fitted regression results.

2.4.3 Regression Results

Environmental Turning Points (ETPs)

One of the major tasks for the regression analysis is to obtain the estimated environmental turning points (ETPs) in terms of the income level for each of six air pollutants covered in the study at the global, regional, and national levels, for individual countries for which the information required for estimation is available. Averaging over the estimated coefficients in the fixed-effects and random-effects models, we obtain the average value of estimated coefficients for each of the six pollutants. Then, using equation $Y(TP) = e^{-\frac{\beta_1}{2\beta_2}}$, the environmental turning points (ETPs) can be calculated in terms of 1995 constant PPP international dollars. The results are shown in Table 7.1.1 through Table 7.2.3 of Appendix D. In essence, there is not much difference in terms of expected signs, but a little difference in the significance level for the estimated coefficients between the fixed-effects model and random-effects model. For the purpose of further comparison among different pollutants across regions and across countries, the average ETPs between the two models are also calculated. As can be seen in the table, the environmental turning points for CO_2, CO, and NO_x, on an average of a global trend are much higher, at above 110,000 international dollars in terms of 1995 PPP. Turning points for SO_2, PM, and VOC, on the other side, are much lower, below 35,000 in 1995 international dollar. It can be explained that, CO_2, CO, and NO_x are relatively less detrimental, and thus less concerned by the public opinion, compared to the other three pollutants, SO_2, PM, and VOC. Therefore, as the economy grows, more efforts including technological innovation, environmental regulation, and even investments on cleaner industries tend to be made to reduce environmental degradation from those the most detrimental polluting sources. Furthermore, the nature of the first three pollutants, CO_2, CO, and NO_x, are more globally oriented that their effects tend to have a large spatial scale, while the latter three, SO_2, PM, and VOC, are more locally oriented. With this respect, it is much possible to focus the treatment on the local pollutants rather than the global ones. Furthermore, there is an over-riding problem in tackling the global pollutants that makes the pollution reduction on these pollutants less effective. The average income values of the six air pollutants at the global average level can also be graphically depicted in Figure 1.1.



In the perspective of regional comparison for CO_2, regions with fast economic growth at the early stage of development, such as Far East Asia and Pacific, Middle East and North Africa, tend to exhibit the highest environmental turning points in terms of income level, that is, above 400,000 in constant 1995 international dollars. On the other extreme, the South Asia region, which includes the least developing countries such as Bangladesh, Bhutan, and SriLanka in the world, turns out to have the lowest ETP, that is, 2,000 in 1995 international dollars[28]. For the rest of the regions, including High Income OECD, Europe and Central Asia, Latin America and Caribbean, and Sub-Saharan Africa, the average income level of the environmental turning points falls into the range between 20,000 and

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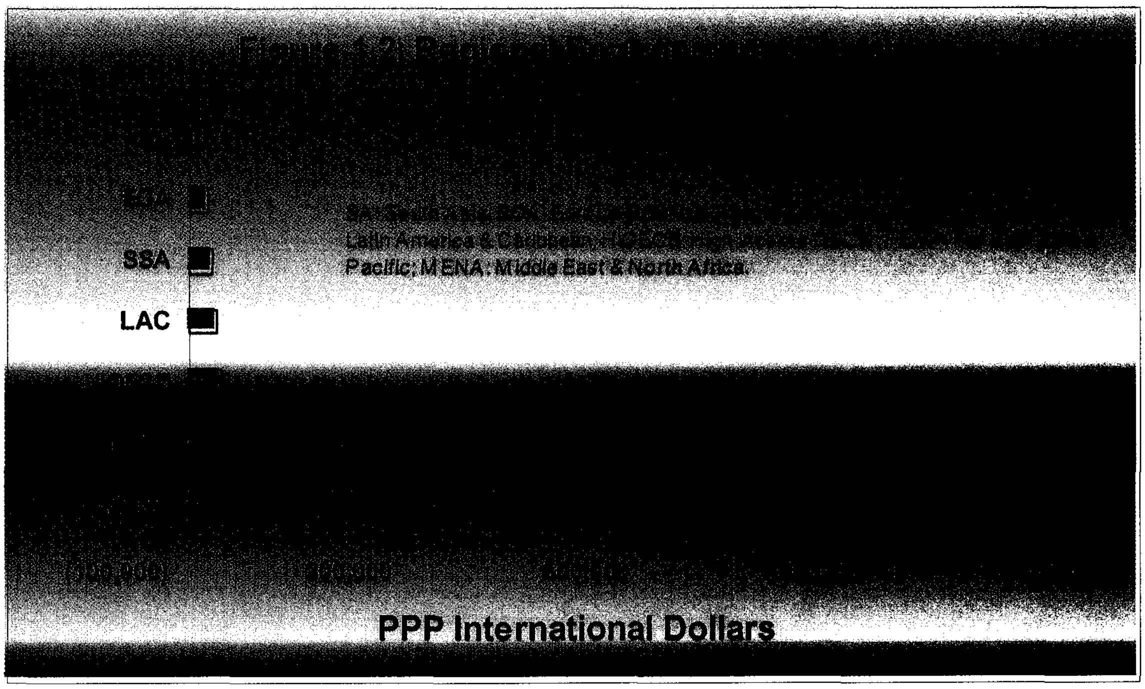
[28] However, in the graphical analysis, countries belonging to the South Asian region are not included due to lacking enough observations for an individual country study.

40,000 in international dollars. Among these regions with ETPs in the middle range, High Income OECD shows a relatively high level of ETP, at above 39,000 and almost close to 40,000 of international income dollars. The result is consistent with the previous graphical analysis, which is also supported by our theoretical underpinnings that the speed of environmental degradation is in the linkage to the scale of an economy. Surprisingly, the ETPs of the Sub-Saharan African region turn out to be at the middle of the income level rather than at the relatively lower income level as indicated in the previous mean curve analysis. This is because the regression analysis incorporates economic activities and environmental regulations while the mean curve study does not, implying that, even though with limited economic activities, polluting industries with less governmental intervention in environmental regulations are probably the most dominant economic activities in the Sub-Saharan African region. As a result, the income level of ETP appears to be pulled up to be higher than it is expected. Figure 1.2 below shows the regional comparison of the estimated environmental turning points for CO_2 graphically. Finally, as can be seen in Table 7.2.1 through Table 7.2.3 of the appendix, the ETP analysis at country level follows a similar pattern to that suggested in the regional study.

In sum, the regression results, to a great extent, conform to the previous graphical analysis. ETPs for those experiencing a vigorous economic boom in the early stage of development show at the highest income levels. ETPs for less developed regions, in general, tend to be at lower income levels. However, some high income countries that maintain relatively high growth rates also exhibit relatively high ETPs with income. Such evidence confirms the assertion that the scale of economy matters to the income level of the environmental turning point, as indicated by the underlying environmental growth theory. However, whether the ETP can be observed or not for some countries depends on the combined effects of their production technological level, abatement effort and the capital return rate.



Economic Structural Impacts on Environmental Quality

In consistent with the theoretical results, as it also has been argued in the formulation of the econometric model in the previous sections, the existence of an EKC relationship between environmental quality and economic growth depends on other determinants in addition to the income level. Among these, structural change (both compositional and decompositional effects), technological improvement, and environmental regulation are the most important and significant factors.

In the regression analysis, the GDP, lagged GDP, and GDPSQ terms in Equation (2.84) are income effect variables, where the linear GDP variables represent the scale of economic activity. Other things remaining equal, the larger the scale of economic activity, the greater the generation of pollution. On the other hand, the GDPSQ term is acting as an indicator of the structural compositional change due to the increase of income, which is expected to have a negative sign, since in a long run the compositional change is moving in favor of environmental improvement, while the change of decompositional effects within economic structure is represented by the sectoral share variables that have mixed impacts on environmental quality. In this regression study, the technique effect is represented by the constant term to capture, more or less, the technological improvement over time that is unexplained by any other factor specified in the econometric model. Finally, the price variable, which is associated with the increasing environmental awareness and policy regulation, implies a policy response. The estimated impacts, without accounting for the decompositional effects, from the regression analysis are reported in Table 8.1.1 through 8.7.2 of the appendix. These tables with the results include those from both the fixed-effects model and random-effects model, as well as the average values of them.

At an average of the global estimation in Table 8.1.2, the change rate of positive scale effect on the environmental degradation is smaller for CO_2 and NO_x, less than a ten percent change in response to a one percent increase in economic scale. While these for the other four pollutants, CO, SO_2, PM, and VOC, are relatively large, ranging from 29 to 42 percentage change with a one percent increase in economic scale. Correspondingly, the negative impacts of compositional effect, technical effect, and policy stringency on the environmental degradation are also smaller for CO_2, NO_x, than for CO, SO_2, PM, and VOC. For CO_2 and NO_x, the change rates of compositional effect, technical effect, and policy implication are less than 0.5%, 40%, and 0.5%, respectively, while those for CO, SO_2, PM, and VOC, are more than 1.5%, 100%, and 0.8%, respectively[29]. On the other hand, for each pollutant, the absolute value of the percentage change of scale effect is greater than the combined effects of compositional and policy stringency impacts. However, the technological effect is the largest for all six pollutants. That is, the absolute value of the percentage change rate of technique effect is much greater than those of the aggregation of the scale effect, compositional effect, and policy implications. Table 8.2.1 to Table 8.4.6 present the results for the cross-country study, while Table 8.5.1 to Table 8.7.2 focus on reporting CO_2 pollutant. The global average of the economic structural impacts on environmental quality for the six air pollutants are highlighted in Figure 1.3.

In sum, the regression study on the effects of economic structures reveals that increases of economic scale will worsen the environmental status, while structural compositional change, technological innovation, and stringency of environmental regulation tend to make environmental quality improved. Besides, pollutants, such as CO, SO_2, PM, and VOC that have larger impacts on environmental degradation due to economic scale, are likely to be more awared by the public, thus effects from the compositional change,

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[29] Note that, when calculating the percentage change of technical effect, lnA is specified to be one for the ease of comparing the results. In the growth accounting, A is usually considered to be less than 10, therefore such specification of lnA will not affect the results too much.

technique change, and policy implementation to improve environmental quality tend to be more obvious for these pollutants. In the perspective of horizontal comparison among pollutants, the damaging effect of economic scale on the environment is, in general, greater than the combined effects of structural change and environmental regulation that are in favor of environmental improvement. In this sense, the damaging effect cannot be offset by these two favorable effects combined. However, technological innovation tends to have a much greater impact on the improvement of environmental quality than the aggregation of all the other effects in absolute value. This implies that environmental amenities rely, to a great extent, on an improvement of technological innovation.

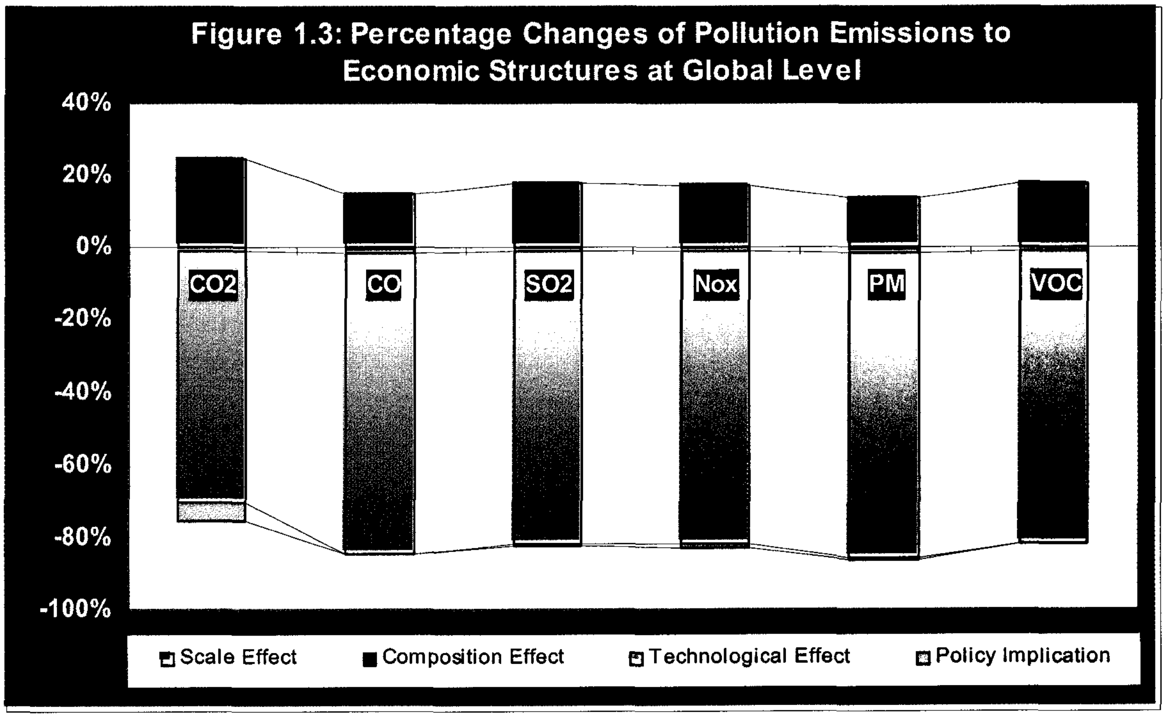

Figure 1.3: Percentage Changes of Pollution Emissions to Economic Structures at Global Level

Decompositional Impacts on Environmental Quality

It has been claimed that environmental degradation has undergone dramatic change along the course of economic development. At low levels of development, environmental degradation is limited, as economic development accelerates, the environmental situation worsens along with the economic structural change from rural to urban and from agricultural to industrial. At higher levels of development, a new structural transformation begins towards services, information and technological intensive industries, coupled with increased environmental awareness and enforcement of environmental regulations, which result in a gradual decline of environmental degradation. All of these factors together are usually believed to be the causes of the Environmental Kuznets Curve phenomenon. In this study, it is also claimed that the structural change consists of two components that have impacts on the environmental situation. The first one is called the compositional effect (or inter-sectoral compositional effect). That is, as the economy grows, the economic structures shift from agricultural to industrial, and further from industrial to the service and information sectors. The second component of the structural change is called the decompositional effect (or intra-sectoral decompositional effect). That is, economic structural change is caused by within-sectoral capital accumulation. The regression results of the compositional effects are reported in Table 8.1.1 to 8.7.2 and they have been extensively discussed in the previous section. Table 9.1 through Table 9.2.6 in Appendix H thus display the regression results of the decompositional impacts of structural change on environmental degradation.

As shown in Table 9.1 for the average impacts on environmental degradation at the global and regional levels, there is in general a negative effect within the service sector, a positive effect within the industrial-related sectors and energy use, but within the agricultural sector and food and beverage processing sector, their impacts on the environmental indicators are mixed. The largest effects from a one percent increase in the share of the service sector to GDP on environmental degradation at the global level are for PM and SO_2 pollutants, that is, declining at 9.76% and 5.31%, respectively. In contrast, the percentage changes in the shares of industrial-related sectors bring about the greatest impacts also on PM and SO_2, but in the opposite direction, that is, accelerating the environmental degradation by more than two percentage point. The agricultural sector shows a negative impact with respect to the accumulation of CO_2, but a positive impact with respect to that of the other five pollutants. Structural change within the food and beverage processing industry tends to improve the environmental situation in terms of CO_2, CO, and VOC pollutants, but is likely to worsen the environment in terms of SO_2, NO_x, and PM. However, the absolute values of their change rates are very small, less than one percentage point for all six air pollutants. The percentage change rate of energy use on environmental degradation is also small, though positive for all the pollutants, at around one percent. From the regional and cross-country analyses, it can be seen that the effect of within-structural change on the environment follows a similar pattern to that at the global average level, but sometimes varies according to different specializations in economic activities across regions or across countries.

In sum, the effects of within-structural change on the environmental degradation are negative for the service sector, and positive from various industrial sectors and energy use, but the agricultural and food and beverage sectors have mixed impacts at all studies for the global, regional and country levels. The magnitudes of these impacts vary according to different sectors with different pollutants, and they also differ across regions and across countries. However, the absolute values of these impacts in terms of percentage change within each sector on the environmental situation are small in general, at less than ten percentage point for all pollutants at each level of the analysis.

2.4.4 Comparison With Previous Empirical Evidence

Most of earlier empirical studies, including those of Grossman and Krueger [1995], Selden and Song [1994], and Holtz-Eakin and Selden [1995], generally show an inverted U relationship with income for air pollutants, e.g. NO_x, SO_2, and CO. These outcomes seem to be confirmed by the present study. However, compared to their empirical analyses, this study shows that the estimated income levels of the turning points of NO_x, SO_2, and CO are somewhat higher than those by Grossman and Krueger, but similar to those of Selden and Song, while the CO_2 turning point at the income level is lower than that found by Holtz-Eakin and Selden in 1995[30]. The difference of this paper's results from those of

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[30] Using ambient concentration data, Grossman and Krueger estimated the income levels of the turning points to lie between \$4,000-\$5,000 per capita (in 1985 international \$) for SO_2, and \$10,000-\$11,000 per capita for NO_x. Selden and Song found that the turning-point income levels for CO, SO_2, and NO_x are between \$8,000-\$22,000 of per capita GDP (in international U\$) with air emission data. Using the log-quadratic specifications in their models, Holtz-Eakin and Selden estimated that the turning points for CO_2 is at a very high level of per capita income, above \$8 million.

other researchers is probably due to the different approach used in measuring the income and choosing different functional forms and sample data.

Selden and Song use a small sample size of observations and GDP per capita in terms of 1985 US dollars for their estimation. This may cause a bias in the sense that a small sample size is unlikely to have representative characteristics[31]. Besides, GDP without PPP comparison may not be an appropriate measurement of incomes for the cross-country study. Whether air pollution is measured on emission data or concentration data may also have some influence on the income level at which the turning point for air pollutants occurs. Grossman and Krueger use ambient concentration data in their study. In fact, ambient concentration data are collected by monitoring stations at the local level. These data may not necessarily reflect the country-wide air pollution level.

Difference in model specifications causes the major difference of income levels estimated for the environmental turning points. This study suggests that the cubic model is not an appropriate functional form in describing the relationship between economic growth and environmental quality both theoretically and empirically. In contrast, the quadratic model under the dynamic setting and incorporating the underlying causes of structural determinants is considered to be the best empirical model for the analysis of the EKC hypothesis.

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[31] Although the relationship between economic growth and environmental quality has been an issue of large debate in the economic literature for many years, in the past this debate has not got any empirical evidence to support one or another, remaining on a purely theoretical basis for a long time. This is mainly due to lacking available environmental data to conduct the empirical work (Shafik [1994]).

2.5 Concluding Remarks

The econometric model (2.84) of this study, which admits the advantages of both reduced-form and structural form based on the theoretical results developed from the environmental growth models in the previous chapter, is primarily used for the regression analysis to obtain reliable estimators, where fixed-effects and FGLS random-effects techniques are essentially adopted in the estimation.

The empirical results show that the six air pollutants (CO_2, CO, SO_2, NO_x, PM, and VOC) examined in this study do exist environmental turning points (ETPs) corresponding to the income level for a global study. In general, ETPs for areas experiencing fast economic boom in the early stage of development show at higher income levels. ETPs for less developed regions tend to be at lower income levels. However, some high income countries that maintain relatively high growth rates also exhibit relatively high ETPs with income.

Compared to previous empirical analyses, this study shows that the estimated income levels of the turning points for NO_x, SO_2, and CO are a little bit higher than those by Grossman and Krueger, but similar to those of Selden and Song, while the CO_2 turning point of income level is lower than that found by Holtz-Eakin and Selden in 1995.

One of the most important tasks of this empirical study is to examine the impacts of increases in the economic scale, economic structural change, and environmental policy change on the speed of environmental degradation, whereas the economic structural change includes two effects, compositional effect and decompositional effect. It shows that the increase of economic scale will worsen the environmental status, while the structural compositional change, technological innovation, and stringency of environmental regulation tend to improve the quality of the environment.

The effect of within-structural change (or intra-sectoral decompositional effect) on environmental degradation is negative for the service sector, and positive for various industrial sectors and energy use, while the effect of agricultural and food and beverage sectors on the environment is mixed. The magnitude of such impacts varies according to different sectors and on different pollutants, and it also differs across regions and across countries. However, the absolute value of this impact in terms of the percentage change of the environmental situation in response to a one percent change within each sector is generally small.

In overall, technological innovation tends to have a much larger impact on the improvement of environmental quality than the aggregation of all the other effects in absolute value. This implies that environmental amenities rely, to a great extent, on technological improvement.

Chapter 3
Summary and Discussion

The Environmental Kuznets Curve hypothesis states that there exists an inverted U-shaped relationship between environmental pollution and income level. That is, environmental degradation initially increases, but eventually declines as income further increases after certain peak point has been reached. Although debates over EKC have been lasting for almost a decade, they continue to have revived interest to researchers and policymakers. The reasons could be several. Perhaps the most important is that the EKC theme implies a critical policy issue, for which an important question could be raised whether economic growth should continue to be the main priority with protection of the environment a secondary consideration to be addressed mainly in the future, or whether explicit policies to control environmental degradation are urgently required today [Barbier, 1997]. As for the developing countries, an important lesson could be learned from the experience of the industrialized nations in devising development strategies that can go through a potential EKC path avoiding the same stages of growth that involve relative high or even irreversible levels of damage to the environment. In addition, the inverted U-shaped EKC is a perfectly reasonable hypothesis in speculating about the income-environmental relationship, as has been observed by many empirical studies and simultaneously has been implied by other theoretical findings.

However, most of growth models in general overlook the interaction between economic growth and environment, which virtually ignore the externality aspect of pollution problems in affecting social welfare and thus impairing the objective of economic growth. Moreover, there are strong intertemporal characteristics of the pollution problems, which reinforce the relevance of a dynamic approach using optimal control theory in tackling the growth model involving environmental pollution. However, there are not many previous researches having used environmental growth models to derive the pattern of Environmental Kuznets Curve, except for those by Selden and Song [1995] and Stokey [1998]. In her article, Stokey posits several growth models that derive similarly an inverse V-shaped pollution-income relationship where preference differing upon the quality of environment over time plays a critical role. She assumes that below a threshold level of economic activity, only the dirtiest technology is used. With economic growth only when the threshold is passed, then cleaner technologies can be used. The resulting pollution-income path is therefore inverse V-shaped, with a sharp peak at the point where a continuum of cleaner technologies becomes available [Andreoni and Levinson, 2001].

Another contributors to this literature, Selden and Song [1995] describe a variety of possible pollution-income paths including the inverted U curve for pollution. However, multiple outcomes as a result of their paper may obscure the central focus of their arguments. The theoretical models presented in this study are intended to construct two environmental growth systems in differentiating the characteristics of pollution as a stock or flow, in order to identify the conditions under which an inverted U pattern of EKC can be explicitly proved to exist as an outcome of the income-pollution relationship. In deriving these conditions for the existence of EKC under the setting of a growth model, a dynamic approach according to the optimal control theory is best called to use for the analytical evaluation of optimal growth path of the relationship between environmental pollution and economic development.

The most important conclusion drawn from the environmental growth models developed in this study is that the Environmental Kuznets Curve (EKC) is a consequence of combined impacts among pollution intensity, technological innovations of abatement and production, and the return rate of capital stock. Whereas, the occurrence of the inverted U shape for EKC depends only if the negativity of pollution intensity from production is outweighed by the interacting effect of technological changes between abatement and production, along with the capital investment enjoying a higher return rate. This conclusion has been confirmed by both the numerical simulations for the theoretical models and the estimated empirical evidence.

It can be easily seen that, at the early stage of economic development, environmental amenity is less valued while natural resources tend to be extracted inefficiently, therefore the environmental pollution intensity (B) is relatively high in comparison with the relative low level of techniques in the production process, provided $\phi A^2 \leq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$, in the case that pollution is increasing with the capital stock. On the other side, with economic wealth further accumulating, the real value of aesthetic amenity begins to rise rapidly, along with the technological progress that makes possible the capital substitution for raw resources and the pollution abatement expenditures less costly. Note that there are two-sided effects in which technological change affects environmental pollution. First, technological change increases the stock of research and development of knowledge that enables firms to expend less to control the pollution, which is called the effect of technological change on abatement cost. Second, technological change augments productivity and hence reduces the need for polluting inputs, which is termed the effect of technological change on productivity. Both of these two effects tend to counteract against the pollution intensity effect. Whenever the technological effects dominate the intensity effect, the trajectory of environmental degradation tends to decline with a further increasing of economic development. In this case, $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$ is provided, in which the inverted U-shaped curve can be observed.

In an economy, services that are provided to preserve or improve natural environment increase the opportunity cost of using capital stock for investment, provided that the level of consumption is not falling. If the capital return rate is relatively low, then eventually capital as a resource stock will be exhausted in a long run in order to maintain continuous growth in consumption. Therefore, sustainable growth in consumption requires that the marginal productivity of capital resources is increasing, that is, the return rate of capital stock is relatively high, e.g. $\alpha > \frac{1}{2}$. Under such a condition, permanent preservation of the natural environment would be possibly warranted by better services. In the meantime, technological progress provides means by which continuous growth in consumption and environmental preservation can be simultaneously guaranteed. Development on both sides of the effects in an economy provides with an explanation as to why the inverted U-shaped EKC can be observed only if the pollution intensity is outweighed by the technological improvement, as well as the return rate of capital stock must be relatively high.

Another important result of the theoretical models for this study concludes that the peak of inverted U-shaped EKC, or Environmental Turning Point (ETP), may occur differently with various income levels, depending on the scale of the economy over time or, alternatively to say, on the accumulating rate of capital stock over time. With fast accumulating rate of the capital stock, ETP for an inverted U curve tends to peak at a higher income level. Vice versa, ETP tends to occur at a lower income level when the economy develops in a slower fashion. This pattern of income level change for ETP is independent of whether pollution is treated as a flow or as a stock. But the pollution level will be lower along the optimal path when it is treated as a stock in the entire range of income than when it is a flow, since the decaying factor is additionally taken into account for the pollution stock. It can be seen obviously that rich countries with an abundance in capital resources tend to take the lead in technological enhancement both on research and development, and productivity innovation, which provide the means for these countries to go through faster from a production level with dirtier and lower technologies to that with cleaner and higher technologies. Therefore, these countries tend to overcome the peak of the inverted U with a lower income level than those countries experiencing fast development at their initial stages however using raw resources intensively. In practice, there may have a certain concern for these emerging economies that grow vigorously at the present stage, on how they can develop beyond the environmental turning point quickly without retarding economic growth at the same time. As Ekins [1997] points out, for the developing countries, if economic growth is good for the environment then policies that stimulate growth should also be good for the environment, since resources can best be focused on achieving rapid economic growth to move quickly through the environmentally unfavorable stage of development to the environmentally favorable range of EKC.

In the first part of this study, two environmental growth models have been developed under which the optimal growth paths and their solutions are generated, and most importantly the Environmental Kuznets Curve (EKC) is proved to exist under the settings for both models, whereas some critical conditions are primarily required. The importance of these theoretical results is discussed in the previous sections. The next challenging issue accompanying to this study would appear to find empirical evidence to buttress these theoretical results if there is any in reality. The subsequent sections, following the theoretical part, are designed for this purpose. There, six major air pollution indicators with most recent time-series data for globally 131 countries whose information are available from several reliable sources are basically used to estimate the EKC relationship between environment and income. These indicators can be interpreted as related to a broad set of environmental amenities associated with environmental quality, ranging from those affecting human living standards to those related to general ecosystem health. Therefore, these indicators are of representative characteristics in testing the environmental growth path of the EKC hypothesis. The empirical results, in general, support the EKC theorem. However, the underlying causes that drive the environmental growth path to be an inverted U shape are deemed important thus considered to be another important task. And they are subject to the investigation in the empirical part of the study. Therefore, a structural econometric model, taking into account the theoretical results, is constructed as a basic functional form for the regression analysis, among which the underlying determinants of the income-environmental relationship, distinguishing between scale, composition (or inter-sectoral structural change), technique effect, and policy response have been broadly explored and estimated. Rather, the structural change effect has been further decomposed into an intra-sectoral decompositional change to examine the effect coming from within-sectoral structural change, besides the inter-sectoral compositional effect discussed previously.

Economic growth at the initial stage increases emission levels, but technological progress in the later stages reduces the emissions. As it has been argued, technological changes that affect pollution emissions are two-fold. One is to improve production efficiency, while the other results in using less pollution-oriented input substitutes, which in turn decreases the pollution intensity in outputs in the latter stages of economic development. However, shifting of structural composition can also alter the pollution intensity in output, and trade liberalization makes it possible for earlier industrialized countries to change the structure of the economy by shifting economic activities from primary and more polluted industries to sectors with higher technology and cleaner services. Such shifting of structural composition induces less pollution intensive use in economic activities. In the empirical analysis of this study, it is claimed that the structural change consists of two components that have impacts on the environmental situation. The first is called the inter-sectoral compositional effect. That is, as the economy grows, economic structures shift from agricultural to industrial, and further from industrial to service and information sectors. The second component of the structural change is called the intra-sectoral decompositional effect. That is, the structural change is due in scale within the sectoral capital accumulation. Generally, from the intra-sectoral perspective of view, the primary sectors, such as agriculture, food and beverage, and basic industries, tend to be more resource-intensive than either the secondary (especially manufacturing and chemical industries) or tertiary (mostly referring to service and information) sectors. On the other hand, manufacturing and chemical industries tend to be more pollution-intensive than either primary or tertiary sectors. In this study, both of the inter-sectoral compositional effect and intra-sectoral decompositional effect that have impacts on the change of pollution intensity are examined in the regression analysis. Finally, various environmental policies spurred to develop the pollution-abatement technologies are necessary, to some extent, to avoid the growth path deviating from the optimal trajectory in an imperfect economy.

As a result of the regression analysis, all the six air pollutants examined in the study have exhibited an EKC pattern, whereas the environmental turning points (ETP) for CO_2, CO, and NO_x are over \$110,000 in 1995 PPP on the global average level. They are shown to have higher levels with income than those for SO_2, PM, and VOC (less than \$35,000 in 1995 PPP). However, the income levels of ETP for the former three pollutants are far above the current observed income range of the maximum level at around \$50,000 in 1995 PPP. This implies that pollution abatement technology and public concern are less focused on these three air pollutants, since they tend to be globally oriented and less detrimental compared to the other three air pollutants. On the other side, a regional comparison for CO_2, but not for the other pollutants due to the limitation of data availability, indicates that those regions with fast economic growth, such as Far East Asia and Pacific, Middle East and North Africa, exhibit the highest ETP at the income level above \$400,000 in the 1995 PPP, far beyond the sample range. At the other extreme, the South Asian region, which includes the least developed countries such as Bangladesh, Bhutan, and SriLanka, turns out to have the lowest ETP at the income level of $2,000 in the constant 1995 PPP. For the individual country study, there even does not exist an EKC relationship for these countries. For the rest of the regions, High Income OECD, Europe and Central Asia, Latin America and Caribbean, the average income level of ETP falls into the range between $20,000 and $40,000 in the 1995 PPP. Whereas the High Income OECD countries that maintain relatively high growth rates also display relatively high ETPs at above $39,000 and almost close to $40,000 PPP, the income level of the upper limit for regions in the middle range. The estimated evidence confirms the theoretical assertion developed from the environmental growth models that the existence of EKC requires the level of capital stock accumulates at a rate sufficiently high, which represents a wealthy level of the economy, along with the negative impact of pollution emission intensity due to economic activities must be fully compensated by the positive effects of technological induced abatement innovation and improved production efficiency.

In analyzing the determinants for the existence of EKC, the estimated regression study for all the six air pollutants on the effects of economic structural change confirms that increases in economic scale tend to worsen environmental quality, while inter-sectoral compositional change, technological innovation, and stringency of environmental regulation improve the environmental quality. Among these factors, technological change has a dominant impact on the change of pollution intensity. For the intra-sectoral decompositional change, the estimation results reveal for both the global and regional study that there is positive effect (decreasing) in the change rate within service sector, negative effect (increasing) within industrial-related sectors such as manufacturing, chemical production, and energy use. But within agricultural, food and beverage processing sectors, the impacts on pollution intensity are mixed, since they depend largely on what resources are intensively involved in production. However, the absolute values of all the intra-sectoral percentage changes for the six air pollutants included in this study are very small, within a single percentage point, and much smaller than those for the technological change. For almost all pollutants, the change rate of the technical effect are over two percentage point. Therefore, this study concludes that environmental amenities rely, to a great extent, on the improvement of technological innovation.

There, nevertheless, exist some limitations in this study. In the theoretical part of the study, some assumptions have been made that may limit the generalization of the results. For instance, the environmental growth models are developed under an autarchy system where trade between sectors or across economies is not considered, in the sense that the market may be imperfectly defined. One consequence of this limitation is that the EKC relationship derived under such a system is only internally determined by a single production-related factor, which may mask some of the other important underlying causes that also determine the existence of EKC. The limitation of this caveat is also relevant in the context of the subsequent analysis of the econometric model. Secondly, the labor issue, or furthermore that of human capital, is not incorporated in the framework of the model. In this sense, it may be irrelevant to regard the environmental growth models developed here as those of endogeneity per se. Finally, the growth rate of an economy, or simply put an accumulation rate of the capital stock, determines the shape of the environmental path, which is partially determined by the intertemporal discounting rate of consumption. Thus, people's utility may indirectly affect the growth path of the environment via the economy's growth rate. Hence, the separate utility functional form assumed in the study restricts the models' capacity to illustrate these relationships. However, the models developed here are simply to describe the most obvious and direct linkage on the seemingly relationship between environment and development that has been argued for decades, and there is no intention to make the theoretical model to be the most comprehensive and to solve all the problems involved in the environmental growth models. But it would be useful to develop a more complete model that reflects every aspect of the economy; this can be considered as one of the tasks for future research.

The shortcoming of the empirical work of this study mainly lies in the accuracy of the estimated results. Therefore, there is plenty of room remaining to make the regression analysis more accurate and consistent. For example, the economic development and environment are, in general, jointly determined within the dynamics of an economic system. In regressing the empirical relationship between economic output (or GDP) and its impacts on environmental degradation (or pollution emissions), it may be inappropriate to estimate a single-equation model assuming unidirectional causality from economy to environment where simultaneity exists that produces biased and inconsistent estimates [Stern et. al, 1996], although the econometric model incorporating the structural determinants to some degree has remedied such weakness of the study. However, a question may be raised as to what would be the best instrumental variable that can be used to correct this problem without at the same time deviating from the underlying theory.

Finally, there is a policy related issue that needs to be clarified. This study has shed some light on investigating the shape of the relational path between environment and development under the optimality of a market system, and the conditions and determinants that such a path follows conventionally believed to be an inverted U pattern, or Environmental Kuznets Curve, which as a consequence has been unequivocally supported by both the theoretical results of the environmental growth models and the empirical evidence from the regression analyses. All these facts imply that it is possible that, beyond a certain point of economic development, the economy moves towards solving the problem of environmental degradation without retarding the growth pace. But this does not mean that environmental improvement will come automatically. On the contrary, policies actively seeking both environmental and economic gains, such as pollution standard induced abatement technology, are not only necessary but sometimes required in an imperfect economy.

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Appendix A
World GNP per capita, Atlas Method and PPP

This appendix contains a table listing the world GNP per capita in 1997, according to different income level in both the Atlas method and PPP dollars[32].

PPP is purchasing power parity. GDP PPP is gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar in the United States. GDP measures the total output of goods and services for final use occurring within the domestic territory of a given country, regardless of the allocation to domestic and foreign claims. Gross domestic product at purchaser values (market prices) is the sum of gross value added by all resident and nonresident producers in the economy plus any taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.

When GNP is calculated using the World Bank Atlas method, the estimate is based on regression; others are extrapolated from the latest International Comparison Programme benchmark estimates.

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[32] Source of Appendix A is from World Resource Institute, Database, 1998-1999.

	Atlas methodology (US $)	Purchasing Power Parity (international $)
World	5,180	6,260
Low Income	350	1,400
Middle Income	1,890	4,320
Lower Middle Income	1,230	3,500
Upper Middle Income	4,540	7,590
Low & Middle Income	1,250	3,100
East Asia & Pacific	970	3,170
Europe & Central Asia	2,310	4,420
Latin America & Caribbean	3,940	6,730
Middle East & North Africa	2,070	4,630
South Asia	380	1,590
Sub-Saharan Africa	510	1,460
High Income	25,890	22,930
European EMU	23,450	20,230

Note that the rankings in the above table include all 210 Atlas economies, but only those with confirmed 1997 Atlas GNP per capita estimates or those in the top twenty are shown in rank order.

1. Estimate used for ranking purposes only.
2. GNP data refer to GDP.
3. Estimate is based on regression. Other PPP figures are extrapolated from the latest International Comparison Programme benchmark estimates.
4. Data refer to mainland Tanzania only.
5. Estimated to be high income ($9,656 or more).
6. Estimated to be upper middle income ($3,126 to $9,655).
7. Estimated to be lower middle income ($786 to $3,125).

8. Estimated to be low income ($785 or less).

Appendix B
Tables of Simulation Results

Table 1.1: Simulation Results of Pollution Emissions in Fixed Time Periods

For Case $\varphi A^2 <= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

One-State Variable Model: $\alpha=0.8$, $\varphi=0.9$, $B=10$, $A=0.1$, $\pi=0.1$, $\beta=0.01$, $K_0=0$

	t=1		t=5		t=10		t=15		t=20		t=25	
K(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
0	100.00		100.00		100.00		100.00		100.00		100.00	
1	110.90	10.90	110.18	10.18	110.09	10.09	110.06	10.06	110.05	10.05	110.04	10.04
2	116.98	6.08	115.54	5.36	115.36	5.27	115.30	5.24	115.27	5.23	115.25	5.22
3	122.09	5.10	119.93	4.38	119.66	4.29	119.57	4.26	119.52	4.25	119.49	4.24
4	126.66	4.58	123.78	3.86	123.42	3.77	123.30	3.74	123.24	3.72	123.21	3.71
5	130.89	4.23	127.29	3.51	126.84	3.42	126.69	3.39	126.61	3.37	126.57	3.36
6	134.86	3.98	130.54	3.26	130.00	3.17	129.82	3.14	129.73	3.12	129.68	3.11
7	138.64	3.78	133.60	3.06	132.97	2.97	132.76	2.94	132.66	2.92	132.60	2.92
8	142.27	3.62	136.51	2.90	135.79	2.81	135.55	2.78	135.43	2.77	135.35	2.76
9	145.76	3.49	139.28	2.77	138.47	2.68	138.20	2.65	138.06	2.64	137.98	2.63
10	149.14	3.38	141.94	2.66	141.04	2.57	140.74	2.54	140.59	2.53	140.50	2.52

Table 1.2: Simulation Results of Pollution Emissions in Fixed Time Periods

For Case $\varphi A^2 <= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

Two-State Variable Model: $\alpha=0.8$, $\varphi=0.1$, $B=10$, $A=1$, $\pi=0.1$, $\beta=0.01$, $K_0=0$, $\delta=0.9$, $D=100$

	t=1		t=5		t=10		t=15		t=20		t=25	
K(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
0	40.66		1.11		0.01		0.00		0.00		0.00	
1	51.78	11.12	12.14	11.03	11.03	11.02	11.02	11.02	11.02	11.02	11.02	11.02
2	57.55	5.77	17.83	5.68	16.70	5.67	16.69	5.67	16.68	5.66	16.68	5.66
3	62.24	4.69	22.42	4.60	21.29	4.59	21.27	4.58	21.26	4.58	21.26	4.58
4	66.34	4.10	26.43	4.01	25.29	4.00	25.26	4.00	25.26	3.99	25.25	3.99
5	70.05	3.71	30.06	3.62	28.90	3.61	28.87	3.61	28.86	3.61	28.86	3.61
6	73.48	3.43	33.40	3.34	32.24	3.33	32.20	3.33	32.19	3.33	32.18	3.33
7	76.70	3.22	36.53	3.13	35.35	3.12	35.31	3.11	35.30	3.11	35.29	3.11
8	79.74	3.04	39.48	2.95	38.29	2.94	38.25	2.94	38.24	2.94	38.23	2.94
9	82.64	2.90	42.29	2.81	41.09	2.80	41.05	2.79	41.03	2.79	41.02	2.79
10	85.41	2.78	44.98	2.69	43.77	2.68	43.72	2.67	43.70	2.67	43.69	2.67

Table 2.1: Simulation Results of Pollution Emissions in Fixed Capital Stocks

For Case $\varphi A^2 >= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

One-State Variable Model: $\alpha=0.8$, $\varphi=0.9$, $B=10$, $A=10$, $\pi=0.1$, $\beta=0.01$, $K_0=0$

	K(t)=1		K(t)=5		K(t)=10		K(t)=15		K(t)=20		K(t)=25	
t	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
1	101.99		98.60		92.92		87.08		81.27		75.54	
2	101.54	-0.45	96.35	-2.25	88.42	-4.50	80.33	-6.75	72.27	-9.00	64.29	-11.25
3	101.39	-0.15	95.60	-0.75	86.92	-1.50	78.08	-2.25	69.27	-3.00	60.54	-3.75
4	101.32	-0.08	95.23	-0.38	86.17	-0.75	76.96	-1.13	67.77	-1.50	58.67	-1.88
5	101.27	-0.05	95.00	-0.23	85.72	-0.45	76.28	-0.67	66.87	-0.90	57.54	-1.13
6	101.24	-0.03	94.85	-0.15	85.42	-0.30	75.83	-0.45	66.27	-0.60	56.79	-0.75
7	101.22	-0.02	94.74	-0.11	85.21	-0.21	75.51	-0.32	65.84	-0.43	56.26	-0.54
8	101.20	-0.02	94.66	-0.08	85.05	-0.16	75.27	-0.24	65.52	-0.32	55.86	-0.40
9	101.19	-0.01	94.60	-0.06	84.92	-0.13	75.08	-0.19	65.27	-0.25	55.54	-0.31
10	101.18	-0.01	94.55	-0.05	84.82	-0.10	74.93	-0.15	65.07	-0.20	55.29	-0.25

Table 2.2: Simulation Results of Pollution Emissions in Fixed Capital Stocks

For Case $\varphi A^2 >= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

Two-State Variable Model: $\alpha=0.8$, $\varphi=0.1$, $B=10$, $A=50$, $\pi=0.1$, $\beta=0.01$, $K_0=0$, $\delta=0.9$, $D=100$

	K(t)=1		K(t)=5		K(t)=10		K(t)=15		K(t)=20		K(t)=25	
t	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
1	46.33		50.32		51.06		50.42		49.12		47.41	
2	22.15	-24.18	25.91	-24.40	26.38	-24.68	25.46	-24.96	23.88	-25.24	21.89	-25.52
3	12.32	-9.83	16.01	-9.90	16.38	-9.99	15.38	-10.09	13.70	-10.18	11.62	-10.27
4	8.33	-4.00	11.98	-4.03	12.30	-4.08	11.25	-4.13	9.53	-4.17	7.40	-4.22
5	6.70	-1.63	10.33	-1.65	10.63	-1.68	9.54	-1.70	7.79	-1.73	5.64	-1.76
6	6.04	-0.66	9.65	-0.68	9.93	-0.70	8.83	-0.71	7.06	-0.73	4.88	-0.75
7	5.77	-0.27	9.37	-0.28	9.63	-0.29	8.52	-0.31	6.74	-0.32	4.55	-0.33
8	5.66	-0.11	9.25	-0.12	9.51	-0.13	8.38	-0.14	6.59	-0.15	4.39	-0.16
9	5.61	-0.05	9.20	-0.05	9.45	-0.06	8.32	-0.07	6.51	-0.08	4.31	-0.08
10	5.59	-0.02	9.17	-0.02	9.42	-0.03	8.28	-0.04	6.47	-0.04	4.26	-0.05

Table 3.1: Simulation Results of Pollution Emissions in Fixed Time Periods

For Case $\varphi A^2 >= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

One-State Variable Model: $\alpha=0.8$, $\varphi=0.9$, $B=10$, $A=10$, $\pi=0.1$, $\beta=0.01$, $K_0=0$

	t=1		t=5		t=10		t=15		t=20		t=25	
K(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
0	100.00		100.00		100.00		100.00		100.00		100.00	
1	101.99	1.99	101.27	1.27	101.18	1.18	101.15	1.15	101.14	1.14	101.13	1.13
2	101.47	-0.52	100.03	-1.24	99.85	-1.33	99.79	-1.36	99.76	-1.38	99.74	-1.39
3	100.63	-0.84	98.47	-1.56	98.20	-1.65	98.11	-1.68	98.06	-1.69	98.04	-1.70
4	99.65	-0.98	96.77	-1.70	96.41	-1.79	96.29	-1.82	96.23	-1.83	96.20	-1.84
5	98.60	-1.05	95.00	-1.77	94.55	-1.86	94.40	-1.89	94.33	-1.91	94.28	-1.91
6	97.50	-1.10	93.18	-1.82	92.64	-1.91	92.46	-1.94	92.37	-1.95	92.32	-1.96
7	96.38	-1.12	91.34	-1.84	90.71	-1.93	90.50	-1.96	90.40	-1.98	90.33	-1.99
8	95.24	-1.14	89.48	-1.86	88.76	-1.95	88.52	-1.98	88.40	-2.00	88.33	-2.01
9	94.09	-1.15	87.61	-1.87	86.80	-1.96	86.53	-1.99	86.39	-2.01	86.31	-2.02
10	92.92	-1.16	85.72	-1.88	84.82	-1.97	84.52	-2.00	84.37	-2.02	84.28	-2.03

Table 3.2: Simulation Results of Pollution Emissions in Fixed Time Periods

For Case $\varphi A^2 >= 4B((2\alpha-1)/\alpha^2)(1/t+\pi)$

Two-State Variable Model: $\alpha=0.8$, $\varphi=0.1$, $B=10$, $A=50$, $\pi=0.1$, $\beta=0.01$, $K_0=0$, $\delta=0.9$, $D=100$

	t=1		t=5		t=10		t=15		t=20		t=25	
K(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)	P(t)	Chg P(t)
0	40.66		1.11		0.01		0.00		0.00		0.00	
1	46.33	5.68	6.70	5.59	5.59	5.58	5.57	5.57	5.57	5.57	5.57	5.57
2	48.07	1.74	8.35	1.65	7.23	1.64	7.21	1.63	7.20	1.63	7.20	1.63
3	49.12	1.05	9.31	0.97	8.18	0.95	8.16	0.95	8.15	0.95	8.15	0.95
4	49.83	0.71	9.93	0.62	8.79	0.61	8.76	0.60	8.75	0.60	8.75	0.60
5	50.32	0.49	10.33	0.40	9.17	0.39	9.14	0.38	9.13	0.38	9.13	0.38
6	50.65	0.33	10.57	0.25	9.41	0.23	9.37	0.23	9.36	0.23	9.36	0.23
7	50.87	0.22	10.70	0.13	9.53	0.12	9.49	0.12	9.48	0.11	9.47	0.11
8	51.00	0.13	10.75	0.04	9.56	0.03	9.52	0.03	9.50	0.02	9.49	0.02
9	51.06	0.06	10.72	-0.03	9.52	-0.04	9.47	-0.05	9.45	-0.05	9.44	-0.05
10	51.06	0.00	10.63	-0.09	9.42	-0.10	9.37	-0.11	9.35	-0.11	9.34	-0.11

Appendix C
Tables of Regression Results (I)

Table 6.1: Regression For CO_2 at Global Level

	Fixed Effect		Random Effect	
ln_co$_2$	Coef	t-val	Coef	z-Val
ln_GDP	1.18	0.85	4.81	15.45
ln_GDP(SQ)	-0.04	-0.52	-0.21	-19.39
ln_GDP(-1)	0.58	3.02	0.14	0.50
ln_Energy	0.49	1.81	1.03	28.21
ln_Price(-1)	-0.09	-1.47	-0.30	-7.93
Constant	-5.00	-0.85	-20.31	-25.08
F_test(k, n-g-k)		16.51		
Wald Chi^2 (5)				25362
Log Likelihood				23
No. of obs		203		203
No. of grp		74		74

Table 6.2: Regression Analysis for CO at Global Level

	Fixed Effect Model									
	Basic Model		w/ Energy		w/ Service		w/ Industry		w/ Agri.	
ln_co	Coef	t-val	Coef	t-val	Coef	t-val	Coef	t-val	Coef	t-val
ln_GDP	6.26	0.58	3.02	0.25	11.68	0.94	8.26	0.71	14.21	1.07
ln_GDP(SQ)	-0.39	-0.69	-0.22	-0.35	-0.66	-1.02	-0.49	-0.81	-0.82	-1.18
ln_GDP(-1)	-0.04	-0.10	-0.15	-0.33	-0.06	-0.15	-0.30	-0.76	0.74	1.28
ln_Energy			0.50	0.63						
ln_Service					-2.46	-2.63				
ln_Industry							0.99	2.71		
ln_Ariculture									0.76	2.07
ln_Price(-1)	-0.54	-3.16	-0.57	-3.18	-0.29	-1.50	-0.31	-1.65	-0.52	-3.03
Constant	-18.30	-0.36	-2.35	-0.04	-35.03	-0.60	-29.29	-0.53	-63.92	-1.01
F_test(k, n-g-k)		23.20		18.28		20.28		23.94		18.23
No. of obs		54		54		49		47		49
No. of groups		19		19		18		17		18

Table 6.3: Regression Analysis for SO_2 at Global Level

	Fixed Effect				Random Effect			
	Basic Model		w/ Energy		Basic Model		w/ Energy	
ln_so_2	Coef	t-val	Coef	t-val	Coef	t-val	Coef	t-val
ln_GDP	77.71	4.93	74.64	4.23	16.08	2.68	9.47	1.64
ln_GDP(SQ)	-4.10	-5.01	-3.94	-4.30	-1.08	-3.72	-0.51	-1.68
ln_GDP(-1)	0.32	0.51	0.22	0.32	4.53	3.60	0.25	0.19
ln_Energy			0.48	0.41			0.34	1.75
ln_Price(-1)	-0.89	-3.62	-0.92	-3.54	-2.63	-25.42	-2.04	-12.11
Constant	-365.49	-4.90	-350.35	-4.17	-90.81	-3.33	-40.02	-1.46
F_test(k, n-g-k)		11.07		8.65				
Wald Chi^2 (5)						769.65		244.54
Log Likelihood						-5.47		-37.87
No. of obs		54		54		54		54
No. of grp		19		19		19		19

Table 6.4: Regression Analysis for NO_x at Global Level

	Fixed Effect				Random Effect			
	Basic Model		w/ Energy		Basic Model		w/ Energy	
ln_no$_x$	Coef	t-val	Coef	t-val	Coef	z-Val	Coef	z-Val
ln_GDP	28.54	4.15	23.60	2.80	2.51	0.83	0.75	0.29
ln_GDP(SQ)	-1.47	-4.13	-1.21	-2.77	-0.14	-0.89	-0.03	-0.24
ln_GDP(-1)	-0.23	-0.66	-0.36	-0.97	1.20	1.78	0.85	1.15
ln_Energy			0.63	1.02			0.21	2.62
ln_Price(-1)	-0.06	-0.46	-0.10	-0.73	-1.00	-8.63	-0.82	-7.49
Constant	-132.22	-4.03	-108.11	-2.67	-17.85	-1.23	-8.25	-0.72
F_test(k, n-g-k)		4.36		3.70				
Wald Chi^2 (5)						216.60		279.04
Log Likelihood						29.40		30.85
No. of obs		61		61		61		61
No. of grp		20		20		20		20

Table 6.5: Regression for PM at Global Level

	Fixed Effect		Random Effect	
ln_PM	Coef	t-val	Coef	z-Val
ln_GDP	11.63	0.71	107.33	2.45
ln_GDP(SQ)	-0.59	-0.70	-5.57	-2.42
ln_GDP(-1)	-0.30	-0.43	1.77	0.74
ln_Price(-1)	-0.39	-1.59	-3.56	-6.50
Constant	-51.47	-0.67	-526.89	-2.47
F_test(k, n-g-k)		1.11		
Wald Chi^2 (5)				237.77
Log Likelihood				-0.25
No. of obs		20		20
No. of grp		4		4

Table 6.6.1: Regression Analysis for VOC at Global Level

	Fixed Effect Model							
	Basic Model		w/ Energy		w/ Manuf.		w/ Industry	
ln_VOC	Coef	t-val	Coef	t-val	Coef	t-val	Coef	t-val
ln_GDP	29.25	1.49	20.17	0.89	11.91	1.32	88.18	1.93
ln_GDP(SQ)	-1.51	-1.52	-1.05	-0.91	-0.64	-1.39	-4.48	-1.95
ln_GDP(-1)	-0.65	-1.13	-0.68	-1.16	-0.50	-0.74	-0.68	-1.47
ln_Energy			0.58	0.82				
ln_Manufact					0.23	0.93		
ln_Industry							1.16	4.44
ln_Price(-1)	-0.46	-3.41	-0.50	-3.47	-0.05	-0.24	-0.15	-1.23
Constant	-123.84	-1.28	-79.55	-0.71	-40.41	-0.95	-419.51	-1.84
F_test(k, n-g-k)		7.46		6.02		1.62		14.11
No. of obs		46		46		26		39
No. of grp		18		18		12		16

Table 6.6.2: Regression Analysis for VOC at Global Level

	Random Effect Model							
	Basic Model		w/ Energy		w/ Manuf.		w/ Industry	
ln_VOC	Coef	t-val	Coef	t-val	Coef	t-val	Coef	t-val
ln_GDP	16.90	8.23	18.33	6.92	7.35	1.46	15.94	2.33
ln_GDP(SQ)	-0.91	-9.12	-1.00	-7.40	-0.51	-1.82	-0.90	-2.45
ln_GDP(-1)	1.47	2.48	1.71	2.53	3.61	4.00	2.33	3.07
ln_Energy			0.07	0.70				
ln_Manufact					0.03	0.15		
ln_Industry							0.64	2.94
ln_price(-1)	-1.28	-35.27	-1.27	-15.02	-1.29	-11.78	-1.24	-14.03
_cons	-79.80	-8.58	-87.79	-7.00	-45.63	-1.86	-82.01	-2.56
Wald Chi^2 (5)		2330.18		1648.45		621.52		626.72
Log Likelihood		26.82		28.39		15.23		22.03
No. of obs		46		46		26		39
No. of grp		18		18		12		16

Appendix D
Tables of Regression Results (II)

Table 7.1.1: Environmental Turning Points for the Six Air Pollutants

	Fixed Effect Model					
	CO_2	CO	SO_2	NO_x	PM	VOC
Global Average	115,082	13,964	13,450	266,400	60,367	16,181
Regional Average						
(1) High Income OECD	21,544	–	–	–	–	–
(2) Far East Asia & Pacific	683,701	–	–	–	–	–
(3) Europe and Central Asia	12,115	5,215	7,657	17,725	6.68E+06	–
(4) Latin America & Carribean	46,293	–	–	–	–	–
(5) Middle East & North Africa	80,002	–	–	–	–	–
(6) South Asia	1,590	–	–	–	–	–
(7) Sub-Saharan Africa	28,829	–	–	–	–	–

Table 7.1.2: Environmental Turning Points for the Six Air Pollutants

	Random Effect Model					
	CO_2	CO	SO_2	NO_x	PM	VOC
Global Average	105,772	2,714,222	10,228	225,022	7,078	9,528
Regional Average						
(1) High Income OECD	56,854	_	14,213	29,791	1,245	27,361
(2) Far East Asia & Pacific	179,134	5,973	432,503	13,953	6,387	_
(3) Europe and Central Asia	31,024	6,978	9,924	23,949	_	6,331
(4) Latin America & Carribean	22,504	_	_	_	_	_
(5) Middle East & North Africa	2.06E+06	_	_	_	_	_
(6) South Asia	2,415	_	_	_	_	_
(7) Sub-Saharan Africa	30,481	_	_	_	_	_

Table 7.1.3: Environmental Turning Points for the Six Air Pollutants

	Average Effect (Fixed and Random Effects)					
	CO_2	CO	SO_2	NO_x	PM	VOC
Global Average	110,427	1.36E+06	11,839	245,711	33,723	12,855
Regional Average						
(1) High Income OECD	39,199	_	14,213	29,791	1,245	27,361
(2) Far East Asia & Pacific	431,418	5,973	432,503	13,953	6,387	_
(3) Europe and Central Asia	21,570	6,096	8,790	20,837	6.68E+06	6,331
(4) Latin America & Carribean	34,399	_	_	_	_	_
(5) Middle East & North Africa	1.07E+06	_	_	_	_	_
(6) South Asia	2,002	_	_	_	_	_
(7) Sub-Saharan Africa	29,655	_	_	_	_	_

Table 7.2.1: Environmental Turning Points for Country Study

	Fixed Effect Model					
	CO_2	CO	SO_2	NO_x	PM	VOC
Australia	213,157	_	_	18,789	_	_
Austria	14,413	20,398	15,873	23,245	_	38,048
Belgium	15,216	_	_	_	_	_
Bolivia	2,202	_	_	_	_	_
Brazil	6,822	_	_	_	_	_
Bulgaria	3.98E+07	9,135	22,616	53,283	_	7,379
Canada	22,657	19,343	14,602	20,033	22,340	22,049
Chile	42,144	_	_	_	_	_
China	8.98E+08	_	_	_	_	_
Denmark	28,341	_	_	_	_	_
Ecuador	1,836	_	_	_	_	_
Elsalvador	8,928	_	_	_	_	_
Finland	19,557	18,577	18,313	16,857	18,712	20,325
France	15,052	23,957	12,880	18,950	_	20,377
Greece	_	7,753	16,752	_	_	27,678
Guatemala	265,232	_	_	_	_	_
Honduras	2,410	_	_	_	_	_
Hungary	47,425	_	8,159	11,499	9,997	13,111
Iceland	_	21,580	22,084	22,731	_	23,145
India	27,893	_	_	_	_	_
Ireland	44,159	2,531	17,075	28,417	_	2.45E+06
Italy	12,499	18,763	1.55E+09	23,638	_	18,474
Jamaica	1.40E+12	_	_	_	_	_
Japan	4.21E+12	_	_	_	_	_
Jordan	9,677	_	_	_	_	_
Kenya	952	_	_	_	_	_
Korea	13,750	5,203	7,001	11,236	10,492	_
Luxembourg	206,007	_	_	_	_	_
Morocco	4,844	_	_	_	_	_
Netherlands	17,023	16,385	14,931	17,680	_	16,386
New Zealand	20,980	_	_	_	_	_
Nicaragua	3,465	_	_	_	_	_
Norway	_	21,154	14,825	28,504	_	4.50E+25
Pakistan	5,167	_	_	_	_	_
Panama	5,703	_	_	_	_	_
Philippines	4,127	_	_	_	_	_
Poland	25,457	6,219	6,496	7,709	5,766	17,163
Portugal	15,378	_	2,806	2,467	_	7,458
Romania	12,314	121,049	_	30,004	_	_
Saudi Arabia	18,584	_	_	_	_	_
Senegal	875	_	_	_	_	_
South Africa	10,154	_	_	_	_	_
Spain	16,509	12,043	10,379	13,415	_	13,056
Sudan	1,034	_	_	_	_	_
Sweden	14,986	23,976	_	17,545	_	20,043
Thailand	3.03E+14	_	_	_	_	_
Tunisia	38,975	_	_	_	_	_
Turkey	9,143	_	6,290	7,751	_	_
Uganda	894	_	_	_	_	_
UK	16,513	14,409	16,343	16,971	42,670	17,085
Uruguay	9,067	_	_	_	_	_
US	843,818	15,568	28,534	21,766	28,099	22,254
Zambia	1,448	_	_	_	_	_
Zimbabwe	2,795	_	_	_	_	_

Table 7.2.2: Environmental Turning Points for Country Study

	Random Effect Model					
	CO_2	CO	SO_2	NO_x	PM	VOC
Australia	582,583	_	_	15,249	_	_
Austria	_	_	_	_	_	_
Belgium	_	_	_	_	_	_
Bolivia	_	_	_	_	_	_
Brazil	6,783	_	_	_	_	_
Bulgaria	7.97E+07	10,518	14,849	53,283	_	9,200
Canada	_	33,236	19,956	30,701	1.51E+06	_
Chile	42,144	_	_	_	_	_
China	53,982	_	_	_	_	_
Denmark	31,587	_	_	_	_	_
Ecuador	_	_	_	_	_	_
Elsalvador	_	_	_	_	_	_
Finland	20,145	_	_	13,616	_	20,256
France	_	_	_	_	_	_
Greece	_	_	_	_	_	33,002
Guatemala	_	_	_	_	_	_
Honduras	_	_	_	_	_	_
Hungary	_	_	_	_	_	_
Iceland	_	21,580	21,622	22,580	_	22,634
India	53,975	_	_	_	_	_
Ireland	93,711	2,531	30,258	15,235	_	16,142
Italy	2,101	17,838	15,797	17,826	_	16,152
Jamaica	_	_	_	_	_	_
Japan	_	_	_	_	_	_
Jordan	1.17E+07	_	_	_	_	_
Kenya	917	_	_	_	_	_
Korea	_	5,973	1,001	5,843	6,387	_
Luxembourg	19,374	_	_	_	_	_
Morocco	5,773	_	_	_	_	_
Netherlands	10,026	16,364	15,249	17,622	_	16,685
New Zealand	_	_	_	_	_	_
Nicaragua	_	_	_	_	_	_
Norway	_	20,348	12,898	27,960	_	184,499
Pakistan	_	_	_	_	_	_
Panama	_	_	_	_	_	_
Philippines	_	_	_	_	_	_
Poland	_	6,145	4,550	3,483	_	5,387
Portugal	15,378	_	5,198	810	_	11,410
Romania	_	_	_	_	_	_
Saudi Arabia	43,996	_	6,732	8,852	5,724	8,303
Senegal	_	_	_	_	_	_
South Africa	10,136	_	_	_	_	_
Spain	26,439	12,043	10,321	10,937	_	13,056
Sudan	_	_	_	_	_	_
Sweden	_	_	_	_	_	_
Thailand	_	_	_	_	_	_
Tunisia	_	_	_	_	_	_
Turkey	9,143	_	6,764	7,751	_	_
Uganda	_	_	_	_	_	_
UK	16,184	15,698	15,997	16,480	26,657	16,557
Uruguay						
US	843,820	22,751	28,665	19,569	26,448	22,786
Zambia	_	_	_	_	_	_
Zimbabwe	_	_	_	_	_	_

Table 7.2.3: Environmental Turning Points for Country Study

	Average Effect (Fixed and Random Effect Models)					
	CO_2	CO	SO_2	NO_x	PM	VOC
Australia	397,870	_	_	17,019	_	_
Austria	14,413	20,398	15,873	23,245	_	38,048
Belgium	15,216	_	_	_	_	_
Bolivia	2,202	_	_	_	_	_
Brazil	6,802	_	_	_	_	_
Bulgaria	5.98E+07	9,826	18,733	53,283	_	8,289
Canada	22,657	26,290	17,279	25,367	764,112	22,049
Chile	42,144	_	_	_	_	_
China	4.49E+08	_	_	_	_	_
Denmark	29,964	_	_	_	_	_
Ecuador	1,836	_	_	_	_	_
Elsalvador	8,928	_	_	_	_	_
Finland	19,851	18,577	18,313	15,236	18,712	20,290
France	15,052	23,957	12,880	18,950	_	20,377
Greece	_	7,753	16,752	_	_	30,340
Guatemala	265,232	_	_	_	_	_
Honduras	2,410	_	_	_	_	_
Hungary	47,425	_	8,159	11,499	9,997	13,111
Iceland	_	21,580	21,853	22,656	_	22,889
India	40,934	_	_	_	_	_
Ireland	68,935	2,531	23,666	21,826	_	1.23E+06
Italy	7,300	18,301	7.76E+08	20,732	_	17,313
Jamaica	1.40E+12	_	_	_	_	_
Japan	4.21E+12	_	_	_	_	_
Jordan	5.84E+06	_	_	_	_	_
Kenya	935	_	_	_	_	_
Korea	13,750	5,588	4,001	8,540	8,439	_
Luxembourg	112,691	_	_	_	_	_
Morocco	5,309	_	_	_	_	_
Netherlands	13,525	16,375	15,090	17,651	_	16,535
New Zealand	20,980	_	_	_	_	_
Nicaragua	3,465	_	_	_	_	_
Norway	_	20,751	13,861	28,232	_	2.25E+25
Pakistan	5,167	_	_	_	_	_
Panama	5,703	_	_	_	_	_
Philippines	4,127	_	_	_	_	_
Poland	25,457	6,182	5,523	5,596	5,766	11,275
Portugal	15,378	_	4,002	1,638	_	9,434
Romania	12,314	121,049	_	30,004	_	_
Saudi Arabia	31,290	_	6,732	8,852	5,724	8,303
Senegal	875	_	_	_	_	_
South Africa	10,145	_	_	_	_	_
Spain	21,474	12,043	10,350	12,176	_	13,056
Sudan	1,034	_	_	_	_	_
Sweden	14,986	23,976	_	17,545	_	20,043
Thailand	3.03E+14	_	_	_	_	_
Tunisia	38,975	_	_	_	_	_
Turkey	9,143	_	6,527	7,751	_	_
Uganda	894	_	_	_	_	_
UK	16,349	15,054	16,170	16,725	34,664	16,821
Uruguay	9,067	_	_	_	_	_
US	843,819	19,160	28,600	20,668	27,274	22,520
Zambia	1,448	_	_	_	_	_
Zimbabwe	2,795	_	_	_	_	_

Appendix E
Tables of Regression Results (III)

Table 8.1.1: Percentage Change of Pollution Emission with respect to Economic Structures at Global Level

	Fixed Effect				Random Effect			
Global Estimation	Income Effect		Tech Effect	Policy Impli.	Income Effect		Tech Effect	Policy Impli.
	Scale Effect	Composition Effect			Scale Effect	Composition Effect		
CO_2	1.65	-0.05	-3.21	-0.09	2.61	-0.08	-8.88	-0.76
CO	7.64	-0.45	-26.54	-0.44	68.28	-7.55	-387.01	-1.25
SO_2	63.16	-3.34	-293.06	-0.64	16.90	-0.90	-73.30	-2.34
NO_x	13.49	-0.69	-62.44	-0.08	2.65	-0.09	-13.05	-0.91
PM	11.60	-0.61	-52.61	-0.30	70.65	-8.41	-450.01	-2.19
VOC	38.37	-1.99	-173.42	-0.31	20.46	-1.02	-90.54	-1.36

Table 8.1.2: Percentage Change of Pollution Emissions with respect to Economic Structures at Global Level

Global Estimation	Average Effect (Fixed and Random Effects)			
	Income Effect		Tech Effect	Policy Implication
	Scale Effect	Composition Effect		
CO_2	2.13	-0.06	-6.04	-0.43
CO	37.96	-4.00	-206.78	-0.85
SO_2	40.03	-2.12	-183.18	-1.49
NO_x	8.07	-0.39	-37.75	-0.50
PM	41.12	-4.51	-251.31	-1.24
VOC	29.42	-1.50	-131.98	-0.83

Table 8.2.1: Percentage Change of Pollution Emissions for Cross-Country Study (CO)

Country Estimation		Fixed Effect Moel		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO	Bulgaria	26.30	-1.51	-110.65
	Canada	479.45	-23.98	-2392.42
	Iceland	112.19	-5.59	-557.93
	Ireland	3.36	-0.21	-8.17
	Italy	25.95	-1.32	-122.58
	Korea	22.57	-1.25	-94.99
	Netherlands	120.76	-6.22	-579.97
	Norway	61.00	-3.09	-296.14
	Poland	294.70	-16.75	-1288.65
	Portugal	_	_	_
	Spain	51.62	-2.71	-240.93
	Turkey	_	_	_
	UK	99.32	-5.10	-482.22
	US	38.94	-1.97	-186.29

Table 8.2.2: Percentage Change of Pollution Emissions for Cross-Country Study (CO_2)

		Fixed Effect Moel		
Country Estimation		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO_2	Bulgaria	8.78	-0.47	-32.61
	Canada	457.88	-22.84	-2281.86
	Iceland	–	–	–
	Ireland	7.94	-0.39	-31.23
	Italy	6.42	-0.30	-25.08
	Korea	36.38	-1.86	-168.89
	Netherlands	30.01	-1.48	-144.02
	Norway	–	–	–
	Poland	192.80	-10.91	-841.47
	Portugal	13.01	-0.65	-58.41
	Spain	214.26	-11.01	-1033.72
	Turkey	22.62	-1.26	-95.48
	UK	34.70	-1.78	-161.33
	US	0.72	-0.02	4.99

Table 8.2.3: Percentage Change of Pollution Emission for Cross-Country Study (NO_x)

		Fixed Effect Moel		
Country Estimation		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
NO_x	Bulgaria	6.90	-0.30	-36.92
	Canada	403.30	-20.13	-2016.72
	Iceland	99.87	-4.95	-499.39
	Ireland	14.71	-0.74	-70.23
	Italy	233.63	-11.78	-1155.44
	Korea	105.32	-5.55	-496.85
	Netherlands	109.60	-5.61	-531.36
	Norway	32.52	-1.62	-159.66
	Poland	98.95	-5.61	-431.59
	Portugal	26.88	-1.30	-134.26
	Spain	34.73	-1.80	-164.02
	Turkey	22.62	-1.26	-100.15
	UK	156.32	-8.01	-763.00
	US	22.19	-1.11	-106.71

Table 8.2.4: Percentage Change of Pollution Emission for Cross-Country Study (PM)

Country Estimation		Fixed Effect Moel		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
PM	Canada	494.73	-24.67	-2476.01
	Iceland	_	_	_
	Ireland	_	_	_
	Italy	_	_	_
	Korea	399.06	-21.09	-1894.03
	Netherlands	_	_	_
	Norway	_	_	_
	Poland	51.57	-2.95	-222.65
	Portugal	_	_	_
	Spain	_	_	_
	Turkey	_	_	_
	UK	112.98	-5.75	-557.22
	US	23.41	-1.19	-112.49

Table 8.2.5: Percentage Change of Pollution Emission for Cross-Country Study (SO_2)

Country Estimation		Fixed Effect Moel		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
SO_2	Bulgaria	14.46	-0.78	-63.06
	Canada	50.30	-2.56	-241.68
	Iceland	167.34	-8.32	-838.06
	Ireland	24.67	-1.28	-115.26
	Italy	102.91	-5.28	-501.40
	Korea	9.85	-0.52	-43.27
	Netherlands	219.57	-11.32	-1059.51
	Norway	57.18	-3.04	-263.69
	Poland	115.10	-6.57	-499.27
	Portugal	19.45	-1.00	-91.13
	Spain	112.68	-6.01	-524.07
	Turkey	138.87	-7.98	-605.39
	UK	298.83	-15.35	-1457.30
	US	305.06	-15.06	-1541.57

Table 8.2.6: Percentage Change of Pollution Emission for Cross-Country Study (VOC)

Country Estimation		Fixed Effect Moel		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
VOC	Bulgaria	162.18	-9.50	-683.01
	Canada	512.51	-25.58	-2555.94
	Iceland	641.08	-31.90	-3200.37
	Ireland	22.28	-1.13	-99.63
	Italy	77.63	-3.89	-376.16
	Korea	–	–	–
	Netherlands	147.58	-7.57	-707.92
	Norway	28.36	-1.35	-137.65
	Poland	32.41	-1.85	-131.52
	Portugal	28.65	-1.45	-132.55
	Spain	39.96	-2.11	-178.19
	Turkey	–	–	–
	UK	105.13	-5.39	-505.34
	US	66.90	-3.35	-321.72

Appendix F
Tables of Regression Results (IV)

Table 8.3.1: Percentage Change of Pollution Emission for Cross-Country Study (CO)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO	Bulgaria	26.30	-1.51	-110.65
	Canada	9.92	-0.49	-46.76
	Iceland	112.19	-5.59	-557.93
	Ireland	3.36	-0.21	-8.17
	Italy	37.57	-1.92	-178.85
	Korea	_	_	_
	Netherlands	118.38	-6.10	-568.37
	Norway	73.99	-3.75	-359.98
	Poland	204.60	-11.60	-897.20
	Portugal	_	_	_
	Spain	51.62	-2.71	-240.93
	Turkey	_	_	_
	UK	145.29	-7.46	-705.87
	US	33.29	-1.69	-156.47

Table 8.3.2: Percentage Change of Pollution Emission for Cross-Country Study (CO_2)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO_2	Bulgaria	8.78	-0.47	-32.61
	Canada	–	–	–
	Iceland	–	–	–
	Ireland	5.35	-0.24	-20.51
	Italy	1.08	-0.03	1.54
	Korea	21.09	-1.17	-85.92
	Netherlands	13.43	-0.61	-66.00
	Norway	–	–	–
	Poland	5.36	-0.25	-20.76
	Portugal	13.01	-0.65	-58.41
	Spain	–	–	–
	Turkey	22.62	-1.26	-95.48
	UK	45.91	-2.35	-215.82
	US	0.72	-0.02	4.99

Table 8.3.3: Percentage Change of Pollution Emission for Cross-Country Study (NO_x)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
NO_x	Bulgaria	6.90	-0.30	-36.92
	Canada	6.24	-0.30	-29.47
	Iceland	99.87	-4.95	-499.39
	Ireland	27.25	-1.40	-128.61
	Italy	87.15	-4.43	-425.31
	Korea	2.07	-0.09	-8.21
	Netherlands	116.83	-5.98	-566.68
	Norway	34.91	-1.74	-171.49
	Poland	15.19	-0.86	-63.50
	Portugal	17.89	-0.82	-93.15
	Spain	10.38	-0.51	-49.08
	Turkey	22.62	-1.26	-100.15
	UK	205.99	-10.55	-1004.64
	US	21.60	-1.09	-102.87

Table 8.3.4: Percentage Change of Pollution Emission for Cross-Country Study (PM)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
PM	Canada	0.57	-0.02	–
	Iceland	–	–	–
	Ireland	–	–	–
	Italy	–	–	–
	Korea	3.15	-0.16	-12.78
	Netherlands	–	–	–
	Norway	–	–	–
	Poland	48.23	-2.75	-208.16
	Portugal	–	–	–
	Spain	–	–	–
	Turkey	–	–	–
	UK	162.56	-8.29	-800.00
	US	23.72	-1.21	-114.12

Table 8.3.5: Percentage Change of Pollution Emission for Cross-Country Study (SO_2)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
SO_2	Bulgaria	16.17	-0.85	-73.56
	Canada	50.30	-2.56	-241.68
	Iceland	167.34	-8.32	-838.06
	Ireland	11.38	-0.56	-55.22
	Italy	236.02	-12.17	-1140.14
	Korea	2.73	-0.15	-9.13
	Netherlands	225.72	-11.63	-1089.61
	Norway	57.18	-3.04	-263.69
	Poland	48.12	-2.77	-205.82
	Portugal	23.68	-1.22	-111.48
	Spain	110.52	-5.90	-513.79
	Turkey	138.87	-7.98	-605.39
	UK	394.50	-20.25	-1922.51
	US	374.50	-18.48	-1893.95

Table 8.3.6: Percentage Change of Pollution Emission for Cross-Country Study (VOC)

Country Estimation		Random Effect Model		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
VOC	Bulgaria	174.33	-10.18	-737.53
	Canada	_	_	_
	Iceland	224.00	-11.09	-1120.74
	Ireland	32.81	-1.68	-150.06
	Italy	18.63	-0.94	-82.04
	Korea	_	_	_
	Netherlands	159.92	-8.20	-768.18
	Norway	7.79	-0.31	-36.94
	Poland	16.98	-0.97	-64.65
	Portugal	33.20	-1.71	-154.73
	Spain	39.96	-2.11	-178.19
	Turkey	_	_	_
	UK	140.14	-7.18	-675.64
	US	60.25	-3.03	-286.61

Table 8.4.1: Percentage Change of Pollution Emission for Cross-Country Study (CO)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO	Bulgaria	26.30	-1.51	-110.65
	Canada	244.69	-12.24	-1219.59
	Iceland	112.19	-5.59	-557.93
	Ireland	3.36	-0.21	-8.17
	Italy	31.76	-1.62	-150.71
	Korea	22.57	-1.25	-94.99
	Netherlands	119.57	-6.16	-574.17
	Norway	67.49	-3.42	-328.06
	Poland	249.65	-14.17	-1092.93
	Portugal	_	_	_
	Spain	51.62	-2.71	-240.93
	Turkey	_	_	_
	UK	122.31	-6.28	-594.05
	US	36.12	-1.83	-171.38

Table 8.4.2: Percentage Change of Pollution Emission for Cross-Country Study (CO_2)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
CO_2	Bulgaria	8.78	-0.47	-32.61
	Canada	457.88	-22.84	-2281.86
	Iceland	—	—	—
	Ireland	6.65	-0.32	-25.87
	Italy	3.75	-0.17	-11.77
	Korea	28.74	-1.51	-127.41
	Netherlands	21.72	-1.04	-105.01
	Norway	—	—	—
	Poland	99.08	-5.58	-431.12
	Portugal	13.01	-0.65	-58.41
	Spain	214.26	-11.01	-1033.72
	Turkey	22.62	-1.26	-95.48
	UK	40.30	-2.06	-188.57
	US	0.72	-0.02	4.99

Table 8.4.3: Percentage Change of Pollution Emission for Cross-Country Study (NO_x)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
NO_x	Bulgaria	6.90	-0.30	-36.92
	Canada	204.77	-10.22	-1023.09
	Iceland	99.87	-4.95	-499.39
	Ireland	20.98	-1.07	-99.42
	Italy	160.39	-8.10	-790.37
	Korea	53.70	-2.82	-252.53
	Netherlands	113.22	-5.79	-549.02
	Norway	33.71	-1.68	-165.57
	Poland	57.07	-3.24	-247.54
	Portugal	22.39	-1.06	-113.71
	Spain	22.56	-1.16	-106.55
	Turkey	22.62	-1.26	-100.15
	UK	181.15	-9.28	-883.82
	US	21.90	-1.10	-104.79

Table 8.4.4: Percentage Change of Pollution Emission for Cross-Country Study (PM)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
PM	Canada	247.65	-12.34	-2476.01
	Iceland	_	_	_
	Ireland	_	_	_
	Italy	_	_	_
	Korea	201.10	-10.63	-953.40
	Netherlands	_	_	_
	Norway	_	_	_
	Poland	49.90	-2.85	-215.41
	Portugal	_	_	_
	Spain	_	_	_
	Turkey	_	_	_
	UK	137.77	-7.02	-678.61
	US	23.57	-1.20	-113.30

Table 8.4.5: Percentage Change of Pollution Emission for Cross-Country Study (SO_2)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
SO_2	Bulgaria	15.32	-0.82	-68.31
	Canada	50.30	-2.56	-241.68
	Iceland	167.34	-8.32	-838.06
	Ireland	18.02	-0.92	-85.24
	Italy	169.47	-8.73	-820.77
	Korea	6.29	-0.34	-26.20
	Netherlands	222.64	-11.48	-1074.56
	Norway	57.18	-3.04	-263.69
	Poland	81.61	-4.67	-352.54
	Portugal	21.56	-1.11	-101.30
	Spain	111.60	-5.95	-518.93
	Turkey	138.87	-7.98	-605.39
	UK	346.67	-17.80	-1689.90
	US	339.78	-16.77	-1717.76

Table 8.4.6: Percentage Change of Pollution Emission for Cross-Country Study (VOC)

Country Estimation		Average Effect		
		Income Effect		Tech Effect
		Scale Effect	Composition effect (Btw Structural Change)	
VOC	Bulgaria	168.26	-9.84	-710.27
	Canada	512.51	-25.58	-2555.94
	Iceland	432.54	-21.49	-2160.55
	Ireland	27.54	-1.41	-124.85
	Italy	48.13	-2.41	-229.10
	Korea	–	–	–
	Netherlands	153.75	-7.88	-738.05
	Norway	18.08	-0.83	-87.30
	Poland	24.70	-1.41	-98.08
	Portugal	30.92	-1.58	-143.64
	Spain	39.96	-2.11	-178.19
	Turkey	–	–	–
	UK	122.64	-6.28	-590.49
	US	63.57	-3.19	-304.17

Appendix G
Tables of Regression Results (V)

Table 8.5.1: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

Percentage Change Effects	Fixed Effect Model			
	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition Effect		
Global Estimation	1.65	-0.05	-3.21	-0.09
Regional Estimation				
(1) High Income OECD	19.82	-0.97	-92.09	-0.08
(2) Far East Asia & Pacific	2.40	-0.08	-7.22	-0.50
(3) Europe and Central Asia	8.75	-0.45	-33.57	_
(4) Latin America and Carribean	3.16	-0.12	-11.07	_
(5) Middle East and North Africa	6.80	-0.34	-25.47	-0.09
(6) South Asia	18.36	-1.16	-66.69	_
(7) Sub-Saharan Africa	5.14	-0.15	-24.54	-0.47

Table 8.5.2: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

	Fixed Effect Model			
Percentage Change Effects	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition Effect		
Country Estimation				
Australia	17.93	-0.85	-85.46	-0.16
Brazil	189.09	-10.68	-829.84	-0.16
Bulgaria	8.78	-0.47	-32.61	_
Canada	457.88	-22.84	-2281.86	-0.31
Chile	4.75	-0.21	-20.08	_
China	2.15	-0.11	-2.90	_
Denmark	41.48	-2.08	-198.55	_
Finland	146.17	-7.39	-713.58	_
France	112.35	-5.66	-548.62	-0.22
India	9.23	-0.52	-35.85	_
Ireland	7.94	-0.39	-31.23	_
Italy	6.42	-0.30	-25.08	_
Japan	0.98	-0.03	1.29	-0.06
Jordan	13.92	-0.79	-53.20	_
Kenya	105.19	-7.57	-359.78	_
Korea	36.38	-1.86	-168.89	-0.10
Luxembourg	18.91	-0.93	-86.37	_
Morocco	21.34	-1.25	-83.58	_
Netherlands	30.01	-1.48	-144.02	_
Poland	192.80	-10.91	-841.47	_
Portugal	13.01	-0.65	-58.41	_
Saudi Arabia	17.07	-0.89	-72.75	_
South Africa	45.91	-2.49	-202.33	_
Spain	214.26	-11.01	-1033.72	-0.14
Thailand	14.27	-0.74	-60.05	-0.13
Turkey	22.62	-1.26	-95.48	_
UK	34.70	-1.78	-161.33	_
US	0.72	-0.02	4.99	_

Table 8.6.1: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

	Random Effect Model			
Percentage Change Effects	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition Effect		
Global Estimation	2.61	-0.08	-8.88	-0.76
Regional Estimation				
(1) High Income OECD	4.49	-0.20	-16.10	–
(2) Far East Asia & Pacific	3.94	-0.13	-11.02	-0.99
(3) Europe and Central Asia	16.87	-0.92	-69.67	–
(4) Latin America and Carribean	7.81	-0.38	-31.99	–
(5) Middle East and North Africa	125.19	-7.42	-520.03	-0.24
(6) South Asia	55.16	-3.69	-200.91	–
(7) Sub-Saharan Africa	6.02	-0.28	-23.65	-1.10

Table 8.6.2: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

Percentage Change Effects	Random Effect Model			
	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition Effect		
Country Estimation				
Australia	4.91	-0.19	-22.46	_
Brazil	69.60	-3.90	-304.05	_
Bulgaria	8.78	-0.47	-32.61	_
Canada	_	_	_	_
Chile	4.75	-0.21	-20.08	_
China	2.41	-0.12	-4.04	_
Denmark	41.95	-2.09	-202.52	_
Finland	67.00	-3.39	-322.53	_
France	_	_	_	_
India	9.23	-0.52	-35.85	_
Ireland	5.35	-0.24	-20.51	_
Italy	1.08	-0.03	1.54	_
Japan	_	_	_	_
Jordan	8.91	-0.46	-35.95	_
Kenya	112.92	-8.12	-387.11	_
Korea	21.09	-1.17	-85.92	_
Luxembourg	13.26	-0.63	-60.83	_
Morocco	5.17	-0.25	-18.22	_
Netherlands	13.43	-0.61	-66.00	_
Poland	5.36	-0.25	-20.76	_
Portugal	13.01	-0.65	-58.41	_
Saudi Arabia	18.12	-0.95	-77.41	_
South Africa	41.49	-2.25	-182.08	_
Spain	_	_	_	_
Thailand	_	_	_	_
Turkey	22.62	-1.26	-95.48	_
UK	45.91	-2.35	-215.82	_
US	0.72	-0.02	4.99	_

Table 8.7.1: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

Percentage Change Effects	Average Effect			
	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition effect		
Global Estimation	2.13	-0.06	-6.04	-0.43
Regional Estimation				
(1) High Income OECD	12.16	-0.58	-54.10	-0.08
(2) Far East Asia & Pacific	3.17	-0.10	-9.12	-0.75
(3) Europe and Central Asia	12.81	-0.69	-51.62	_
(4) Latin America and Carribea	5.48	-0.25	-21.53	_
(5) Middle East and North Africa	66.00	-3.88	-272.75	-0.16
(6) South Asia	36.76	-2.42	-133.80	_
(7) Sub-Saharan Africa	5.58	-0.22	-24.09	-0.79

Table 8.7.2: Percentage Change of Pollution Emission with Respect to Economic Structures for CO_2

Percentage Change Effects	Average Effect			
	Income Effect		Tech Effect	Policy Imp.
CO_2	Scale Effect	Composition Effect		
Country Estimation				
Australia	11.42	-0.52	-53.96	-0.16
Brazil	129.35	-7.29	-566.94	-0.16
Bulgaria	8.78	-0.47	-32.61	_
Canada	457.88	-22.84	-2281.86	-0.31
Chile	4.75	-0.21	-20.08	_
China	2.28	-0.11	-3.47	_
Denmark	41.72	-2.08	-200.53	_
Finland	106.59	-5.39	-518.05	_
France	112.35	-5.66	-548.62	-0.22
India	9.23	-0.52	-35.85	_
Ireland	6.65	-0.32	-25.87	_
Italy	3.75	-0.17	-11.77	_
Japan	0.98	-0.03	1.29	-0.06
Jordan	11.41	-0.63	-44.57	_
Kenya	109.05	-7.85	-373.44	_
Korea	28.74	-1.51	-127.41	-0.10
Luxembourg	16.09	-0.78	-73.60	_
Morocco	13.26	-0.75	-50.90	_
Netherlands	21.72	-1.04	-105.01	_
Poland	99.08	-5.58	-431.12	_
Portugal	13.01	-0.65	-58.41	_
Saudi Arabia	17.59	-0.92	-75.08	_
South Africa	43.70	-2.37	-192.20	_
Spain	214.26	-11.01	-1033.72	-0.14
Thailand	14.27	-0.74	-60.05	-0.13
Turkey	22.62	-1.26	-95.48	_
UK	40.30	-2.06	-188.57	_
US	0.72	-0.02	4.99	_

Appendix H
Tables of Regression Results (VI)

Table 9.1: Percentage Change of Structural Effect Within Sectors on Pollution Emissions (Decomposition Effect) at Global Level

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average								
CO_2	_	0.76	0.17	0.32	0.26	0.23	-0.17	-0.01
CO	-2.46	0.50	0.14	0.15	0.16	0.99	0.76	-0.07
SO_2	-5.31	0.41	1.34	0.40	0.25	2.29	1.22	0.62
NO_x	-0.53	0.42	0.11	0.01	0.02	0.55	0.71	0.04
PM	-9.76	1.31	0.50	_	0.39	4.13	0.52	0.31
VOC	-2.47	0.32	0.13	_	0.75	0.90	0.76	-0.19
Regional Average (CO_2)								
(1) High Income OECD	-0.40	1.25	_	_	_	0.29	0.12	0.13
(2) Far East Asia & Pacific	-2.53	1.73	_	0.77	_	_	_	-0.54
(3) Europe & Central Asia	-0.60	1.51	0.43	_	_	0.81	0.28	-0.24
(4) Latin America & Carribean	_	1.57	_	0.04	0.26	_	_	_
(5) Middle East & North Africa	-0.32	0.16	0.40	0.93	_	0.89	0.14	0.24
(6) South Asia	-1.00	3.30	0.96	0.44	1.83	1.73	-2.37	-0.11
(7) Sub-Saharan Africa	_	2.26	_	1.41	0.35	0.89	_	-0.48

Table 9.2.1: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (CO)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	-2.46	0.50	0.14	0.15	0.16	0.99	0.76	-0.07
Europe & Central Asia	-0.58	0.61	0.35	_	_	0.83	_	-0.20
Austria	-4.11	_	2.02	1.47	1.57	2.29	0.55	0.09
Canada	_	_	_	_	0.93	0.94	_	1.80
Finland	-3.69	_	_	_	_	2.20	_	1.07
France	-5.94	_	_	_	_	2.56	3.74	_
Hungary	_	_	_	_	_	_	_	_
Iceland	_	_	_	_	_	_	_	_
Italy	-0.42	_	0.14	_	_	0.33	0.09	-0.01
Korea	-7.15	_	_	0.04	_	1.53	1.06	-0.55
Netherlands	-4.35	_	0.89	0.39	-0.27	1.85	0.64	-1.34
Norway	-0.04	_	_	_	_	_	0.52	_
Poland	_	_	_	_	_	_	-0.08	-4.17
Sweden	-4.27	_	_	_	_	_	0.82	_

Table 9.2.2: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (CO_2)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	_	0.76	0.17	0.32	0.26	0.23	-0.17	-0.01
Europe & Central Asia	-0.60	1.51	0.43	_	_	0.81	0.28	-0.24
Austria	_	1.53	_	_	_	_	-0.12	-0.61
Canada	-4.91	_	_	_	_	1.04	-0.33	1.32
Finland	-1.13	0.70	0.47	0.56	0.54	0.97	0.11	-0.65
France	-1.32	_	_	_	_	0.52	1.78	_
Hungary	_	_	0.03	_	_	_	0.32	_
Iceland	_	_	_	_	_	_	_	_
Italy	_	1.23	_	_	_	_	-0.07	0.08
Korea	-7.15	_	_	0.04	0.07	1.53	_	-0.08
Netherlands	_	3.53	_	_	_	_	-0.57	0.40
Norway	_	_	_	_	_	_	_	_
Poland	_	1.35	_	_	_	_	_	-2.57
Sweden	-2.62	_	_	_	_	1.25	0.51	_

Table 9.2.3: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (NO_x)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	-0.53	0.42	0.11	0.01	0.02	0.55	0.71	0.04
Europe & Central Asia	-0.65	1.37	0.03	_	_	1.10	0.29	-0.03
Austria	-2.41	_	1.27	0.70	0.84	1.56	0.29	0.01
Canada	_	_	_	_	0.58	0.63	-0.73	1.21
Finland	-1.97	_	_	_	_	1.10	0.43	_
France	-3.46	_	_	_	_	1.06	2.59	_
Hungary	-0.48	2.89	_	_	_	0.76	0.27	_
Iceland	_	0.39	_	_	_	_	_	_
Italy	-0.67	_	0.20	_	_	0.54	1.94	0.01
Korea	_	3.24	0.13	0.05	0.36	_	_	0.25
Netherlands	-2.12	_	0.95	0.29	0.16	0.69	0.58	-0.97
Norway	-0.34	0.18	_	_	_	0.15	0.11	_
Poland	-0.62	1.46	_	_	_	_	0.44	-3.18
Sweden	-5.25	_	_	_	_	2.59	0.98	_

Table 9.2.4: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (PM)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	-9.76	1.31	0.50	_	0.39	4.13	0.52	0.31
Europe & Central Asia	_	_	_	_	_	_	_	_
Canada	-0.88	_	0.53	1.26	0.20	0.28	_	2.10
Finland	-5.88	_	_	_	_	_	1.61	1.55
France	_	_	_	_	_	_	_	_
Hungary	_	_	_	0.62	_	_	_	-0.32
Iceland	_	_	_	_	_	_	_	_
Italy	_	_	_	_	_	_	_	_
Korea	-1.80	_	15.85	_	_	9.01	-2.60	-7.81
Netherlands	_	_	_	_	_	_	_	_
Norway	_	_	_	_	_	_	_	_
Poland	-0.42	0.85	_	_	_	0.56	0.28	_
Sweden	_	_	_	_	_	_	_	_

Table 9.2.5: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (SO_2)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	-5.31	0.41	1.34	0.40	0.25	2.29	1.22	0.62
Europe & Central Asia	-1.09	2.28	0.41	_	_	1.47	0.68	-0.25
Austria	_	_	4.72	2.48	3.31	8.72	0.88	-0.94
Canada	-4.34	_	1.41	_	1.70	2.12	_	_
Finland	-15.37	_	_	_	_	9.33	_	3.66
France	-9.41	_	_	_	_	3.99	6.80	_
Hungary	_	_	0.78	0.40	1.69	_	_	-0.09
Iceland	_	2.07	_	_	_	_	_	_
Italy	_	_	3.66	0.28	2.91	_	3.29	0.07
Korea	_	0.34	_	_	_	_	_	0.46
Netherlands	-3.71	_	_	0.36	_	1.54	0.44	-1.67
Norway	-1.64	_	_	_	_	0.37	_	_
Poland	-1.00	2.36	_	_	_	1.27	0.71	-3.67
Sweden	_	_	_	_	_	_	_	_

Table 9.2.6: Percentage Change of Decomposition Effect on Pollution Emission for Cross-Sectional Study (VOC)

	Decomposition Effect (Within Structural Change)							
	Services	Energy Use	Manu-factures	Chemical Ind.	Base Ind.	Industry	Agri-culture	Food & Bev.
Global Average	-2.47	0.32	0.13	_	0.75	0.90	0.76	-0.19
Europe & Central Asia	-1.49	_	1.18	_	_	_	_	_
Austria	-5.03	_	2.96	1.98	2.27	2.76	_	-0.79
Canada	_	_	_	_	_	0.42	-0.56	0.88
Finland	-2.15	_	_	_	_	1.08	0.54	0.57
France	-4.11	_	_	_	_	1.51	3.42	_
Hungary	-0.70	4.68	_	_	_	1.11	0.42	0.07
Iceland	-11.35	_	_	_	_	2.92	0.00	_
Italy	-0.44	_	0.09	_	_	_	1.17	_
Korea	_	_	_	_	_	_	_	_
Netherlands	-4.22	_	1.66	0.52	0.06	1.48	1.03	-1.59
Norway	_	1.73	_	_	_	0.07	-1.10	_
Poland	-0.53	1.25	_	_	_	_	0.38	-1.95
Sweden	-3.34	_	_	_	_	1.71	0.58	_

Appendix I
Figure of Dynamics of Environmental Growth Model

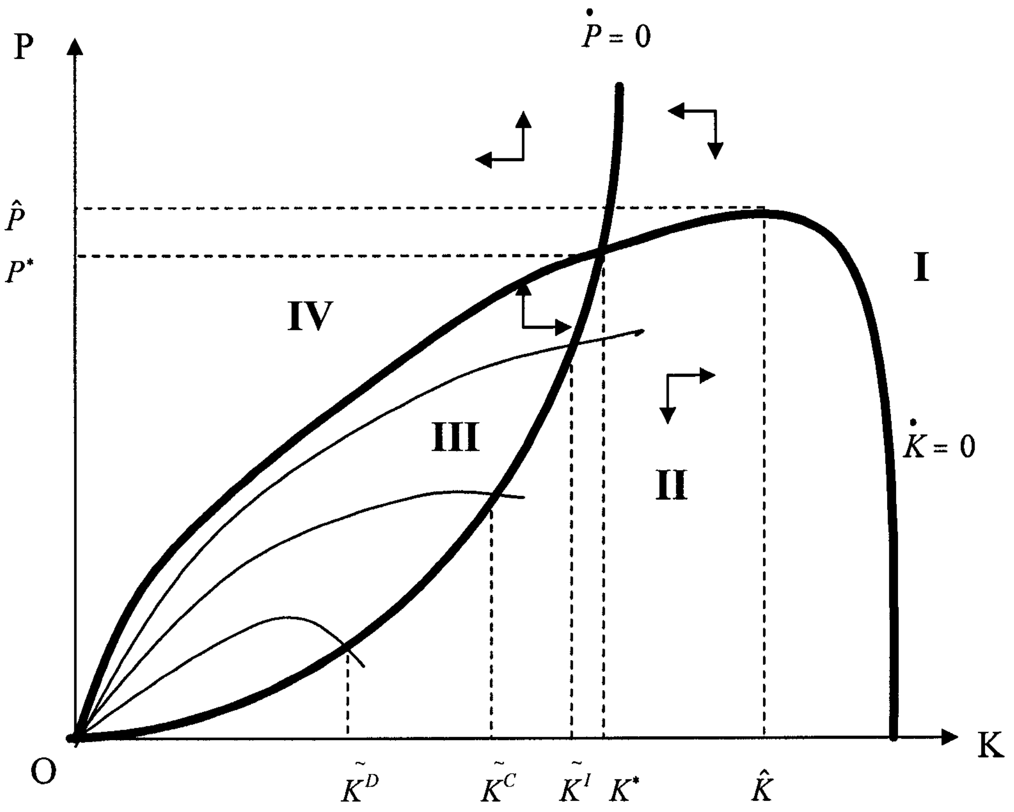

Figure 2: The Dynamics of Environmental Growth Model, $\alpha > \frac{1}{2}$.

Appendix J
Figures of Simulation Results

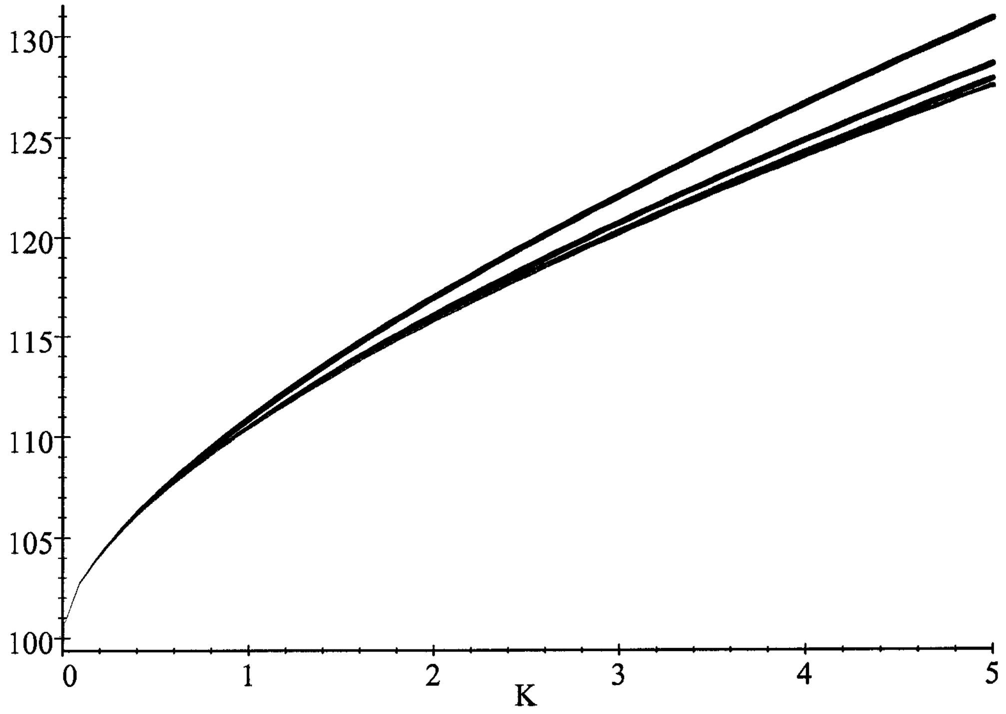

Figure 3: One-state Variable Model for $\phi A^2 \leq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$.

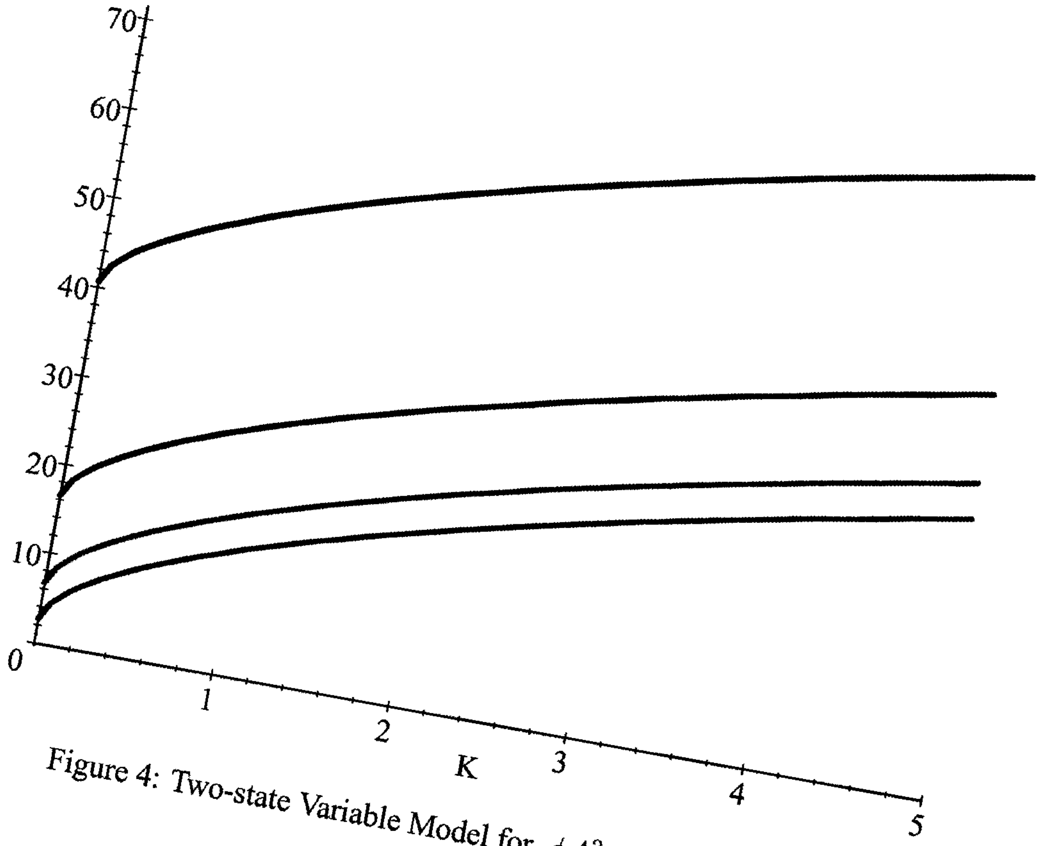

Figure 4: Two-state Variable Model for $\phi A^2 \leq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$.

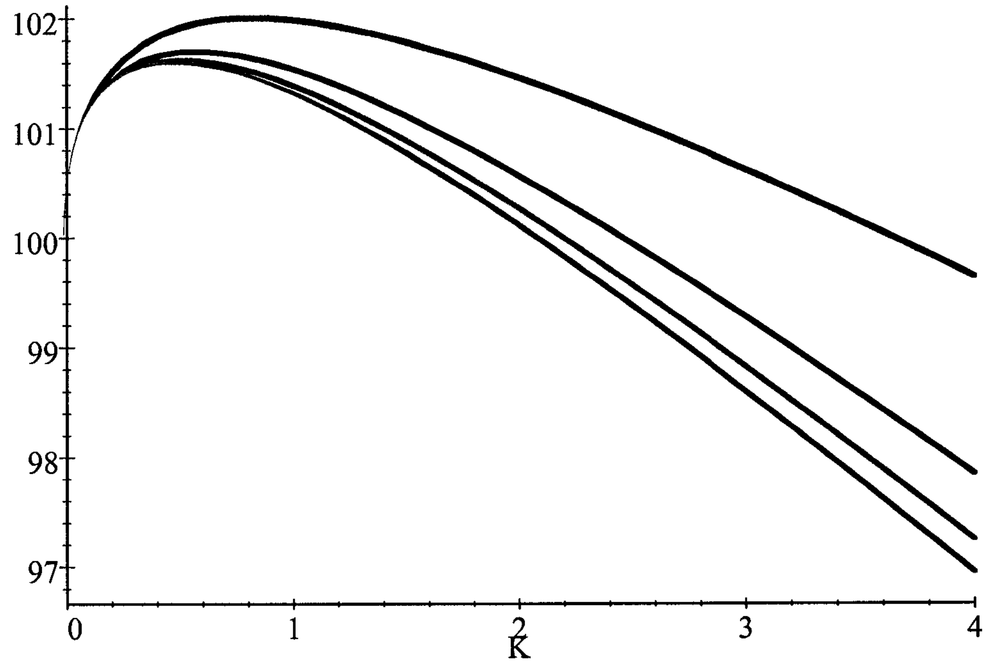

Figure 5: One-state Variable Model for $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$.

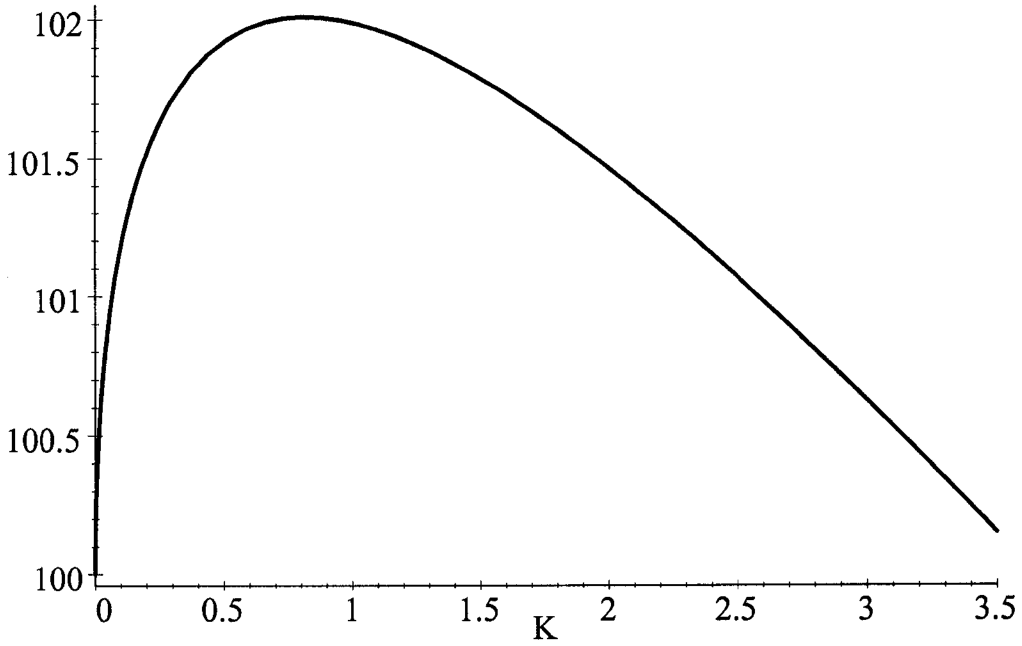

Figure 6: One-state Variable Model for $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$.

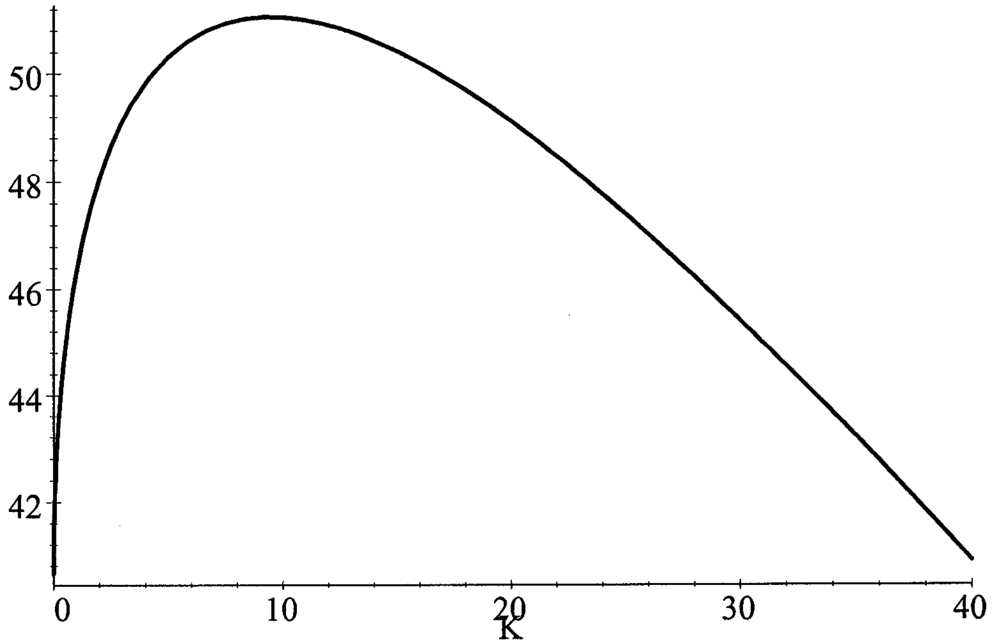

Figure 7: Two-state Variable Model for $\phi A^2 \geq 4\frac{(2\alpha-1)}{\alpha^2}B(\frac{1}{t}+\pi)$.

Appendix K
Figures of Six Air Pollutants' Scatterplots

Figure 8: Scatterplots of Lowess Curve (Left) vs. Mean Curve (Right)
For CO_2 (Upper), PM (Middle), and SO_2 (Lower), 1980 - 1998

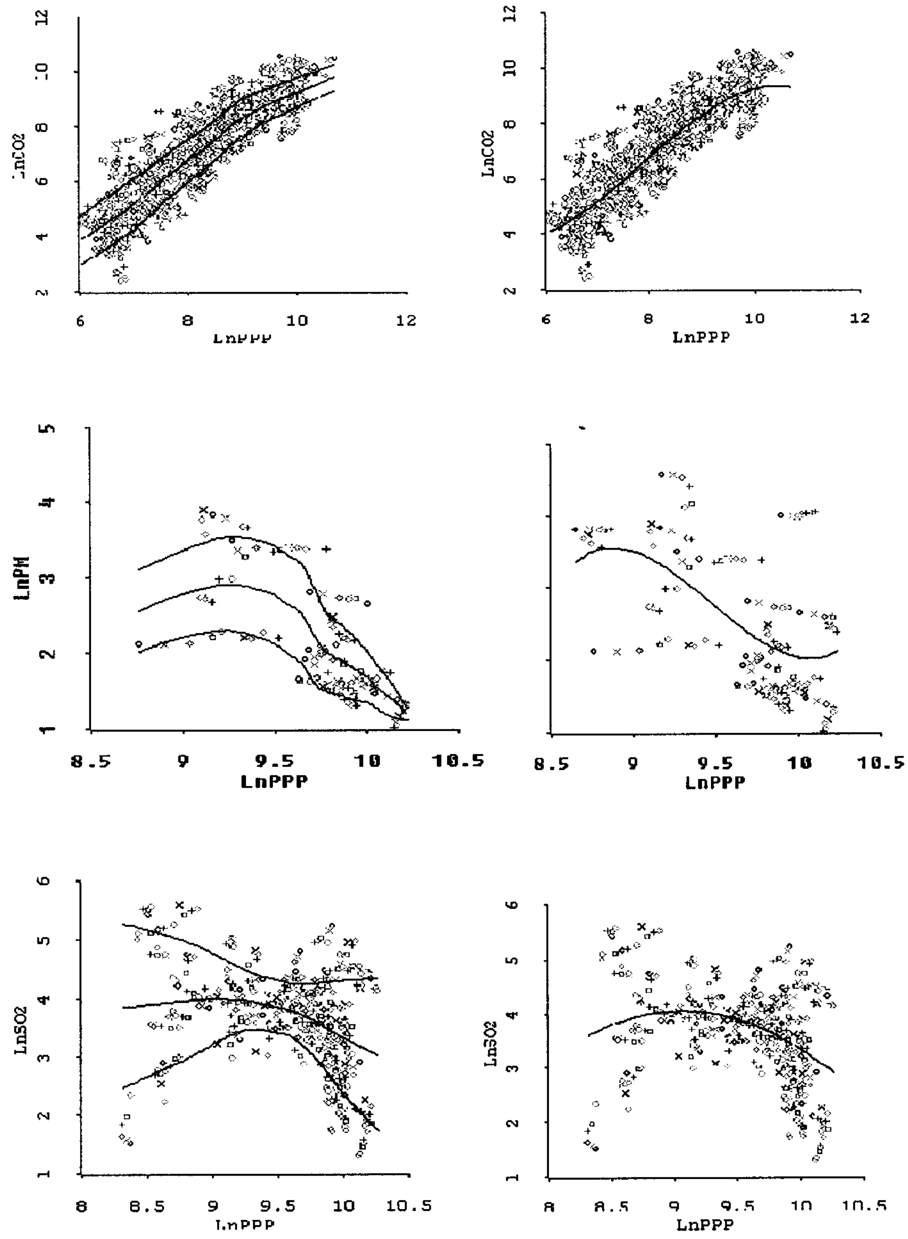

Figure 9: Scatterplots of Fitted Curves in 1990, CO_2 (Upper-left), CO (Upper-right), NOx (Middle-left), PM (Middle-right), SO_2 (Lower-left), and VOC (Lower-right)

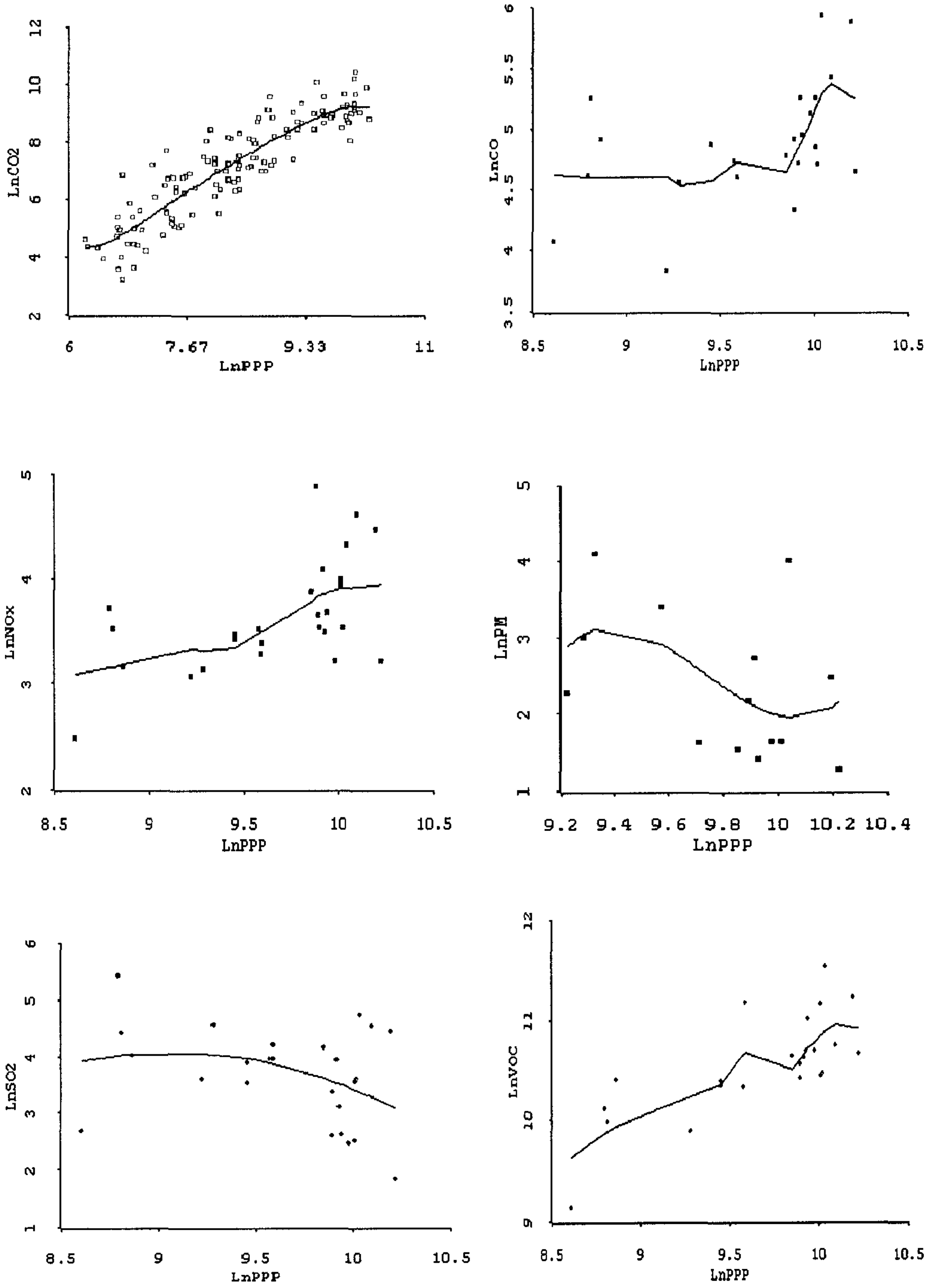

Figure 10: Scatterplots of Fitted Curves for CO2, 1980-1998, for Brazil (upper-left), Denmark (upper-right), Luxembourg (middle-left), Niger (middle-right), South Africa (lower-left), and UK (lower-right).

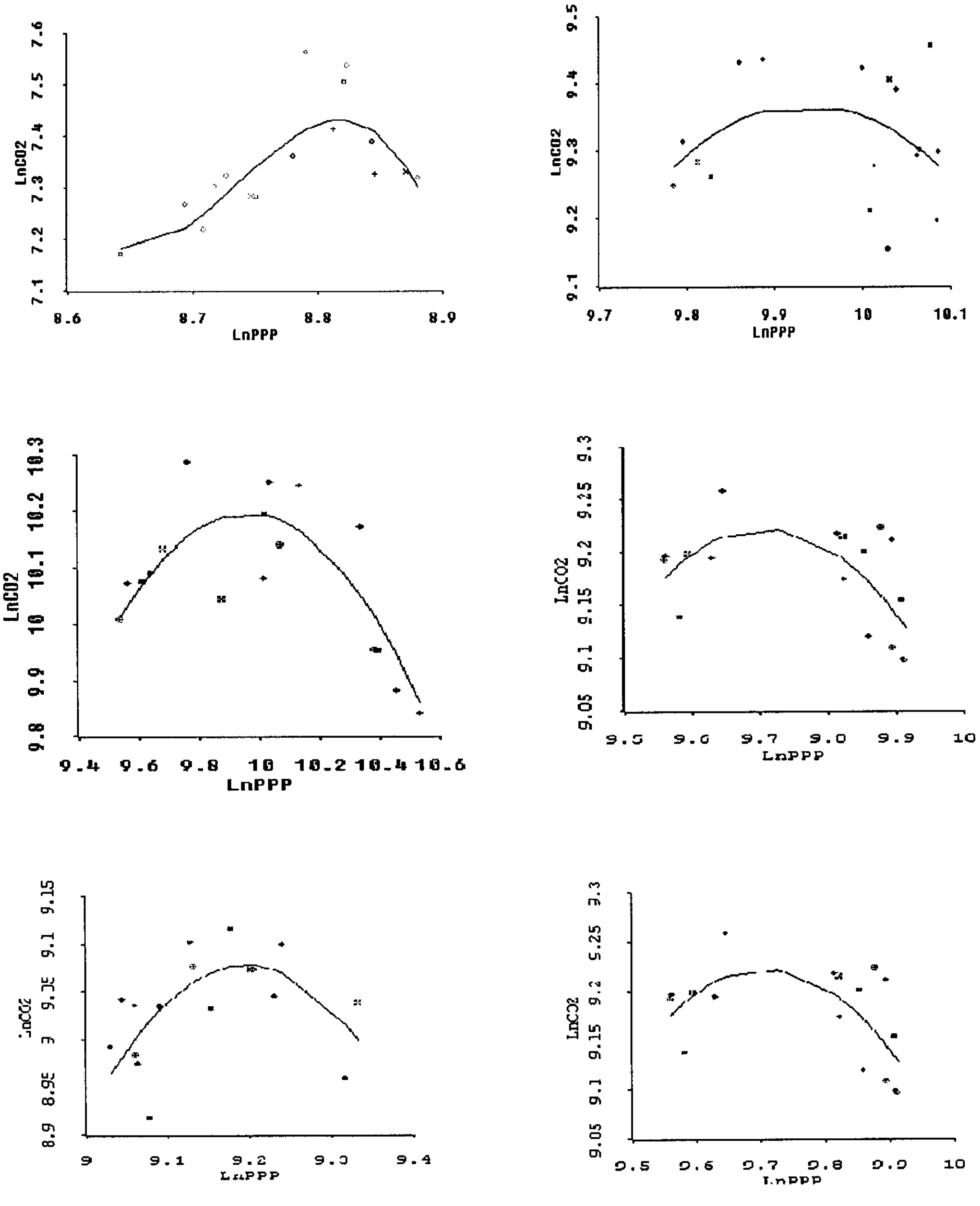

Figure 11: Scatterplots of Fitted Curves for CO, 1980-1998, for Austria (upper-left), Belgium (upper-right), Italy (middle-left), Korea (middle-right), UK (lower-left), and US (lower-right).

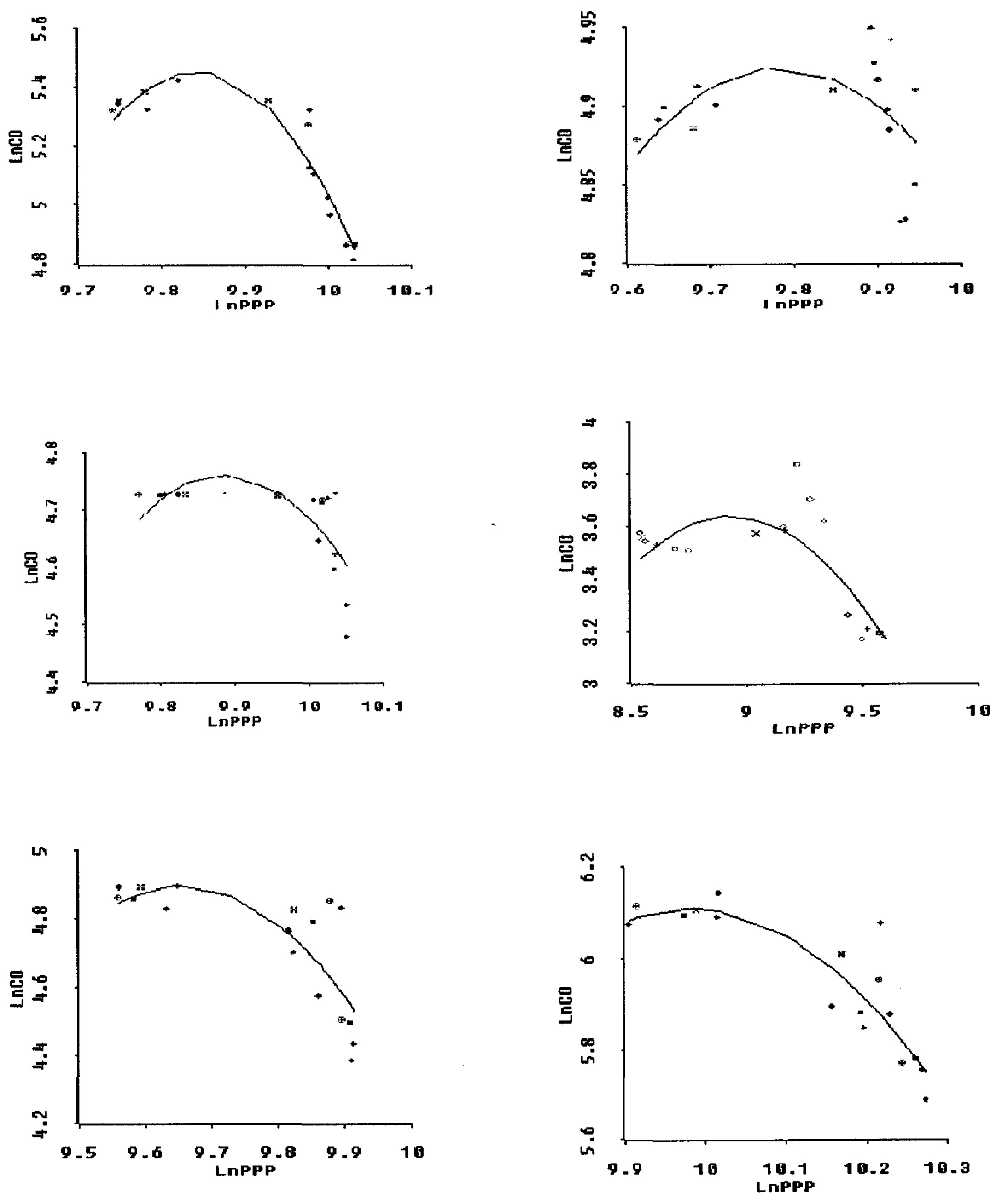

Figure 12: Scatterplots of Fitted Curves for NOx, 1980-1998, for Australia (upper-left), France (upper-right), Iceland (middle-left), Ireland (middle-right), Netherlands (lower-left), and Norway (lower-right).

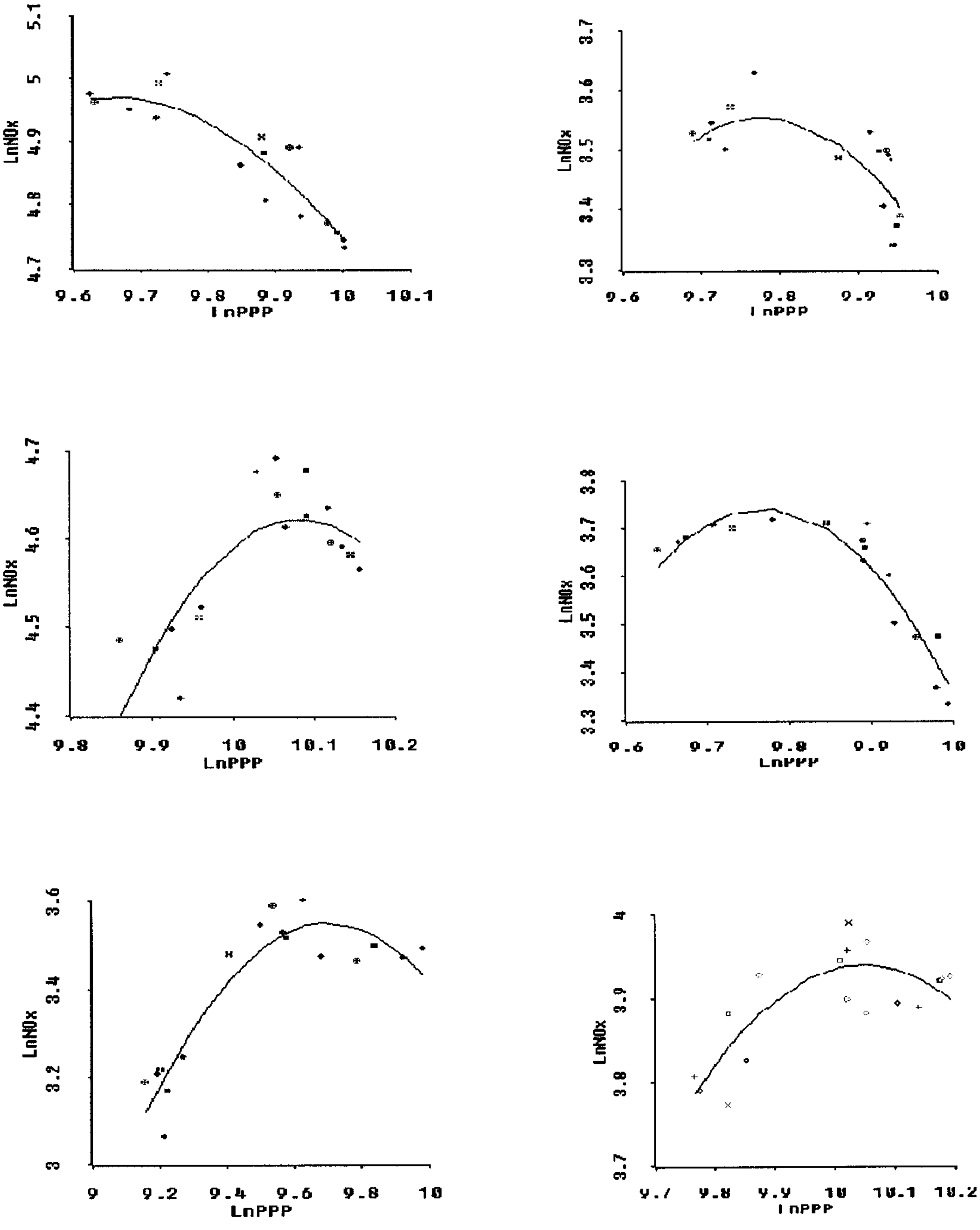

Figure 13: Scatterplots of Fitted Curves for PM, 1985-1995, for Czech (upper-left), Germany (upper-right), Hungary (lower-left), and Korea (lower-right).

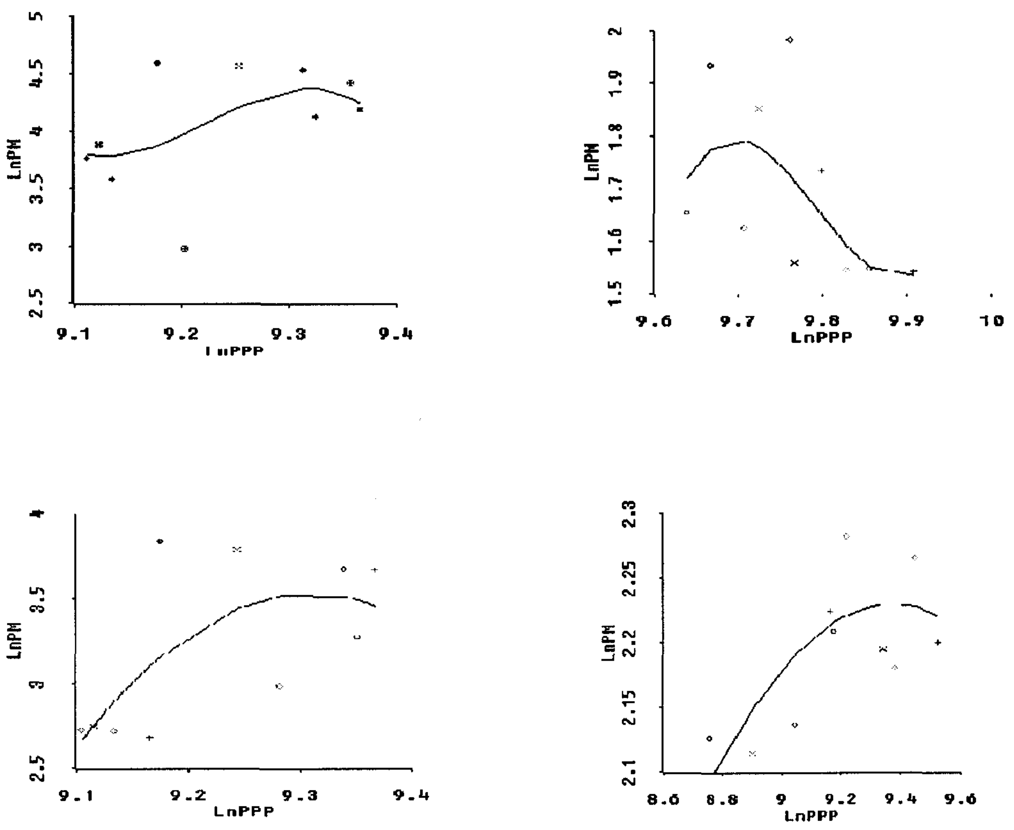

Figure 14: Scatterplots of Fitted Curves for SO2, 1980-1998, for Austria (upper-left), Belgium (upper-right), Iceland (middle-left), France (middle-right), UK (lower-left), and US (lower-right).

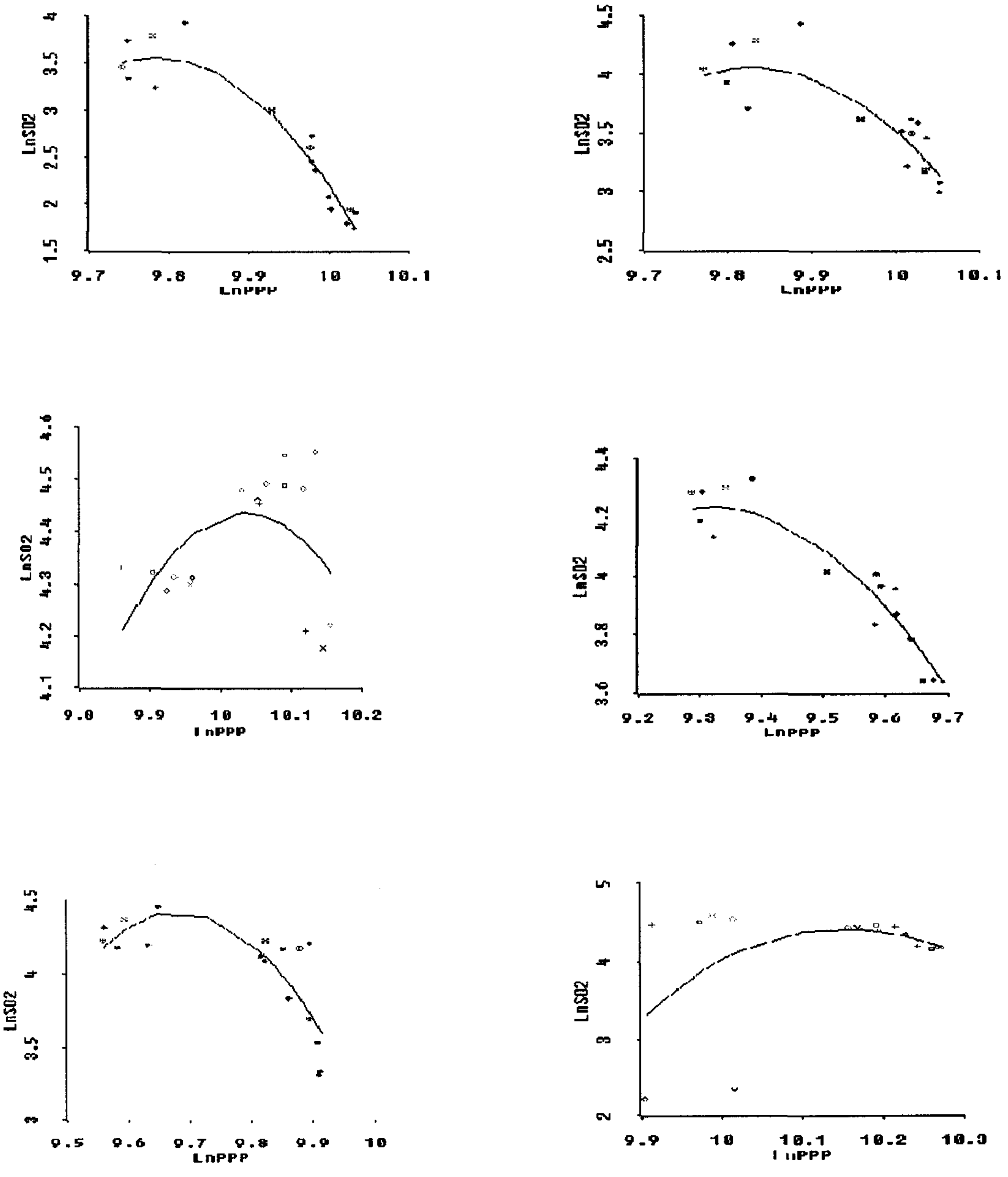

Figure 15: Scatterplots of Fitted Curves for VOC, 1980-1998, for Denmark (upper-left), Finland (upper-right), Netherlands (middle-left), Spain (middle-right), UK (lower-left), and US (lower-right).