AN ABSTRACT OF THE THESIS OF

Eirik Romstad for the degree of Doctor of Philosophy in Agricultural and Resource Economics presented on January 17, 1990.

Title: Pollution Control Mechanisms When Abatement Costs Are Private Knowledge

Redacted for Privacy

Abstract Approved: ______________________________
Olvar Bergland

This dissertation addresses two issues in pollution control (i) determining the optimal level of emissions, and (ii) the design of a system to induce compliance with this emission level at minimum costs. The starting points for this research are that the regulatory agency does not know the individual firm's pollution abatement costs and that firms are generally reluctant to reveal these costs.

The optimal emission level of a particular pollutant is found by creating a market for emission permits for this pollutant. By comparing the resulting cost for emission permits with the inferred price from the known damage function of that pollutant at a particular aggregate level of emissions, the optimal aggregate emission level can be determined. The cost for emission permits equals the market price for emission permits times the competitive interest rate. The resulting aggregate emission level is shown to be a second-best Pareto-optimal allocation.

A dynamic principal-agent is developed with the purpose of inducing compliance with the individual firm emission quotas. Firms are monitored, and if found in violation of the emission standard, the firms are penalized. Emissions are assumed to vary stochastically around their target levels. Measurement errors of the emission levels may also occur. To avoid sub-optimal firm behavior, the regulatory agency therefore sets the individual firm's emission standard above the ex-ante optimal firm emission levels. This results in an ex-post monitoring optimal aggregate emission level that generally exceeds the ex-ante monitoring emission level. The model allows the regulatory agency to find the second-best Pareto optimal standard for stochastic emissions through a search procedure.

Firms with a record of compliance are monitored less frequently than firms whose status are uncertain, while firms with a history of non-compliance are monitored most frequently. The proposed monitoring scheme is found to have expected monitoring costs below those of a single-group model.

Key words: principal-agent models, monitoring, stochastic emissions, resource allocation mechanisms, welfare economics.

# Pollution Control Mechanisms
# When Abatement Costs Are Private Knowledge

by

Eirik Romstad

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed January 17, 1990

Commencement June 1990

APPROVED:

Redacted for Privacy

Professor of Agricultural and Resource Economics in charge of major

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Date thesis is presented January 17, 1990

## ACKNOWLEDGEMENTS

Many people have, directly or indirectly, contributed to varying phases of my education. I will take this opportunity to explicitly acknowledge some of them.

My parents, Aase and Halvard Romstad, have always stressed the importance of education and knowledge, and encouraged me to use whatever intellectual gifts I possess. I will always remain grateful for their continued support.

Dr. Olvar Bergland has served as director of this dissertation and has been my major professor while at Oregon State University. His assistance and guidance have been of great value. He taught me never to be satisfied with my work, and always to look for ways to improve it as well as my own academic qualities. It has been enjoyable, challenging and sometimes stressful working for Olvar. I hope to have the opportunity to continue to work with him in the future.

Dr. Halvor J. Kolshus at the Agricultural University of Norway encouraged me to go to the United States for my PhD. Without his encouragement I would never have dreamt of doing what I have done. I started my graduate education in the United States at the University of Kentucky. While at Kentucky, Dr. Eldon D. Smith provided guidance and support, for which I will always be grateful.

The members of my advisory committee, Drs. Richard M. Adams, Emery N. Castle, H. Alan Love, and Bruce Rettig, have given valuable assistance to the various phases of this work and my graduate studies. I am also grateful to Dr. David A. Philbrick, who served as the graduate school's representative on my committee.

Special thanks are given to fellow graduate students, Seung-Woo Kim and Donald McLeod, for numerous valuable discussions on the various aspects of economics and other issues.

Financial support from the Department of Agricultural Economics while at the University of Kentucky, the Department of Agricultural and Resource Economics, and the R.E. Johnson Fellowship Fund while at Oregon State University, the Fulbright foundation and the Norway-American Association is gratefully appreciated.

I would also like to thank my exchange family parents, Diane and Wesley B. Price of Albany, Oregon, for always being there when I needed help, for offering me a true home when I grew homesick, and for being great friends.

Finally I would like to thank my cohabitant and fellow student, Grete Stokstad, for her patience and understanding. Her support and company, while she was at Oregon State University, made my life more enjoyable and helped me endure the difficult times every graduate student encounters at one stage or another. After she returned to Norway, life has not been quite the same, and the pressure to complete this dissertation has been mounting.

# TABLE OF CONTENTS


Chapter

1 INTRODUCTION 1

- 1.1 Background 1
- 1.2 The Optimal Level of Emissions 2
- 1.3 Compliance with Environmental Standards 4
- 1.4 Organization of the Chapters 6

2 REVIEW OF LITERATURE 7

- 2.1 Optimal Emission Levels 7
  - 2.1.1 Command and Control Schemes 7
  - 2.1.2 Marketable Emission Permits 9
    - 2.1.2.1 Types of Marketable Permits 9
    - 2.1.2.2 The Problem of Non-Participation 11
  - 2.1.3 Pigouvian Taxes 11
  - 2.1.4 Incentives for Revealing the True Abatement Costs 14
- 2.2 Inducing Compliance with the Optimal Emission Levels 15

3 RESOURCE ALLOCATION MECHANISMS 19

- 3.1 Firms 20
  - 3.1.1 Production Without Externalities 20
  - 3.1.2 Production With Externalities 23
  - 3.1.3 Technology Adoption 24
- 3.2 Consumers 25
  - 3.2.1 Consumption of Private Goods 25
  - 3.2.2 Consumption of Private Goods and Public Bads 27
  - 3.2.3 The Damage Function from Emissions 28
- 3.3 The Regulatory Agency 31
  - 3.3.1 Aggregate Money Metric Utility 31
  - 3.3.2 The Bergson-Samuelson Social Welfare Function 31
  - 3.3.3 Pareto-Optimality 33
  - 3.3.4 Second-Best Pareto-Optimality 35
  - 3.3.5 The Regulatory Agency's Choice of Welfare Indicator 36
- 3.4 Desireable Properties for Resource Allocation Mechanisms 37

4 DETERMINING OPTIMAL POLLUTION QUOTAS WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE 41

- 4.1 Optimal Emission Levels in an Atemporal Setting 42
- 4.2 A Dynamic Model for Optimal Emission Levels 45
- 4.3 Evaluating the Proposed System as a Resource Allocation Mechanism 47
  - 4.3.1 Individual Rationality 47
  - 4.3.2 Informational Viability and Efficiency 48
  - 4.3.3 Incentive Compatibility 50
  - 4.3.4 Second-Best Pareto-Optimality 53

4


4.4 Issues Related to the Proposed Scheme 54
4.4.1 The Adjustment of Aggregate Quotas 55
4.4.2 Initial Allocation of Firm Quotas 57
4.4.3 Firm Entry and Exit 58
4.5 Conclusions 59

5 INDUCING INDIVIDUAL FIRM COMPLIANCE TO EMISSION QUOTAS WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE 62

5.1 An Outline of the Proposed Model for Pollution Control 64
5.2 A Single-Period Principal-Agent Model for Inducing Compliance to Environmental Standards 66
5.3 A Dynamic Model of Firm Behavior and Regulatory Agency Response 72
5.3.1 Single-Period Compliance in Group Three 76
5.3.2 Multi-Period Compliance in Group Two 77
5.3.3 Multi-Period Compliance in Group One 79
5.3.4 Obtaining the Fractions of Firms in the Various Groups 81
5.4 An Evaluation of the Suggested Monitoring System as a RAM 82
5.4.1 Individual Rationality 82
5.4.2 Informational Viability and Efficiency 83
5.4.3 Incentive Compatibility 84
5.4.4 Second-Best Pareto-Optimality 84
5.4.4.1 Comparison of the Expected Monitoring Costs: The Single-Group Model 86
5.4.4.2 The Expected Societal Welfare for a Given Vector of the Agency's Choice Variables 86
5.4.5 Balancing the Budget for the Regulatory Agency 89
5.5 The Optimality of Emission Quotas 89
5.6 Conclusions 90

6 SUMMARY AND CONCLUSIONS 92

BIBLIOGRAPHY 97

APPENDIX: EXPLANATION OF NOTATION AND SYMBOLS 105
A.1 Special Characters 105
A.2 Symbols 105
A.3 Functions 106
A.4 Abbreviations 107

# LIST OF FIGURES


| Figure | | Page |
|---|---|---|
| 1. | The optimal emission level | 3 |
| 2. | Emission level when the true marginal costs of abatement are lower than the anticipated marginal costs | 12 |
| 3. | The marginal damage function | 30 |
| 4. | Aggregate emissions under transferable quotas | 44 |
| 5. | The market price for pollution permits and the confidence interval of the marginal damage function | 56 |
| 6. | The decision tree of the single-period principal-agent model | 69 |

POLLUTION CONTROL MECHANISMS

WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Pollution control has gained increased attention in the 1980s. Notable environmental issues related to pollution control include global warming due to increased $CO_2$ emissions from burning fossil fuels, contamination of drinking water from agriculture and other non-point sources, and increased acidity in rain. The list can be made much longer. The presence of such externalities has been recognized within the field of economics since Pigou's seminal work The Economics of Welfare (1920). By pollution control is meant measures to reduce the level of pollution. The two major issues regarding pollution control are (i) defining an appropriate level of pollution or emissions and (ii) making the polluters comply with these emission levels.

The two principal types of pollution control are command and control (CAC) and incentive based (IB) schemes. Typical CAC schemes consist of setting environmental standards and enforcing these standards through monitoring. The major disadvantage of CAC schemes are that they require more information than is readily available and that they are costly to operate (Mäler, 1974). The two types of IB schemes are (a) Pigouvian taxes and (b) transferable emission quotas through a market for emission rights. Setting the optimal Pigouvian taxes is difficult as this requires the same information as CAC schemes (Baumol and Oates, 1988).

The benefits from employing markets for emissions can be considerable as the following example indicates. In a yet unpublished study, Mäler found that the benefits from a 30 % across-the-board reduction in sulphur emissions in Europe from its current level would bring benefits in the neighborhood of US$ 1.5 billion (Economist, 1989). The same study indicated that a system of transferable emission permits between countries would reduce emissions 39 % from their current level, yielding net benefits of approximately US$ 3.5 billion. One problem with Mäler's study is that it is uncertain if the 39 % reduction in the emissions of sulphur is too large or too small. One reason is that the costs of abatement are not known.

The key objective of this research is, therefore, to devise new institutions that are informationally feasible and less costly to operate.

## 1.2 The Optimal Level of Emissions

Pigouvian taxes and CACs work well when the individual firm's abatement costs and society's estimate of the damages incurring at various levels of pollution are known. Figure 1 shows the optimal emission level when the marginal costs and marginal benefits of abatement are known. It is assumed that the marginal costs of abatement are everywhere increasing. Expressed in terms of the emission level, the marginal costs are decreasing.

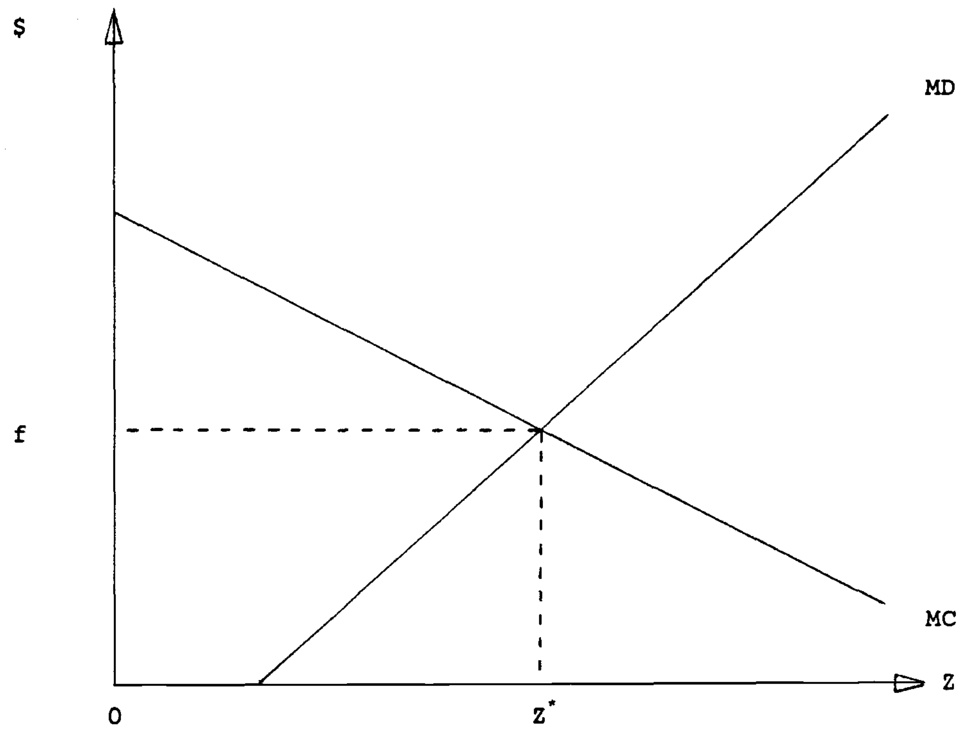


Figure 1: The optimal emission level. MC: marginal costs of abatement, MD: marginal damages, $Z^*$ : optimal quantity, f: Pigouvian tax (fee).

The problem with Pigouvian taxes is that the firms are generally reluctant to disclose their true cost functions for abatement. Therefore the MC curve in figure 1 may not be publicly known, and the regulatory agency[1] is not able to set the correct Pigouvian tax (denoted f in Figure 1). By overstating their abatement costs, firms can increase their profits.

The first objective of this research is to show how transferable

[1] The regulatory agency (also denoted as the planner or just the "agency") represents the public's interests and seeks to maximize societal welfare.

emission quotas make it possible to obtain the optimal level of emissions without the above stated informational difficulties of Pigouvian taxes or CAC schemes. A necessary assumption is that society's damage function for emissions, D(**Z**), is known. However, under the proposed scheme there is no need for the regulatory agency to know the individual firm's abatement costs.

The suggested model establishes markets for emission permits. It is then possible to find the optimal emission level by comparing the inferred prices at the chosen emission levels with the observed prices for various emission permits. Markets for emission permits could be set up as some kind of stock exchange, but instead of trading stocks, emission permits for various pollutants would be traded. There are two reasons for this construction: (i) the market prices for various emission permits are publicly known, and (ii) traders can be anonymous, thus increasing the likelihood of participation in the market.

## 1.3 Compliance with Environmental Standards

As can be seen from Figure 1, it is clear that the question of optimality of emission standards cannot be separated from the issue of compliance with these standards. The second objective of this research is therefore to design a system for (i) monitoring compliance with emission quotas and (ii) punishing non-compliers such that compliance with suggested optimal emission levels is induced.

In principle the firm's degree of conformity depends upon the relative profits of compliance and non-compliance. Principal-agent models seek to modify the agents' (firms') profit functions. The task of the principal (the regulatory agency) is to choose the appropriate policy variables so that the agents, by maximizing their objective functions under the modified payoffs, maximize the principal's objective function (Laffont, 1988; Rasmusen, 1989). In this case of pollution control the regulatory agency chooses a monitoring scheme and a penalty function such that the firms' expected profits from non-compliance are less than those for compliance.

Most industrial processes, including those for pollution control, do not function perfectly: there is a tendency for variation around the targeted value. If the regulatory agency were to penalize all violations of the emission standard and the penalties levied were prohibitively strict, the firm would set a target well below the standard to ensure violations did not occur. Assuming the standard is optimal for society, suboptimal firm behavior would be the rule (Førsund and Strøm, 1980). One way out of this problem would be to allow minor violations, but on the average, the standard would be met. This poses a new question: when should a violation be treated as a violation?

Several studies on pollution control have attempted to deal with this problem. Russell, Harrington and Vaughan (1986), Russell (1987) and Harrington (1988) all use a principal-agent framework that incorporates some of the mentioned elements. None of the existing literature on pollution control appears to have explicitly incorporated all of the above aspects into a formal model.

## 1.4 Organization of the Chapters

The next chapter presents a short review of the literature on methods to obtain optimal emission levels and monitoring/penalty systems to induce compliance. In the third chapter some principles for resource allocation mechanisms are presented. Any system which deals with the production or distribution of economic goods is a resource allocation mechanism. The benefits of the mechanism approach is that it focuses on the principles by which the performance of an economic system is to be judged. These principles will serve as a useful guideline in the design of the emission permit market and the proposed system to induce compliance with the emission standards. The fourth chapter looks more closely at the use of transferable emission quotas to find the optimal level of emissions when the firm's cost of abatement is not publicly known. In chapter five, a cost-effective system for inducing compliance with the optimal emission levels derived in chapter four is developed. Finally the major findings and implications of this research are summarized.

# CHAPTER 2

# REVIEW OF LITERATURE

The literature on the economics of pollution control can be divided into two groups; (i) models designed to lead to optimal emission levels and (ii) monitoring and penalty schemes to induce compliance with a pre-determined environmental standard.

## 2.1 Optimal Emission Levels

Three approaches to obtain optimal emission levels are: (i) command and control schemes (CAC), (ii) Pigouvian taxes, and (iii) marketable emission permits. The latter two belong to the class of incentive based (IB) schemes. Traditionally economists have preferred IB schemes over CAC schemes. All these approaches work well when the firms' costs of pollution abatement are known publicly and the damage function from pollution is known (Baumol and Oates, 1988). Except in the case of publicly known abatement costs (Montgomery, 1972; Baumol and Oates, 1988), little work has been done to determine the optimal level of emissions when these costs are not known to the public. In this review the focus is on the informational requirements of these various approaches, and more specifically how they are able to deal with the lack of public knowledge about the firms' abatement costs.

### 2.1.1 Command and Control Schemes

Economists have traditionally preferred IB schemes over CAC schemes. Generally these preferences have been based on the assumption that IB schemes will accomplish the same level of externalities as CAC schemes, but at lower costs to society (Oates, Portney and McGartland, 1989).

Oates et al. (1989) question this assumption. In a recent paper they compare the welfare resulting from an optimal IB scheme with that of an optimal CAC scheme using air pollution data from the Baltimore region. Their results indicate that the optimal IB scheme is not obviously superior to the CAC scheme. The reason for this is that under CAC it is possible to limit emissions more where they do the most harm, offsetting the cost advantages of the IB schemes. Three qualifiers are necessary for the above result to hold: (a) the CAC scheme must be designed with emphasis on minimizing costs, (b) the benefit and cost curves must be known by the agency, and (c) the most cost effective type of IB scheme is used in the comparison with the CAC scheme.[2]

Oates et al. (1989) assume that the benefit and cost curves from various emission levels have been correctly estimated. Of particular concern in this connection is the estimation of the abatement cost curve. This was done by categorizing and grouping similar sources together -- for example industrial coal burners, grain shipping facilities (Oates et al., 1989, p. 1235). In their study they do not document that the individual firms have incentives to report their true cost functions. Depending upon the variability of abatement costs

[2] Under certain conditions, Pigouvian taxes and marketable emission permits yield different outcomes (see section 2.1.3).

within each of these source types, it appears that the estimated abatement cost curve is an approximation. According to Baumol and Oates (1988) optimality of the aggregate emission level is therefore not guaranteed.[3]

Pearce (1986) addresses the informational requirements of CAC schemes. He concludes that for the outcome of any CAC to be optimal, the environmental standard itself must be optimal, i.e. the marginal abatement costs must equal the marginal benefits at the set standard. Again, because there are no incentives for the firms to report their true abatement costs, the standard itself is unlikely to be optimal.

On this basis, Oates et al.'s use of "optimality" when referring to CACs and IBs in their Baltimore study is at best an approximation. In general CACs will not yield optimal outcomes unless firms have incentives to disclose their abatement costs.

### 2.1.2 Marketable Emission Permits

#### 2.1.2.1 Types of Marketable Permits

Several types of marketable permit systems have been developed, including emission based permits (Dales, 1968), ambient pollution permits (Montgomery, 1972) and pollution offset permits (Krupnick, Oates and Van De Verg, 1983; McGartland and Oates, 1985; McGartland, 1988).

A system of emission permits is very simple; in each time period the polluting firm can emit up to the permit level. The advantage with

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[3] Also see section 2.1.3.

this type of permit is that the resulting permit market functions just like any other market. Thus the firms are dealing with a familiar concept, reduces the chances for misunderstanding and lowering implementation costs.

From the view point of regional economic efficiency smaller regional markets are preferred to larger national markets, as the damages from emissions may vary from one region to another (Baumol and Oates, 1988). Consequently the permit price in each market may differ. A necessary condition for aggregate efficiency is that the emission permit prices in each region are the same (Baumol and Oates, 1988). The informational requirements for this to occur are prohibitive under a system of emission permits where the optimality of each regions emission quota is not known as the damage function or the abatement cost functions are not publicly known (Krupnick et al. 1983; McGartland and Oates, 1985; and McGartland, 1988; Baumol and Oates, 1988).

Ambient permits (Krupnick et al. 1983) and pollution offset permits (McGartland and Oates, 1985) are designed to alleviate the problem of regional coordination by the regulatory agency. Under a system of ambient permits, the effects of pollution at a particular receptor point need to be evaluated. In general this implies that trading of permits will not occur on a one-to-one basis. The price of a permit depends on the pollution level at the particular receptor points, i.e. the price of new permits at a point with high pollution levels will be higher than at a point with lower levels of pollution. This should cause pollution levels, and thus environmental damages, to be more evenly spread than would be the case under a system of emission permits. Pollution offset permits require that the environmental quality standard not be violated at any receptor point as a result of the permit trade.

For a further look at the various pollution standards/types of emission permits, the reader is referred to Joeres and David (1983, pp. 267-270), and Baumol and Oates (1988, pp. 177-189).

#### 2.1.2.2 The Problem of Non-Participation

Hahn (1989) argues that the constraints implicit in a system of ambient or pollution offset permits make the permit market complex. According to Hahn, one reason for the lack of participation in permit markets using ambient or pollution offset permits is their complex design. This provides some of the motivation behind this research: keep it simple.

### 2.1.3 Pigouvian Taxes

The problems of finding the optimal emission levels when the agency does not know the firms' abatement costs are demonstrated by the following observation. A system of fees will lead to emissions below the social optimum if the true cost of abatement is lower than the anticipated costs of pollution reduction, while a system of non-transferable permits will result in too much emission (Baumol and Oates, 1988). In the first case the fee, f, and in the second case the permit level, $Z^p$, is set at the level where marginal damages equal anticipated marginal costs. The converse holds if the true costs of pollution reduction are higher than the anticipated costs. It is assumed that the marginal costs of pollution abatement is everywhere increasing. Expressed in terms of emission levels, the marginal costs are decreasing. The magnitude of these distortions depends upon the shapes of the marginal damage and cost curves and is treated in detail by Baumol and Oates (1988) for the atemporal case. Figure 2 shows the resulting emission level when the true costs of pollution abatement are lower than the anticipated marginal costs.

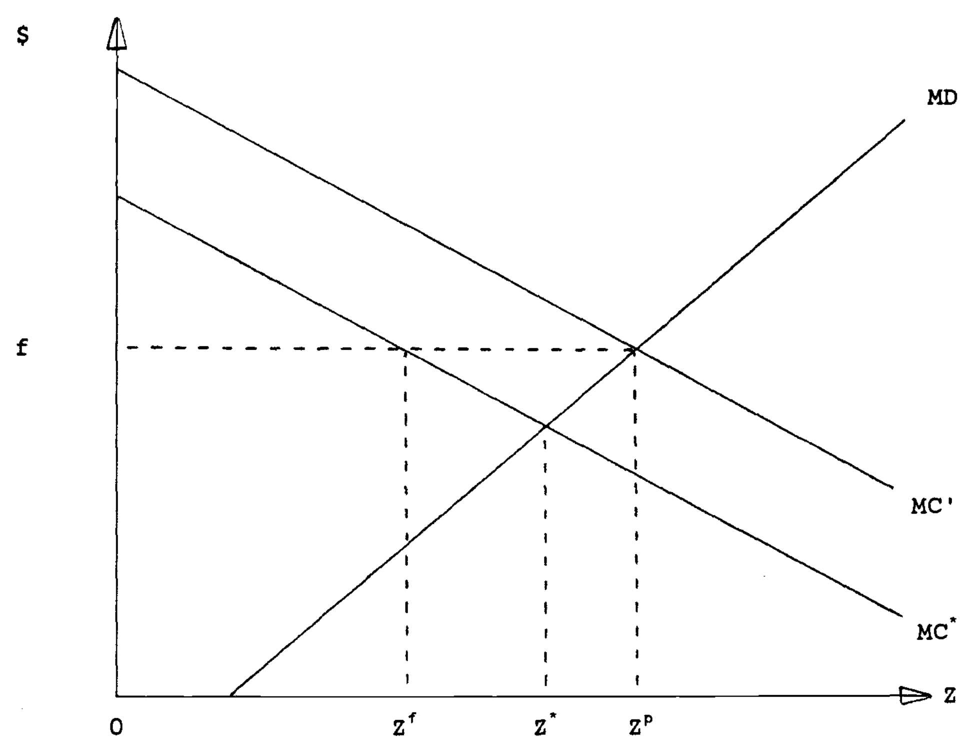


Figure 2: Emission level when the true marginal costs of abatement (MC* ) are lower than the expected marginal costs (MC'). $Z^*$ : optimal quantity, $Z^P$ : emissions under permits, $Z^f$ : emissions under fees, MD: marginal damage, f: Pigouvian tax.

Due to the above problems Siebert (1987) suggests to iteratively adjust the Pigouvian tax, f, until the optimal emission level, $Z^*$, is achieved. One difficulty with this approach is that firms may have chosen their production abatement technology on the basis of the initial Pigouvian tax. As the fee is adjusted, this technology choice may no longer be optimal from the firms' perspectives, and overall loss of welfare may occur. Cyert and deGroot (1987) argue that adjustments are costly. Consequently, repeated adjustments may cause losses which are larger than the incremental benefits derived from approaching $Z^*$.

Pearce (1986) criticizes the Pigouvian tax approach from a somewhat different perspective. The basis of his criticism is that even if this method has incentives for compliance -- each firm will choose not to pollute when its marginal abatement costs are less than the fee -- there is no built-in mechanism in this approach to obtain the optimal emission level and thus setting the optimal fee.

Roberts and Spence (1976) combine marketable emission permits and Pigouvian taxes to get around the problem of the regulatory agency not knowing the individual firms' costs of pollution abatement. The problem with their approach is that the Pigouvian tax needs to be adjusted several times to lead to the optimal emission level, $Z^*$. Their method is therefore subject to the same criticism as that of a system of iterated Pigouvian taxes.

## 2.1.4 Incentives for Revealing the True Abatement Costs

A key element in the criticism of the optimality of CAC schemes and Pigouvian taxes is that these approaches contain no incentives for each firm to truthfully reveal their abatement costs (Pearce, 1986). Groves (1976) has designed a system where the incentives for truthful behavior on behalf of the firms is the firms' optimal strategy when emissions from some firms negatively affect other firms. This approach is an extension of research on teams (Groves, 1973; Groves and Loeb, 1975).

Groves' starting point is that under the presence of externalities and no coordination, a Nash equilibrium[4] may result. Generally Nash equilibria are not optimal, i.e. the firms' joint profits can be increased by cooperation among the firms. Groves then introduces a center (the equivalent of the regulatory agency) whose task is to coordinate the firms' actions such that an optimal outcome is achieved. Each firm is to disclose its profit function, incorporating the effect of the externality vector on its profits, to the center. On the basis of this information, the center then chooses the externality vector that maximizes the joint profits. Assuming that the center can observe each firm's chosen level of externalities produced, the dominant behavior for each firm is to submit their true profit functions. Consequently the optimal externality vector results.

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[4] An allocation $\bar{y} = [\bar{y}_1, \ldots, \bar{y}_N]$ is a Nash equilibrium if for every $n \in N$, $y_n$ maximizes the nth firm's profits for each n over all possible $y_n$.

There are three unresolved problems with Groves' approach; (i) the informational viability[5] of the method, (ii) the informationally efficiency[6] of the method, and (iii) as the firms do not know what their allowed externality output will be, the optimality of the center's externality vector requires each firm to know its profit function for all levels of the externality vector. If (iii) is not met, another potential difficulty arises: who is to bear the cost of repeated adjustment of the aggregate externality vector until the optimal externality vector is found? Barring these difficulties, Groves' approach underlines the importance of creating incentives for truthful behavior from the firms and the need for monitoring the firms' actual actions.

## 2.2 Systems for Inducing Compliance with the Optimal Emission Levels

Pearce (1986) and Malik (1987) both stress the importance of compliance; any system seeking the optimal emission level needs a mechanism inducing firms to comply with the standards. This section reviews some of the literature on enforcement.

The literature on enforcement of environmental standards includes both static models (Downing and Watson, 1974; Harford, 1978; Viscusi and Zeckhauser, 1979; and Linder and McBride, 1984) and dynamic models (Russell, Harrington and Vaughan 1986; Russell, 1987; and Harrington,

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[5] Informational viability: a mechanism is informationally viable if the amount of necessary information does not exceed the amounts of available or processable information.

[6] Informational efficiency: a mechanism is informationally efficient if it conveys the necessary information at least cost.

1988). From this literature, in particular Russell (1987), it is clear that the optimality of any pollution control mechanism cannot be evaluated without considering the incentives for compliance with the proposed standard. In much of the literature on optimal emission levels, this problem has been assumed away. One reason for this may be that finding the optimal emission levels per se, is complicated enough.

Most of the early enforcement literature deals with static models. See for example Downing and Watson (1974) Harford (1978), Viscusi and Zeckhauser (1979), and Linder and McBride (1984). The disadvantage of these atemporal models is that the agency and the firms cannot react to each other's actions. Dynamic models allow for this type of interaction. Some of the first dynamic applications of principal-agent models have been undertaken on tax-cheating (Landsberger and Meilijson, 1982; Greenberg, 1984).

Greenberg's (1984) paper on "avoiding tax avoidance" has inspired some of the recent work done on pollution control using the dynamic principal-agent framework (Russell et al., 1986; Russell, 1987; Harrington, 1988). Greenberg lets agents build a reputation for compliance, and the agents are then divided into three groups depending upon their past record of compliance. Group one has the lowest monitoring probability. If monitored and caught in violation in group one, the agent is moved to a second group, where the probability of being monitored is increased. If monitored and not found in violation while in group two, the agent is moved back to group one. A violation in group two moves the agent to group three where the agent is constantly monitored in perpetuity. Greenberg notes that if one allows for detection errors, eventually all agents would end up in group three, constant monitoring in perpetuity, thus defeating the purpose of reducing overall monitoring costs. If caught in any of the three groups, the agent is assessed a fine.

Russell et al. (1986), Russell (1987) and Harrington (1988) all deal with the design of monitoring schemes for pollution. The characteristics of the Greenberg model are easily recognized in these works. In Greenberg's model, the agent's behavior (cheat or not cheat) is always detected if the agent is audited. The equivalent assumption in pollution control is made by Russell et al.; if monitored and in violation, the polluting firm is caught. Russell et al. outline an approach where this assumption is relaxed, but they do not develop a formal model incorporating the problem of detection. Russell (1987) incorporates the problem of monitoring errors, and thus the need for allowing firms to escape from group three. In so doing, however, his model does not retain all of its incentives for compliance, as his penalty function is such that it necessarily does not induce compliance for all emission levels.

Harrington's (1988) paper differs from Russell et al. (1986) and Russell (1987) in that the agency may face limitations on the kind of penalty function it can choose. In that respect it differs substantially from Becker's (1968) classical article on crime and punishment, where the conclusion was that low monitoring and extremely high penalties constitute the optimal type of action. This view has been called the "hang people with probability zero" proposition. Shavell (1987) showed that Becker's conclusion is incorrect if there is type I detection errors. Under imperfect information Shavell suggests that the penalty levied should be proportional to the harm done to society by the offender. Jones (1989) takes a similar point of view regarding emissions. The penalty function must be everywhere increasing at an increasing rate in the violation to induce compliance over the whole range of possible emission levels.

Fenn and Veljanovski (1988) suggest that it may be cost-effective for the regulatory agency to enter into bargaining with the agents about the standards, thus reducing the cost of litigation. In their model a regulator, who has chosen to adopt a negotiating strategy, is faced with the problem of choosing appropriate responses to offenders. Therefore their model does not differ much the models of Russell et al. (1986), Russell (1987), and Harrington (1988). Fenn and Veljanovski's empirical findings (regarding health and safety compliance in British factories) suggest that confidence ratings from previous years is a better predictor of the firms' responses to regulation than current ratings. The weakness with using historical, rather than current, ratings is that it is not forgiving, i.e. one player's response to other players' change from non-cooperative to cooperative behavior is cooperation. This property has been found to increase the joint payoffs in game theoretical simulations (Axelrod, 1980).

# CHAPTER 3

# RESOURCE ALLOCATION MECHANISMS

The purpose of this chapter is to establish the framework for a welfare analysis of policies to reduce emissions, using the foundation of resource allocation mechanisms (RAMs). This chapter introduces the entities of an economy, and explains the behavioral assumptions of the agents. Next the properties for RAMs are discussed and a foundation for economic welfare analysis is constructed. The latter will be used in evaluating the proposed systems of obtaining optimal emission levels (chapter four) and the suggested monitoring and penalty scheme to induce compliance to environmental standards (chapter five).

The starting point for this discussion is that any economic system or mechanism is a communication process. Each agent transmits messages to which other agents respond according to their self-interest. A successful resource allocation mechanism (RAM) utilizes this, so that each agent without necessarily understanding the complete process, is induced to cooperate in the determination of a satisfactory bundle of goods and services (Campbell, 1987). Under this definition a system of transferable emission permits to obtain the optimal emission level, or a monitoring and penalty scheme attempting to enforce this emission level are RAMs. Treating these cases as abstract RAMs reduces the likelihood of preconceived notions limiting the ingenuity and imagination of the researcher, and the general properties for RAMs aid the researcher in the design of the policy schemes.

An economy consists of firms, consumers and government. Firms produce private goods.[7] Government orders and pays for public goods.[8] A sector of an economy concerns the production and consumption of a particular type of goods or services. Consumers seek to maximize utility from consumption of both private and public goods.

Any RAM must be viewed in conjunction with the environment[9], which is defined as:

DEFINITION 3.1: The economic environment consists of technology, preferences and institutions.

The technology describes the firms' production processes. Preferences influence consumers' choices. Institutions include the legal system and the organization of government.

## 3.1 Firms

### 3.1.1 Production Without Externalities

Let $\mathcal{N}$ denote the index set of all firms, and n index the firms, such that $n \in \mathcal{N}$. The firms are owned by the consumers in the economy. Firms are assumed to maximize profits from the production of private goods. Let there be M private goods, and let $\mathcal{M}$ denote the index set of private goods, and m index these goods such that $m \in \mathcal{M}$. Following

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[7] Whenever the term "private goods" is used, it refers to goods and services that are rival and exclusive (Randall, 1983).

[8] Whenever the term "public goods" is used, it refers to non-rival and non-exclusive goods and services (Randall, 1983).

[9] The term "environment" refers to the economic environment.

McFadden (1978), let $Y$ denote the production possibility set, and assume that $Y$ is closed, non-empty, and that a non-zero output bundle requires a non-zero input bundle. A production possibility set satisfying these properties is called regular. Define the producible output set as $Y^* = \{\mathbf{y} | (\mathbf{q},\mathbf{y}) \in Y\}$, where $\mathbf{y}$ is the product vector and $\mathbf{q}$ is the input vector. Moreover define the input requirement set as $Q(\mathbf{y}) = \{\mathbf{q} | (\mathbf{q},\mathbf{y}) \in Y\}$. A production possibility set is called input-regular if (i) the set of producible outputs, $Y^*$, is non-empty, and (ii) for each $\mathbf{y} \in Y^*$, the input requirement set $Q(\mathbf{y})$ is closed and for a non-zero output bundle does not contain the zero input bundle (McFadden, 1978).

If the input prices, $\mathbf{v}$, are non-negative, the cost function for the nth firm is defined as (McFadden, 1978):

$$c_n(\mathbf{y}_n, \mathbf{v}) = \underset{\mathbf{q}_n}{\text{INF}} \{\mathbf{v}\cdot\mathbf{q}_n | \mathbf{q}_n \in Q_n(\mathbf{y}_n)\} \tag{3.1}$$

where $\mathbf{p}$ is a vector of product prices (not all zero),

$\mathbf{v}$ is a vector of input prices (not all zero),

$\mathbf{q}_n$ is a vector of inputs,

$\mathbf{y}_n$ is a vector of outputs, and

INF denotes the infinum, or greatest lower bound in the set.

The properties of the cost function are well known and given by the following lemma (McFadden, 1978, p. 13):[10]

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[10] For a proof and further discussion of LEMMA 3.1, see McFadden (1978, pp. 10-13).

LEMMA 3.1: Suppose that a firm has an input-regular production possibility set with a producible set $Y^*$ and input requirement set $Q(\mathbf{y})$ for $\mathbf{y} \in Y^*$. Suppose the firm is a price taker in the input markets with a non-negative input price vector v. Then the cost function (3.1) exists for all $\mathbf{y} \in Y^*$ and all non-negative v. Further, for each $\mathbf{y} \in Y^*$, the cost function as a function of v is non-negative, non-decreasing, positively linear homogenous, concave and continuous.

By McFadden's (1978, p. 82-83) duality theorem the profit function exists uniquely:

$$\pi_n(\mathbf{p},\mathbf{v}) = \underset{\mathbf{y}_n \geq \mathbf{0}}{\mathrm{SUP}} \{\mathbf{p}\cdot\mathbf{y}_n - c_n(\mathbf{v},\mathbf{y}_n)\} \tag{3.2}$$

where SUP denotes the supremum or the smaller upper bound.[11]

It also follows from the duality theorem that the profit function satisfies the following conditions (Hanoch, 1978):

CONDITION 3.1:

(i) $\pi_n(\mathbf{p},\mathbf{v})$ is a real, non-negative function of the price vector $(\mathbf{p},\mathbf{v}) \geq \mathbf{0}$ with $\pi_n(\mathbf{0},\mathbf{0}) = 0$ and $\pi_n(\mathbf{p},\mathbf{v}) > 0$ for $(\mathbf{p},\mathbf{v}) \gg 0$.

(ii) $\pi_n(\mathbf{p},\mathbf{v})$ is non-increasing in v and non-decreasing in p.

(iii) If $\mathbf{v} \gg \mathbf{0}$, $\lim_{d\to 0} \pi_n(\mathbf{p},(1/d)\mathbf{v}) \leq \mathbf{p}'\mathbf{a}$, where a is a vector of fixed finite values.

(iv) $\pi_n(\mathbf{p},\mathbf{v})$ is a convex, closed function for $(\mathbf{p},\mathbf{v}) \geq \mathbf{0}$.

[11] Provided strictly positive output prices (p) and input prices (v), SUP in (3.2) can be replaced with MAX.

(v) $\pi_n$ (p,v) is positive linear homogenous in (p,v) > 0, $\lambda > 0$, such that $\pi_n(\lambda(p,v)) = \lambda\pi_n(p,v)$.

### 3.1.2 Production With Externalities

In the production of multiple outputs it is common that if the firm increases the output of one product, the output of some other product(s) also increase. A classical example is the production of wool and mutton. This also applies to the production of some good and a residual product, a pollutant. Without some corrective mechanism, firms produce their profit maximizing quantities given by the first order condition of (3.2) and emit the residual products.

Assume that each polluting firm produces one output, $y_n$, and emits one pollutant, $z_n$. Let $J$ denote the index set of all available production technologies and let j index these technologies, such that $j \in J$. The cost of production for each firm, denoted $C_j(y_n, z_n)$, is twice differentiable with respect to $y_n$ and $z_n$, such that $\partial C_j/\partial y_n > 0$, $\partial C_j/\partial z_n < 0$ for a given output $y_n'$, and $\partial^2 C_j/\partial y_n \partial z_n \leq 0$, for all $n \in N$ and all $j \in J$. Moreover, the second order conditions for profit maximization require that $\partial^2 C_j/\partial y_n^2 \geq 0$ for all $n \in N$ and all $j \in J$. The unconstrained profit maximizing output is found by solving the first order condition of:

$$\pi_{jn} = \sup_{(y_n z_n)} \{p\, y_n - C_j(y_n, z_n)\} \tag{3.3}$$

Assume that for any production technology j, $j \in J$, $\partial y_j/\partial z_n > 0$. Then for a given level of emissions, $z_n$, there exists one level of output, $y_{jn} = y_j(z_n)$. For the marginal costs of production to be non-negative for any emission level, $\partial C_j/\partial z_n = \partial C_j/\partial y \cdot \partial y/\partial z_n + \partial C_j/\partial z_n >$ 0 must hold, requiring $|\partial C_j/\partial y_j \cdot \partial y_j/\partial z_n| > |\partial C_j/\partial z_n|$. Reformulating (3.3) into maximizing profits, denoted $\pi_{jn}$, with the emission level being the only choice variable, yields:

$$\pi_{jn} = \sup_{z_n} \{p\, y_j(z_n) - C_j(z_n)\} \qquad (3.4)$$

Let $z_n^{\circ}$ denote the unconstrained emission level resulting from solving the first order conditions of (3.4).

Let $Z' = \Sigma_{n\in N}\, z_n'$ denote the aggregate constrained emission level. Similarly define $Z^{\circ} = \Sigma_{n\in N}\, z_n^{\circ}$, the unconstrained emission level. Assume that $Z' < Z^{\circ}$. Recall that $\partial y_j/\partial z_n > 0$ for all $n \in N$. Thus less quantities are produced of at least some goods when emission levels are restricted. As the goods produced have downward sloping demand curves in their own price, i.e. $\partial p_m(Y)/\partial Y_m < 0$, the output prices, $p_m$, will increase.

### 3.1.3 Technology Adoption

One important issue in dynamic models of firm behavior is the adoption of new technology. In this research it is assumed that firms behave according to the putty-clay framework (Johansen, 1972). Under this assumption firms are free to choose technologies such that their expected discounted profits are maximized, but once a technology choice has been made, the costs of changing technology may be considerable. Elements entering into the firms' decisions are expectations about future input and output prices and the available information about current technologies and expectations about new technologies. Due to imperfect knowledge regarding future input and output prices, new technologies etc., the firms' ex-ante optimal choice of technology may be ex-post sub-optimal from the firms' perspective. Firms' then choose to use their current technology until the expected discounted profits of adopting a new technology less the costs of switching technology, exceeds the expected discounted profits of the current technology.

## 3.2 Consumers

Consumers seek to maximize utility from the consumption of private goods, $\mathbf{y}$, and public goods, $\mathbf{z}$. Section 3.2.1 presents a model of consumer behavior when only private goods are concerned. In section 3.2.2 the model is expanded to account for the consumption of private goods and public goods. To simplify the model, the only public good considered is a pollutant, Z.

### 3.2.1 Consumption of Private Goods

The consumers' costs of consumption of private goods are given by the market prices for these goods, while their income, X, is the sum of their labor incomes, dividends of their stocks in the firms and their endowments.

Let $I$ denote the index set of all consumers, and i index the consumers, such that $i \in I$. Also let the ith consumer's consumption set, $Y_i$ ,be closed and convex. Moreover, let the ith consumer's preference ordering, $\succsim_i$ , be complete, reflexive, transitive and continuous for all $i \in I$. Then the ith consumers preferences can be represented by a utility function, $U_i(\mathbf{y}_i)$ (Varian, 1984). The set of all bundles on or above an indifference curve, $\{\mathbf{y}_i \in Y_i : \mathbf{y}_i \succsim_i \mathbf{y}_i^\circ\}$, is denoted the upper contour set, and is analogous to the input requirement set of production theory. Indifference curves can be thought of as level sets of the utility function. Let the product prices, $\mathbf{p}$, be non-negative with some elements in $\mathbf{p}$ strictly positive. Moreover let $\succsim_i$ satisfy local nonsatiation.

Under local non-satiation the consumers must utilize all of their respective budgets, $X_i$. Following Varian (1984) and Deaton and Muellbauer (1980) the consumer's choice problem can then be expressed by means of the indirect utility function, $V_i(\mathbf{p},X_i)$:

$$V_i(\mathbf{p},X_i) = \sup_{\mathbf{y}_i \in Y_i} U_i(\mathbf{y}_i) \text{ s.t. } \mathbf{p}\cdot\mathbf{y}_i = X_i \quad (3.5)$$

Varian (1984) lists the following properties for the indirect utility function (3.5):

CONDITION 3.2: The indirect utility function:

(i) $V_i(\mathbf{p},X_i)$ is continuous at all $p \gg 0$, $X_i > 0$.

(ii) $V_i(\mathbf{p},X_i)$ is non-increasing in $\mathbf{p}$ and non-decreasing in $X_i$.

(iii) $V_i(p,X_i)$ is quasi-convex in $\mathbf{p}$; that the lower contour set is $\{\mathbf{p}:V_i(\mathbf{p},X_i) \leq k\}$ is a convex set for all real numbers k.

(iv) $V_i(\mathbf{p},X_i)$ is homogenous of degree 0 in $(\mathbf{p},X_i)$.

If property (ii) is modified to decreasing in $\mathbf{p}$ and increasing in $X_i$, sufficiency for $V_i(\mathbf{p},X_i)$ to be invertible is achieved. Thus the individual expenditure functions, $e_i(\mathbf{p},U_i)$, exist. The expenditure function gives the minimum cost of achieving a fixed utility level (Varian, 1984). Consequently, the money metric utility function

$$M_i(\mathbf{p},X_i;\mathbf{p}^\circ) = e_i(\mathbf{p},V_i(\mathbf{p},X_i)) \tag{3.6}$$

can be derived, where $\mathbf{p}^\circ$ is the reference price vector (Deaton and Muellbauer, 1980). The aggregate money metric utility function is then defined as:

$$M(\mathbf{p},\mathbf{X};\mathbf{p}^\circ) = \Sigma_{i\in I} M_i(\mathbf{p},X_i;\mathbf{p}^\circ) \tag{3.7}$$

where $\mathbf{X} = [X_1,\ldots,X_I]$, a vector of consumer incomes.

The aggregate money metric utility function can now be used to analyze the aggregate welfare effects of certain policies on the consumers, by comparing the differences in the money metric utility at the reference price vector, $\mathbf{p}^\circ$.

### 3.2.2 The Consumption of Private Goods and Public Bads

When consumption of a public bad, Z, is considered, the consumer's preference ordering $\succsim_i$ with respect to Z still satisfies completeness, reflexivity, transitivity, continuity and local nonsatiation. As there exists no market prices for the public bad, it can not be modelled through the indirect utility function. This difficulty can be circumvented using the constrained indirect utility function:

$$V_i(\mathbf{p},X_i|Z') = \max_{\mathbf{y}_i\in Y_i(Z')} U_i(\mathbf{y}_i) \text{ s.t. } \mathbf{p}\cdot\mathbf{y}_i = X_i \tag{3.8}$$

where $\mathbf{y}_i \in Y_i\,(Z')$ denotes the ith consumer's constrained choice set, such that $Y_i\,(Z') = \{\mathbf{y}_i : (\mathbf{y}_i\,,Z') \subset Y_i\}$, the projection from the space $(\mathbf{y},Z)$ onto the space $\mathbf{y}$, and

$Z'$ denotes the constrained emission level.

Thus for each level of the externality, there may exist a different indirect utility function. As the characteristics of the preference ordering $\succsim_i$ remain the same, the constrained indirect utility functions (3.8) have the same properties as the indirect utility function (3.5) in $\mathbf{p}$ and $X_i$ (Condition 3.2). Thus the constrained money metric utility function,

$$M_i\,(\mathbf{p},X_i\,;\mathbf{p}^\circ\,|Z') \tag{3.9}$$

can be obtained in a similar fashion. The aggregate constrained money metric function is thus defined by:

$$M(\mathbf{p},\mathbf{X},;\mathbf{p}^\circ\,|Z') \;=\; \Sigma_{i\in I}\, M_i\,(\mathbf{p},X_i\,;\mathbf{p}^\circ\,|Z') \tag{3.10}$$

### 3.2.3 The Damage Function from Emissions

The damage function has not received much attention in the literature on optimal emission levels. It has been assumed that the damage function captures all the welfare related factors, without specifying what these are (Pearce, 1986; Montgomery, 1972; and Baumol and Oates, 1988).

Clearly the damage function must capture the direct effects to the consumers from emissions. These include health related effects and reduced enjoyment from environmental goods (Mäler, 1974). In section 3.1.2 on production with externalities, it was indicated that if the reduction in the emission level is large, and this reduced the amount of goods produced, the prices of these goods would increase. By the indirect utility function it follows that this causes a loss in welfare to the consumers. Thus the damage function needs to incorporate both the direct and the indirect effects of a reduction in the emission level. This is consistent with findings done by Mäler (1985), suggesting a general equilibrium approach to estimating benefits or damages from changes in for example the level of pollution.

Assume that the marginal costs of abatement are known. The optimal emission level is where the marginal cost curve intersects the marginal damage curve. The following figure illustrates the difference in emission level resulting from a marginal damage curve with and without the indirect effects:

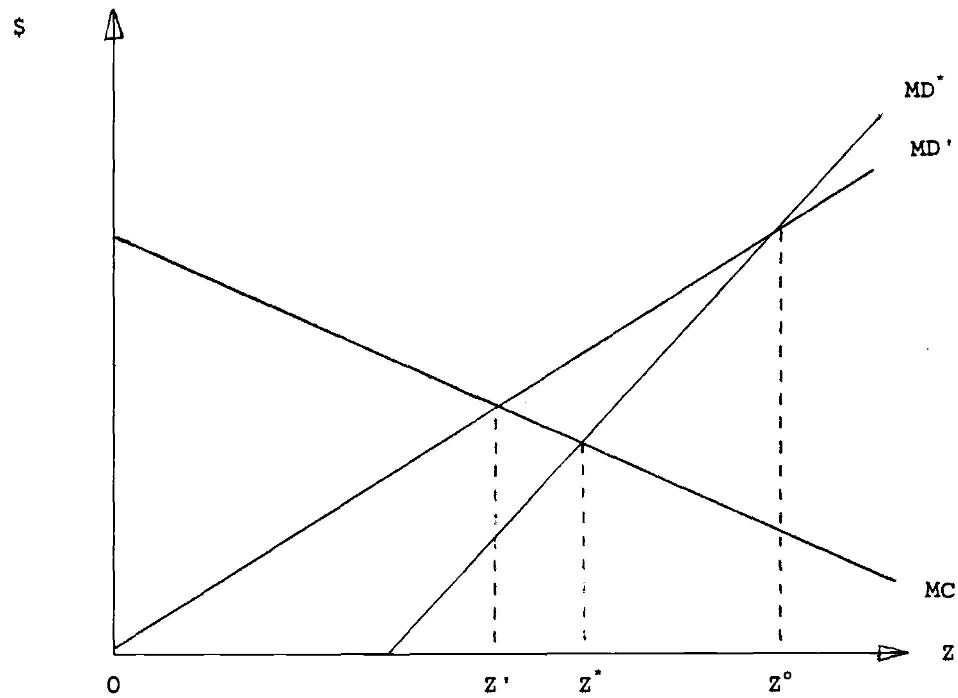


Figure 3: The marginal damage function. MD': marginal damage function including only direct effects, $MD^*$ : marginal damage function including both direct and indirect effects, $Z°$ : initial emission level, Z': "optimal" emission level when only direct effects are incorporated, $Z^*$ : optimal emission level when both direct and indirect effects are incorporated.

For the remainder it is assumed that the marginal damage function captures both the direct and indirect effects, and thus represents the true marginal social damage function needed for the regulatory agency to make optimal decisions. The general specification of the benefit function becomes:

$$B(Z,\mathbf{p},\mathbf{X};\mathbf{p}^{\circ},Z^{\circ}) \tag{3.11}$$

such that: $\partial B/\partial Z < 0$,

$\partial B/\partial p_m < 0$, where $p_m \in \mathbf{p}$ as $m \in M$, and

$\partial B/\partial X_i < 0$, for all $i \in I$.

## 3.3 The Regulatory Agency

The regulatory agency is a subset of the government, and like the government it seeks to maximize societal welfare. The agency's task is to maximize overall benefits from pollution and to enforce environmental standards at minimum loss of welfare. Several welfare measures exists; aggregate money metric utility (AMMU), the Bergson-Samuelson social welfare function (SWF), Pareto-optimality and Second-Best Pareto-Optimality (SBPO). They are presented in the succeeding subsections.

### 3.3.1 Aggregate Money Metric Utility

Using (3.9), the constrained aggregate money metric utility (CAMMU) can be evaluated. From the regulatory agency's point of view, an externality allocation[12] $\mathbf{Z}^a$ is desireable over the externality allocation $\mathbf{Z}^b$, if $M(\mathbf{p}^a, \mathbf{X}^a; \mathbf{p}^o | \mathbf{Z}^a) > M(\mathbf{p}^b, \mathbf{X}^b; \mathbf{p}^o | \mathbf{Z}^b)$, where $\mathbf{X}^a$ and $\mathbf{X}^b$ is a vector of consumer incomes under the externality allocations a and b respectively, and $\mathbf{p}^a$ and $\mathbf{p}^b$ are the corresponding price-vectors.

### 3.3.2 The Bergson-Samuelson Social Welfare Function

The most general form of the Bergson-Samuelson (Bergson, 1938; Samuelson, 1983) social welfare function (SWF) is (Boadway and Bruce, 1984):

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[12] Externality allocation: to each externality allocation there exists a unique equilibrium set of prices, goods consumed by each consumer, $i \in I$, and goods produced by the firms, $n \in N$.

$$W(\mathbf{y}) = F[U_1(\mathbf{y}_1),\ldots,U_I(\mathbf{y}_I)] \tag{3.12}$$

where $W(\bullet)$ is a function that can be evaluated over the whole set of consumers, $i \in I$.

It is generally assumed that $W(\mathbf{y})$ satisfies; (i) the principle of welfareism, i.e. that the ranking of social states only depends on the utility levels of the consumers (Sen, 1977), (ii) the strong Pareto principle, i.e. it is increasing in each consumer's utility, and (iii) strictly quasi-concavity, which implies that equality in utilities among households, all other things equal, is socially desireable.

To construct a Bergson-Samuelson social welfare function one must be able to measure each individual's utility on a comparable scale (Boadway and Bruce, 1984). The individual money metric utility functions (3.6) is a feasible way of doing this. One possible specification of the SWF is to add these money metric utilities. Then the SWF is no different from AMMU. An alternate approach is to weight the individuals money metric utility functions and then add, i.e.

$$W(\mathbf{p},\mathbf{X},\boldsymbol{\beta}) = \Sigma_{i\in I}\ \beta_i M_i(\mathbf{p},X_i;\mathbf{p}^\circ) \tag{3.13}$$

where $\mathbf{X}$ is a vector of individual incomes,

$\beta_i$ is a weight issued to the ith individual on the basis of income and other social characteristics, and

$\boldsymbol{\beta}$ is a vector of these weights.

The problem implementing (3.13) is choosing $\boldsymbol{\beta}$. Other specifications of the SWF have been suggested. For example Rawls (1971) suggests that SWF is the MIN $\{i \in I : V_i(\mathbf{p},X_i)\}$, i.e. the appropriate societal welfare indicator is the utility level reached by the individual in society having the lowest indirect utility.

Reaching consensus regarding the specification of the SWF is the main obstacle with the SWF approach. This is demonstrated by Arrow's (1951) impossibility theorem. The essence of this theorem is that the set of feasible SWFs is empty. Sen (1977) contests this result, working with what he denotes the set of possible SWFs. His approach requires a different set of assumptions regarding the utility function than those used here (Condition 3.2), and is not pursued further.

It is easy to see that the above arguments also holds for the constrained case. The difference is that the money metric utility function is replaced by the constrained money metric utility function.

### 3.3.3 Pareto-Optimality

DEFINITION 3.2: A feasible allocation is an allocation where (i) the ith consumer's consumption bundle must be in his/her choice set (the set of all affordable bundles, i.e. $\{\mathbf{p}\cdot\mathbf{y}_i \leq X_i\}$ for all $i \in I$), and (ii) the total expenditures in the economy cannot exceed the sum of the incomes and the endowments in any period (Campbell, 1987).

DEFINITION 3.3: Pareto-optimality. Let the $\mathbf{y}_I$ be a vector spanning society's consumption bundle, and let $\mathbf{y}_N$ be a vector spanning society's production bundle. Let $U_i(\bullet)$ denote the ith individual's utility function, and let $I$ denote the set of consumers and $N$ the set of producers. A Pareto-optimum is a feasible allocation

$(y_I^b ; y_N^b)$ such that there exists no other feasible allocation $(y_I^a ; y_N^a)$ that would give at least as much utility to all consumers and more utility to at least one consumer, such that

$$U_i (y_i^0) \geq U_i (y_i^1) \text{ for all } i \in I$$

and there exists i' $\in I$ such that

$$U_{i'} (y_{i'}^0) > U_{i'} (y_{i'}^1) \qquad \text{(Laffont, 1989, p. 3).}$$

The implication of this definition is that at a Pareto-optimum, no consumer can be made better off, without at least one other consumer being made worse off. Using Pareto-optimality as the criterion for evaluating policies is difficult for two reasons. First, any policy which makes one or more consumers worse off, does not constitute a Pareto-improvement, and is therefore not admissable.

Second, the existence of externalities implies that the economy is not at a Pareto-optimal state. An externality is an allocation resulting from some kind of market failure, i.e. the agents have for whatever reason, not internalized some activity or activities, resulting in non Pareto-optimal outcome (Coase, 1960). Buchanan and Stubblebine (1962) argue that the reason externalities exist is that the gains from internalizing them are less than the cost of establishing and maintaining the necessary institutions for the externality to be internalized. They conclude their arguments by saying because of this, any existing externality is not Pareto-relevant. In this perspective, the importance of this research is that it seeks to devise new institutions which are less costly to operate. The effect of this is that more externalities are made Pareto-relevant and potential gains in societal welfare can be made.

### 3.3.4 Second-Best Pareto-Optimality

According to the theory of second best it is uncertain whether applying marginal cost pricing in the sectors under consideration will move the entire economy closer to the Pareto-optimum, unless the optimum conditions are met in the rest of the economy (Lipsey and Lancaster, 1956; Boadway and Bruce, 1984). In general the latter will not be the case. Thus Pareto-optimality may not be applicable in the case of RAMs seeking to correct for externalities.

Spulber (1989) suggests replacing Pareto-optimality with SBPO. Expressed in terms of the constrained indirect utility function, SBPO is defined by:[13]

DEFINITION 3.4: Second-Best Pareto-Optimality: Assume that to a certain externality vector, Z, there exists certain prices and consumer incomes. Let $\mathbf{p}^a$ and $\mathbf{p}^b$ denote the price vectors from the externality vectors $\mathbf{Z}^a$ and $\mathbf{Z}^b$ respectively. In a similar fashion let $X_i^a$ and $X_i^b$ be the associated consumer incomes for the ith consumer. An externality vector $\mathbf{Z}^a$ is SBPO if there exists no other externality vector $\mathbf{Z}^b$ such that $V_i(\mathbf{p}^b, X_i^b \mid \mathbf{Z}^b) \geq V_i(\mathbf{p}^a, X_i^a \mid \mathbf{Z}^a)$ for all $i \in I$ and $V_i(\mathbf{p}^b, X_i^b \mid \mathbf{Z}^b) > V_i(\mathbf{p}^a, X_i^a \mid \mathbf{Z}^a)$ for some $i \in I$.

The first objection raised against Pareto-optimality, also applies

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[13] Spulber (1989, p. 355) defines SBPO in terms of the ordinary utility function.

to SBPO; policies that make one consumer worse off, are inadmissable. From the definition of SBPO it is however clear that SBPO does not require that the rest of the economy is at a Pareto-optimal state to be applicable.

### 3.3.5 The Regulatory Agency's Choice of Welfare Indicator

One reason for not choosing a Bergson-Samuelson social welfare function is the problems reaching a consensus on its specification, in particular the choice of weights ($\beta$ in 3.11). Pareto-optimality is not applicable unless the rest of the economy is at an optimum, a very restrictive condition. The problem is therefore choosing either to maximize AMMU or using SBPO as the welfare indicator. To facilitate the choice between these two welfare indicators, consider the following proposition:

PROPOSITION 3.1: Second-Best Pareto-optimality (Definition 3.4) is a necessary condition for Maximum Aggregate Money Metric Utility.

PROOF: Assume that the externality vector $\mathbf{Z}^b$ results in the economy not being in a SBPO state. By Definition 3.4 it then follows that there exists an externality vector $\mathbf{Z}^a$ with a set of prices, p, and income, y, such that $V_i(p^a, X_i^a) \geq V_i(p^b, X_i^b)$ for all $i \in I$. By applying equation (3.6) and (3.7), $M_i(p^a, X_i^a; p^o) \geq M_i(p^b, X_i^b; p^o)$. Consequently $M(p^a, \mathbf{X}^a; p^o) > M(p^b, \mathbf{X}^b; p^o)$. Q.E.D.

This result is not very surprising. If the economy is not in a

SBPO state, a second-best Pareto-improvement is in principle possible, i.e. some individuals could be made better off without making others worse off. Thus an economy that is not SBPO cannot attain maximum AMMU. Making additional assumptions about the individual money metric utility functions would allow for selecting the maximum AMMU allocations among the SBPO allocations. This would complicate the present analysis. SBPO is therefore proposed as the welfare indicator.

## 3.4 Desireable Properties for Resource Allocation Mechanisms

Campbell (1987) lists the following desireable properties of RAMs; (i) individual rationality, (ii) informational viability and efficiency, (iii) incentive compatibility and (iv) Pareto-optimality. The importance of these properties, and necessary modifications due to conflicts between them will be demonstrated.

Individual rationality requires that the suggested RAM generates allocations that make all the firms, $n \in N$, and all consumers, $i \in I$, at least as well off as they were initially. This property is also called the participation constraint (Rasmusen, 1989).

Informational viability is important because RAMs that do not satisfy this property have informational requirements that exceed the available information. Any RAM that is not informationally viable may therefore not yield its intended outcome(s). Informational viability requires (i) that agents only use accessible information about the other agents, and (ii) that the amount of information is such that it can be treated (Campbell, 1987). Formally (i) is called the privacy preserving property of the RAM, implying that only public information about one agent can be used by the other agents. A convenient way of formalizing (ii) is that the message space of the proposed RAM must be finite in Euclidian space. This means that the vector of information exchanged between the agents has a finite dimension.

Informational efficiency means that there exists no known RAM which satisfies the stated objectives at less cost of gathering and processing (Campbell, 1987). Once a useable definition for efficiency of the proposed RAM has been obtained, it will be shown that informational efficiency is a necessary criterion for efficiency of the proposed RAM.

Incentive compatibility means that it should be in the self interest of the firms to act in the prescribed way. Unfortunately joint incentive compatibility and Pareto-optimality are not always possible. The following theorem due to Hurwicz (1972) illustrates this (Campbell, 1987, p. 114):[14]

THEOREM 3.1: Let R' be a mechanism defined on a family of economic environments, the family of self-regarding utility functions that exhibit diminishing marginal rates of substitution everywhere. If for every environment within this family of environments, the mechanism R' generates equilibrium allocations that are Pareto optimal and individually rational, then it can be manipulated.

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[14] The proof of this theorem can be found in Campbell (1987, pp. 114-115).

The proof of Theorem 3.1 assumes that one agent can obtain increased profits (or utility) by manipulative behavior when all the other agents behaves sincerely. Thus each agent is lead behave manipulatively, and the outcome is not Pareto-optimal. Consequently, if the policy maker chooses a RAM that could lead to a Pareto-optimal outcome, such an outcome is not guaranteed.

Now suppose that the policy maker decides to opt for an incentive compatible RAM. Even if Pareto-optimality may not result, the proposed RAM will yield a predictable outcome, whose welfare properties can be evaluated.

To facilitate the analysis of SBPO, it will now be demonstrated that informational efficiency and SBPO are connected. Once this connection has been established, the welfare implications of any RAM is more easily obtained.

PROPOSITION 3.2: Informational efficiency is a necessary criterion of Second-Best Pareto-optimality.

PROOF: Suppose informational efficiency is not necessary for SBPO. Let $C^I(\bullet)$ denote the informational costs. Let there exist an externality vector, Z', which is SBPO, while the proposed RAM, R' is not informationally efficient. Also assume there exists another RAM, R" which results in the same externality vector **Z'** at less informational cost, i.e. $C^I(R") < C^I(R')$. The difference in informational costs between the two RAMs is then $\underline{\Delta}\, C^I(R',R") = C^I(R') - C^I(R") > 0$, which can be used to make some or all the agents better off. Then by the definition of SBPO, the RAM R' is not SBPO. Q.E.D.

Informational viability and efficiency and incentive compatibility are required for the proposed RAM to yield a predictable outcome. Individual rationality is important to facilitate the implementation of the RAM. To evaluate any RAM, a welfare indicator is needed. SBPO is chosen as the welfare indicator because it does not require the RAM to correct for all inefficiencies in the economy and it does not require individual utilities to be comparable.

The modified desireable properties of a RAM are therefore;

(i) individual rationality,

(ii) informational viability and efficiency,

(iii) incentive compatibility, and

(iv) second-best Pareto-optimality.

# CHAPTER 4

# DETERMINING OPTIMAL POLLUTION QUOTAS WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE

Firms are reluctant to disclose information about their cost structure. The consumers on the other hand has no incentives not to reveal their perceived disutility from emissions. One objective of this research is therefore to show how transferable emission quotas can be used to obtain the optimal level of emissions when society's damage function for emissions, D(Z), is known, but the individual firm's abatement cost is unknown to the regulatory agency.

The principle of the suggested model is to establish markets for emission permits, and determine whether the imposed emission levels are too restrictive or too lax. These markets are to be set up like a stock exchange for emission permits, where these permits are traded. The regulatory agency can then compare the inferred prices at the chosen aggregate emission levels with the observed prices for various emission permits.

The next section presents an atemporal version of the proposed model of transferable emission quotas. In the succeeding section an intertemporal version of the proposed model of transferable emission quotas is developed. The last two sections of this chapter evaluate the proposed scheme in light of the criteria outlined for RAMs (chapter three) and look at some of the problems that may arise in implementing and applying the proposed model.

## 4.1 Optimal Emission Levels in an Atemporal Setting

In chapter three it was argued that SBPO is a suitable measure of societal welfare given assumptions made about individual preferences. Using a principal-agent formulation (Rasmusen, 1989), the regulatory agency's objective (the principal) is to choose an aggregate emission level, $Z = \Sigma_{n \in N} z_n$, where $N$ denotes the index set of the firms, such that SBPO is achieved. By Definition 3.4 of SBPO, this implies:

$$\text{Agency: } \underset{Z \neq Z'}{\text{Choose}} \quad \begin{array}{l} V_i\,(p, X_i \mid Z) \geq V_i\,(p', X_i' \mid Z') \text{ for all } i \in I \text{ and} \\ V_i\,(p, X_i \mid Z) > V_i\,(p', X_i' \mid Z') \text{ for some } i \in I. \end{array} \tag{4.1}$$

Assume non-homogenous firms indexed by n with $n \in N$. Also assume that each firm produces one good (y) and emits one pollutant (z). The cost function is assumed to satisfy assumptions made in section 3.1.2. Then the nth firm's unconstrained single-period profit function can be expressed as:

$$\text{Firm n: } \quad \underset{y_n\, z_n}{\text{MAX}} \quad \pi_n\,(y_n, z_n) = p_y\, y_n - C_j\,(y_n, z_n) \tag{4.2}$$

where $p_y$ is the market price for the produced good, y,

$y_n$ is the nth firm's output,

$z_n$ is the nth firm's emission level, and

$C_j\,(\bullet)$ is the firm's cost function of producing $y_n$ with the emission level $z_n$ (which is not known to the regulatory agency).

The principal-agent formulation is then (4.1) subject to (4.2). When each firm is awarded an emission quota, $z_n^o$, each firm must solve the constrained maximization problem, (4.2) st. $(z_n^o - z_n) \geq 0$. This yields the following Lagrangian:

$$\underset{y_n\,z_n}{\text{Choose}} \qquad L = p_y\, y_n \;-\; C_j\,(y_n\,, z_n\,) \;+\; \lambda(z_n^o \;-\; z_n\,) \tag{4.3}$$

In the case of pollution control, the most interesting first order condition of (4.3), using the Kuhn-Tucker approach, and assuming that the emission constraint is binding, is:

$$\partial L/\partial z_n \;=\; -\partial C_j\,/\partial z_n \;-\; \lambda \;=\; 0 \tag{4.4}$$

Given the output level, $\partial C_j\,/\partial z_n < 0$. Consequently the firm maximizes its profits where the marginal costs of abatement equals the shadow price of the constraint. In the case of a permit market, this implies that the firm should buy or sell permits until the shadow price of the constraint equals the market price for permits.

Thus under the atemporal transferable emission permit scenario, each firm will buy or sell pollution permits until the cost of buying one more permit-unit equals the respective firm's marginal cost of pollution abatement. Assume that no firm cheats, that is, does not emit more pollutants than its quota. Then the agency can compare the price on pollution permits with the implied price at a Z level of emissions from the known marginal damage curve of pollution to determine the optimality of the aggregate emission level, Z. The situation where a pollution quota that is too large has been issued is shown in the following figure:

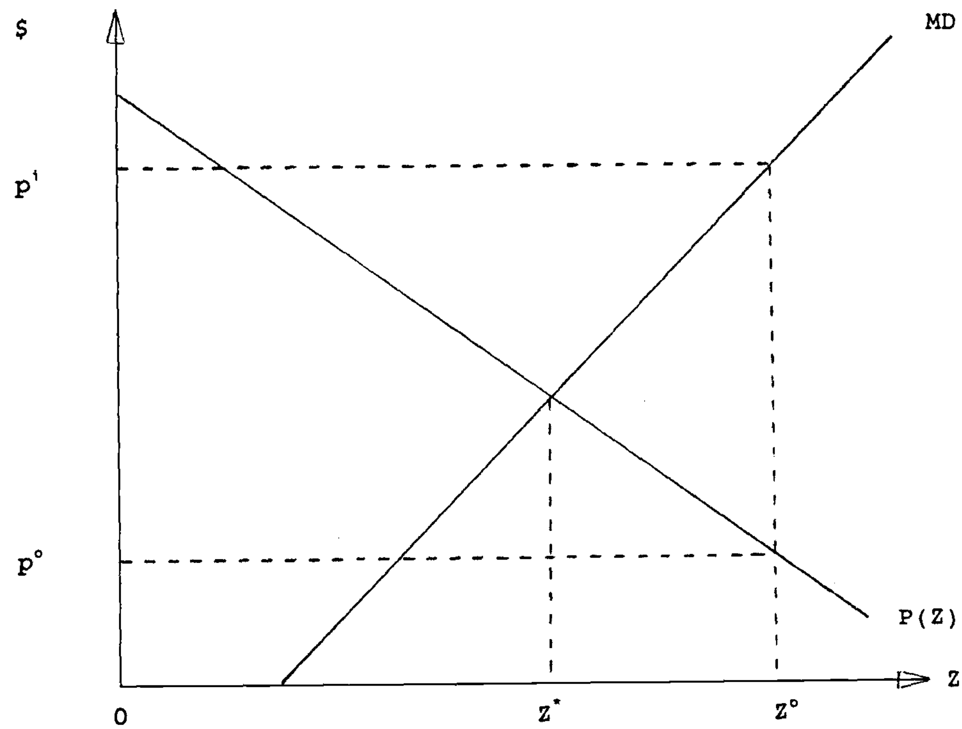


Figure 4: Aggregate emissions under transferable quotas: The issued aggregate emission quota ($Z^{\circ}$) is too large. $p^{1}$ : price implied from the marginal damage curve at the $Z^{\circ}$ emission level, $p^{\circ}$ : observed price at the $Z^{\circ}$ emission level, and P(Z) the price curve of emission permits at various levels of emissions. $Z^{*}$ denotes the optimal aggregate emission level.

The converse situation would arise if $Z^{\circ} < Z^{*}$, as $p^{\circ} > p^{1}$. This discrepancy between the implied price from the damages of pollution and the observed (actual) price for pollution permits signals to the regulatory agency whether the aggregate quota, $Z^{\circ}$, of a particular pollutant is too small or too large.

The above atemporal model illustrates the conditions for optimality of the aggregate emission level. This model does not describe the adjustment patterns leading to the optimal emission level, nor does it indicate the correct interpretation of the price of emission permits when firms are assigned and buy emission permits. To analyze these aspects in a proper fashion, a dynamic model (intertemporal) model is needed.

## 4.2 A Dynamic Model for Optimal Emission Levels

Recall that $p_t^i(Z_t)$ is inferred from the marginal damage function, and $p_t^o(Z_t)$ is derived from the emission permit market. In the intertemporal case, the polluting firms buy permanent emission permits. Thus these permits need to be viewed as an investment. The price of the emission permits reflects this, and can not be used alone to infer the optimal emission level. Assume perfect capital markets. Also assume that the real interest rate, r, is fixed and there is complete knowledge. Let all prices be real prices. By (4.4) and the above assumption, the criterion for optimality of $Z_t$ can be restated as:

$$p_t^i(Z_t) = r\, p_t^o(Z_t), \text{ for all } t \in \{0,1,\ldots,T'\} = \mathcal{T}' \tag{4.5}$$

Let $\lambda_t$ equal $r\, p_t^o$. Using a principal-agent formulation the mathematical expression of the intertemporal model becomes:

$$\left.\begin{array}{lll} \text{Agency:} & \text{Choose} & U_i(Z_t) \geq U_i(Z_t') \text{ for all } i \in I \text{ and} \\ & \{Z_t \neq Z_t'\}_{t\in\mathcal{T}'} & U_i(Z_t) > U_i(Z_t') \text{ for some } i \in I. \\ & & \text{st. } \Sigma_{n\in N} z_{nt}^0 = \Sigma_{n\in N} z_{nt}^1 = Z_t \\ & \text{st.} & \\ \text{Firms:} & \underset{\{z_{nt}\}_{t\in\mathcal{T}'}}{\text{MAX}} & \Sigma_{t\in\mathcal{T}'}\, \beta^t\, [\pi_n(z_{nt}^1) - \lambda_t(Z_t)(z_{nt}^1 - z_{nt}^0)] \end{array}\right\} \tag{4.6}$$

where $z^1_{nt}$ is the nth firm's ex-trade level of emissions,

$z^0_{nt}$ is the nth firm's pre-trade allocation of emissions,

$\beta$ is the discount factor $(1 + r)^{-1}$, where r is the interest rate, and

all other terms remain as defined before.

From (4.6) it is evident that the sequence $\{\lambda_t (Z_t)\}_{t\in T'}$ and thus the sequence $\{p^\circ_t\}_{t\in T'}$ depends upon the solution of the firms' problem of maximizing expected discounted profits. Let $\{z^*_{nt}\}_{t\in T'}$ denote the nth firm's ex-trade profit maximizing solution of (4.6). Further insights into the nature of the sequence $\{p^\circ_t (Z_t)\}_{t\in T'}$ is obtained from looking at the nth firm's cost minimization problem. By duality of the production function the following Lagrangian can be constructed:

$$\underset{\{z^1_{nt}\}_{t\in T'}}{\text{MIN}} \quad \Sigma_{t\in T'} \beta^t [C_{jt} (z^0_{nt}) + \lambda_t (Z_t)\cdot(z^1_{nt} - z^0_{nt})] \tag{4.7}$$

The nth firm's cost function of abatement, $j \in J$, is assumed to be well behaved (Lemma 3.1), i.e. $\partial C_{jt} / \partial z^1_{nt} < 0$ evaluated at $y^*_{nt}$. Thus the firm's minimum cost choice of $z^1_{nt}$ occurs where:

$$\lambda_t (Z_t) + [\partial\lambda_t (Z_t)/\partial Z_t)](z^1_{nt} - z^0_{nt}) = \mu_t = r\ p^\circ_t \tag{4.8}$$

where $\lambda_t$ is the Lagrangian multiplier of the constraint that emissions can not exceed the ex-trade level,

$[\partial\lambda_t (z^1_{nt})/\partial Z^1_{nt})]$ is the change in the product interest times market price of permits as $z^1_{nt}$ changes, and

all other terms are defined as before.

The value of the shadow-price, $\mu_t$, denotes the loss in profits due to the emission constraint. If $\mu_t$ exceeds the left hand side of (4.8), the firm can reduce its costs by buying additional permits until (4.8) holds. Each firm's sequence of ex-trade emission levels, $\{z^1_{nt}\}_{t \in T^*}$, denotes the solution of (4.8), and implies a sequence of emission permit prices, $\{p^\circ_t(Z_t)\}_{t \in T^*}$, provided each firm participates in the market according to (4.8). Thus the optimality of the proposed scheme also depends upon whether the firms behave such that (4.8) is met or not. It remains to be shown that this also is the dominant strategy for the firms. Viewing the market for emission permits as a RAM yields some interesting insights regarding this, and thus into the feasibility of the proposed scheme.

## 4.3 Evaluating the Proposed System as a Resource Allocation Mechanism

The proposed RAM needs to be evaluated on these criteria (section 3.4):

(i) individual rationality,

(ii) informational viability and efficiency,

(iii) incentive compatibility and

(iv) second-best Pareto-optimality.

### 4.3.1 Individual Rationality

Suppose that the current emission level is individually rational to all agents in the economy. This implies that there exists no known RAM that would be able to correct for the externality without making at least one agent worse off. Consequently the externality would be Pareto-irrelevant[15], and the optimal action is not to correct for the externality. To make sense in this setting, the property of individual rationality needs to be modified to apply to any other RAM designed to reduce emissions to a certain level, $Z^*$ .

Baumol and Oates (1988) show that a system of marketable permits is the least cost alternative to the firms for reducing pollution by any amount. Given emissions reductions are to take place, the proposed RAM system of marketable permits therefore meets the criterion of individual rationality from the firms' perspective.

### 4.3.2 Informational Viability and Efficiency

In the proposed system of marketable permits each firm only needs to know its own costs of abatement and to observe the market price for emission permits. The former is needed for the firms to choose their cost minimizing emission levels under any scheme designed to reduce emissions. The latter is easily observed by all firms. Thus from the firms' perspective the proposed system is informationally viable.

The message space for the regulatory agency consists of prices for emission permits, the overall level of emissions at these prices and the consumers' perceived disutility at this level of emissions. This message space is also finite. Moreover, the proposed system does not

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[15] Pareto-irrelevant externality: any externality where the cost of removing or reducing the external effects outweigh the benefits of the change (Dahlman, 1979).

require the agency access to the firms' cost functions, and is therefore privacy preserving. The scheme is therefore informationally viable from the viewpoint of the agency.

By Proposition 3.2 informational efficiency is a necessary condition for the overall efficiency of the proposed RAM. Any RAM seeking to reduce emissions to a certain level requires the individual firm to know its own abatement costs. Assuming that the cost of observing the market prices for permits is negligible, the proposed scheme is informationally efficient from the firms' viewpoint.

The only informational costs incurred by the regulatory agency are (a) obtaining the consumers' valuation of the various levels of reduction in aggregate emissions and (b) administering the market for permits. Informational efficiency from the perspective of the regulatory agency therefore depends upon whether these costs exceed the informational costs of any alternative RAM satisfying the same objectives.

For a system of direct regulation or Pigouvian taxes to yield the optimal level of emissions, $Z^*$, information about the public's valuation of reduced emissions is needed. The same information is needed for the proposed system. In that respect the informational costs of the suggested RAM does not exceed the informational costs of any known alternate RAM.

The particular operating costs of an emissions permit market are the only remaining factor which prevents the suggested RAM from being SBPO. It is reasonable to assume that the particular costs of direct controls exceed these costs. Thus the suggested scheme is more cost efficient than direct controls.

A system of Pigouvian taxes has considerable informational costs when the bargaining costs of changing the fees are incorporated. Because changes in the emission level is not subject to negotiations, the proposed system of marketable emission permits does not have this problem. Under the suggested scheme, reductions in the overall pollution level can only take place by the agency or the public through the purchase of emission permits for retirement.

### 4.3.3 Incentive Compatibility

Incentive compatibility in the case of transferable emission permits has two dimensions. One problem in this aspect is the firms' compliance with the emission levels acquired. For now, this problem is assumed solved, i.e. each firm is in compliance with its ex-trade quota.

DEFINITION 4.1: Strategic behavior in the emission permit market for the nth firm is any action different from the action defined by the nth firm's demand curve for emission permits.

DEFINITION 4.2: A coalition of firms is a collection of firms which coordinate their strategies.

The aim of strategic behavior on behalf of any firm in the emission permit market is to increase its discounted profits. It will be shown that it is not profitable for any firm to behave strategically, alone or in a coalition.

To prove that non-strategic behavior in the emission permit market is the dominant strategy for the firm, the following lemma (Spulber, 1989, p. 353) is needed:

LEMMA 4.1: The market price for emission permits, $p_t^o$, is reduced with increased emissions.

PROPOSITION 4.1: The dominant strategy for any single firm is not to behave strategically.

PROOF: The assumptions leading to definition of the cost function with externalities, $C_J(y_n, z_n)$, assure that the nth firm's demand curve for emitting $z_n$ is single valued, i.e. for a given output level, $y_n$, there exists one and only one emission level. As the profit function is the convex conjugate of the cost function, it therefore follows that to the profit maximizing output level, $y_n^*$, there exists one emission level, $z_n^*$. Suppose one firm decides to behave strategically, and buys emission permits such that its stock of permits, $z_n' > z_n^*$. This action causes (i) the strategically behaving firm's profits to be less than they would under non-strategic behavior, and (ii) the market price for permits to increase as the overall demand for permits increases by lemma 4.1. With the increase in the permit price, the regulatory agency increases the aggregate emission quota, which again lowers the permit price. As the strategically behaving firm already has an excess stock of permits, it will not benefit as much from this reduced permit price as the other firms. Consequently the expected discounted profits from strategic behavior for one firm are less than the expected discounted profits from non-strategic behavior. Q.E.D.

DEFINITION 4.3: A <u>stable coalition</u> is a coalition where the expected profits of every firm in the coalition exceeds the expected profits of belonging to any other coalition or belonging to no coalition (Cornes and Sandler, 1986, p. 96).

PROPOSITION 4.2: Any coalition of strategically behaving firms in the permit market is unstable as any member of the coalition has greater expected profits from non-strategic behavior.

PROOF: This follows directly from Proposition 4.1. As the expected profits from strategic behavior is lower than the profits from non-strategic behavior, any member of the coalition has incentives to pursue the profit maximizing behavior consistent with (4.8). Thus the coalition is unstable. Q.E.D.

A similar result -- often referred to as the "greed process" -- has been obtained by Hurwicz (1959, 1973). He shows that in a dynamic market where there is uncertainty about the environment, the dominant strategy of the firms is to participate in this market without behaving strategically. The environment is allowed to change over time, and the firms do not know which changes will take place. The existing prices in the market are based on the firms' current information.

Hurwicz's analysis applied to the emission permit market indicates it is in the firms' self interest to participate in a market for emission permits without behaving strategically. More specifically, if the price a firm is offered for a permit for an emission quantity is higher than the firm's marginal cost of reducing emissions, the dominant strategy for the firm is to sell emission permits.

### 4.3.4 Second-Best Pareto-Optimality

The suggested scheme is informationally efficient, a necessary condition for SBPO (Proposition 3.2). Propositions 4.1 and 4.2 show that it is the dominant strategy of the firm or a coalition of firms to buy emission permits such that each firm's stock of permits equals $z_n^*$, defined by the firm's demand curve for emission permits. As firms will buy and sell permits such that (4.8) holds, i.e. $\mu_t = r\ p_t^{\circ}$, it is possible for the regulatory agency to infer the optimal aggregate emission level, $Z_t^*$, by comparing the inferred price, $p_t^1$, from the damage function, $D_t(Z_t)$, with $r\ p_t^{\circ}$.

A system of marketable emission permits minimizes the producer's cost of reaching an overall targeted level of emissions compared to a system of Pigouvian taxes or direct regulation (Baumol and Oates, 1988). This is equivalent to maximizing producers' profits, given a certain emission level.

The proposed system also ensures that the optimal level of emissions, $Z^*$, is achieved, resulting in SBPO being achieved. This result follows from Spulber (1989). He showed that when the marginal costs of abatement equals its marginal benefits, the allocation is SBPO.

## 4.4 Issues Related to the Proposed Scheme

Despite the properties of the outlined RAM, there are some related issues that have yet to be commented on. These include:

(i) How often should quotas be adjusted?

(ii) The initial allocation of the aggregate emission quotas.

(iii) Entry and exit of firms.

(iv) Enforcement: The proposed RAM does not deal with the problem of firms complying with their quota, $z_{nt}$. A system for inducing compliance, which can be used jointly with the scheme in this chapter, is developed in chapter five.

(v) The experience with current markets for pollution permits is mixed, as firms have not always participated as expected (Roberts, 1982; Hahn and Noll, 1982; Hahn, 1989). Hahn (1983, 1989) claims that some of this lack of participation may be due to the complicated nature of these markets (pollution rights had limited lifetime and needed to be renewed etc.). These are compelling arguments to keep the markets for pollution permits as simple as possible. The proposed scheme does that. To the firms, the suggested pollution permit market operates like any other input market.

(vi) Long term management: The suggested RAM uses the consumers' current valuation of reduced emissions and does not deal with the problem of unknown environmental effects. This is a shortcoming of the proposed RAM. An approach to deal with this problem has been suggested by Constanza and Perrings (1989) where firms buy bonds before they can undertake projects which may have undesirable environmental consequences in the future.

The first three of these related issues are treated in more detail in the subsequent sections, while the fourth issue is the focus of chapter five. Issues (v) and (vi) have already been commented upon.

### 4.4.1 The Adjustment of the Aggregate Quotas

Recall that the initial quotas given to the firms, $z_t^0$, and the ex-trade quotas, $z_t^1$, are equivalent to property rights. Thus any profit maximizing agent will sell emission permits if this leads to an increase in expected discounted profits. For the proposed scheme to work, it is important that the agency not be able to take away any permit without a level of compensation that increases the above mentioned profits. Barring institutional change, this means that any firm can not be forced to give up their quotas. Any downward adjustment in the aggregate quota thus requires the regulatory agency to buy back emission permits for retirement.

One unresolved question is how often the regulatory agency should intervene and attempt to buy back (or sell) additional permits. In this connection it is important to remember that the damage function is estimated, for example through contingent valuation methods. As such it has certain statistical properties. Thus the observed market price for pollution control can be inside or outside the $1-\alpha/2$ confidence interval at the aggregate emission level $Z_t^0$. An illustration of this phenomena is given in the following figure:

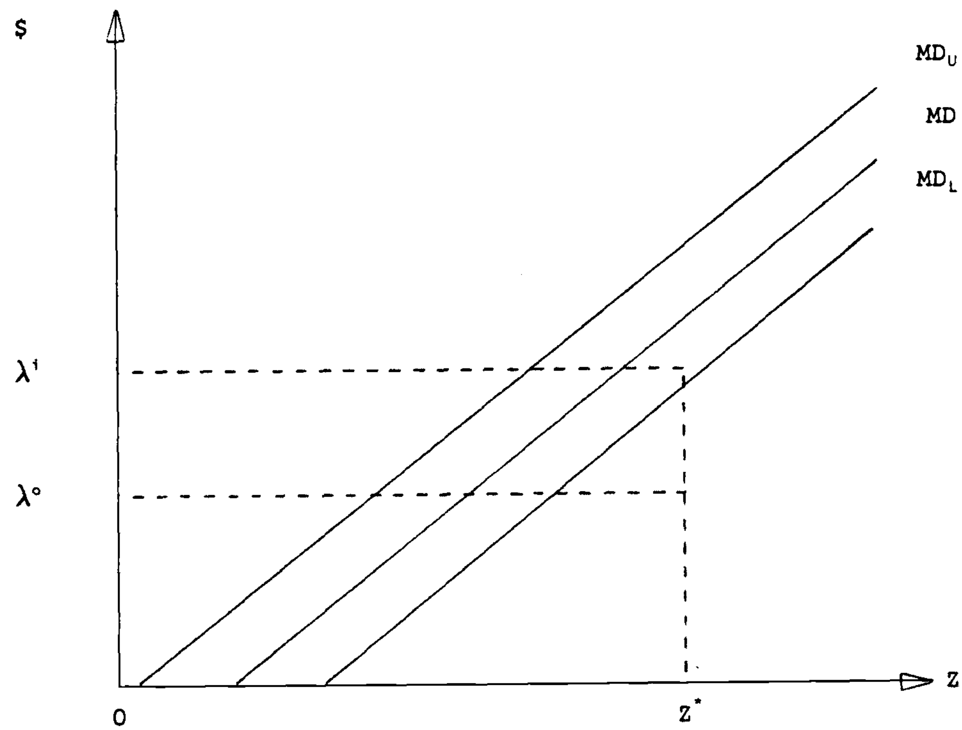


Figure 5: The market price for pollution permits times the interest rate is inside ($\lambda^1$) or outside ($\lambda^0$) the 1-$\alpha$/2 confidence intervals of the estimated damage function (MD).

Thus one may conclude that the agency should only seek to adjust the aggregate emission level if $\lambda_t$ is significantly different from the inferred price from the damage function.

In an intertemporal model, one must also allow for the marginal costs of abatement or the public's valuation of environmental amenities to change over time. For instance, due to technological progress, the firms' cost of pollution abatement may decrease. Keeping in mind the statistical variability in the estimated damage function, this once again means that the regulatory agency should buy permits for retirement if $\lambda_t$ falls below the inferred price given by the damage function, $D_t(Z_t)$.

4.4.2 Initial Allocation of Firm Quotas

Montgomery (1972) and Baumol and Oates (1988) show that a system of marketable pollution permits will lead to a least cost outcome irrespective of the initial firm quotas. This follows directly from the Coase theorem, which states that the introduction of property rights will lead to an efficient outcome independent of the initial allocation. Despite this, the distributional consequences of the original allocation are of importance. As an example consider a case where only a few firms were awarded emission permits while the majority of firms did not receive any such license. For this latter group of firms it is doubtful that the criterion of individual rationality would be met. Most likely these firms would form a lobbying group to get a different permit allocation. Loss of efficiency due to delays and costly bargaining procedures would be a probable outcome in such cases.

The early literature on marketable emission permits (Dales, 1968; Montgomery, 1972) suggests assigning individual firm quotas as a percentage of the firm's initial pollution level. Here a somewhat different approach is suggested: that each firm be given an initial allotment of pollution permits which equals the value of their market shares. The justification for this system of assigning individual firm quotas over assigning initial quotas as a percentage of past emissions is that the latter may lead to excess emissions just prior to the introduction of markets for emission rights.

A potential problem with the suggested principle of assigning initial firm quotas is that the informational costs may increase. This is probably not an important obstacle as the value of the individual firm's market shares are readily available through company reports, tax records etc.

4.4.3 Firm Entry and Exit

One argument against a system of quotas -- transferable or non-transferable -- is that it may affect firm entry and exit. Spulber (1985) shows that a system of tradeable permits among identical firms leads to a long-run industry equilibrium which is optimal. However, Spulber does not extend his analysis to a non-homogenous industry.

The polluting industry views the cost of effluent permits as society's marginal valuation of environmental services. This perspective is consistent with the picture given in Figure 2; the optimal level of emissions is the point at which the permit price equals the marginal damage function.

Now consider a non-homogenous industry. Without loss of generality let there be two types of firms. One group of firms uses a highly polluting technology and therefore requires a large number of permits to produce a certain quantity of output. The other type of firms use a less polluting technology. Entering firms can choose either of these two technologies. If the new firms choose the more polluting technology they need to obtain a larger number of permits. This will drive the price of pollution permits up more than will be the case if the entering firms choose the less polluting technology. Thus new firms are more likely to adopt this type of technology. The entrance of firms into the industry will, however, still drive the price of pollution permits up somewhat, and therefore the costs of production for firms using the more polluting technology increase more than the costs of firms applying the technology with less emissions. Thus firms characterized by the more polluting technology will reduce their production or exit the industry. All other things equal the prices of pollution permits drop. The discrepancy between the new permit price and the public's valuation of the damages incurred by emissions will cause the agency or environmental interest groups to buy permits for retirement as long as $r\ p_t^o < p_t^i$. Thus the new level of emissions , the number of firms and the choice of technology at any time is economically long run optimal. The proposed system of transferable pollution permits (where the aggregate quota is decided as indicated by Figure 4) therefore leads to a less polluting industry in the long run than would be the case under no regulation.

## 4.5 Conclusions

The proposed system of transferable pollution permits, matched with the public's valuation of pollution abatement, satisfies the desired properties of the resource allocation mechanism: (i) individual rationality, (ii) informational viability and efficiency, (iii) incentive compatibility (in the sense that firms will not seek to influence the market price for permits), and (iv) second-best Pareto-optimality. A necessary condition for SBPO to result is that the benefit (or damage) function entails both direct and indirect effects from emissions. Over time the abatement costs or the public's perception of the damages incurred from emissions may change. The proposed system is well suited to deal with these phenomena.

In the long run the marginal costs of abatement decreases with technological progress. This lowers the price on emission permits, and allows the regulatory agency to buy back permits for retirement. Consequently the proposed resource allocation mechanism leads to reduced emissions in the future.

The public's perceptions about the damages from emissions change over time may also change. Suppose there is increased public concern about the effects from emissions. This will shift the damage function in Figure 4 to the left or make the damage function steeper. In either case, the old emission level is excessive. Observing the inferred price being higher than the market price times the capital costs ($\mu$) (in Figure 4 indicated by $p^{\circ}$ ), the regulatory agency can once more buy back emission permits for retirement until $\mu$ equals $p^{1}$ .

Experience from existing markets for pollution permits, for instance in the Wisconsin Fox River area, underscores the importance of keeping the market as simple as possible if firms are to participate (Hahn, 1989), and presents an argument for emission permits over ambient or pollution offset permits. Another reason for non-participation in existing markets may be that firms already undertake some kind of dynamic optimization, treating the permits as an investment, but they are uncertain about the future value of this investment. Reasons for this may be that the property rights to emission permits are yet to be well defined in practice.

In the process of showing that the proposed system is incentive compatible with respect to participation in the emission permit market, additional insights have been gained regarding emission permit prices. Given a particular environment, the emission permit price, $p_t^\circ$, is the price consistent with firms maximizing their expected profits.

The proposed system does not ensure that firms comply with their assigned or ex-trade quotas. This is a necessary criterion for the system to satisfy the desired properties. Several mechanisms exist to ensure compliance on the average. Some of these mechanisms can easily be combined with this system of transferable pollution permits. One such mechanism is presented in chapter five.

# CHAPTER 5

## INDUCING INDIVIDUAL FIRM COMPLIANCE TO EMISSION QUOTAS WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE

The question of optimality of emission standards cannot be separated from the issue of compliance with these standards. In chapter four compliance with the environmental standards was initially assumed. Section 4.4 indicated that the problem of compliance needed to be resolved to attain the optimal emission levels. This research therefore seeks to design a system for monitoring compliance with emission quotas and for punishing non-compliers such that compliance is induced. During the design process the optimality of the pre-monitoring emission standard is questioned. Criteria for finding the optimal post-monitoring standard are developed. One of these criteria is the optimal level of non-compliance.

In principle the firm's degree of conformity depends upon the relative profits of compliance versus non-compliance. Any attempt at modelling firm behavior to pollution control must therefore incorporate these relative profits. The class of models known as principal-agent models, seeks to incorporate this principle in the design of the RAM.

The firms' relative profits are influenced by three factors; (i) the cost of abatement, (ii) the probability of being caught if in non-compliance, and (iii) the penalty if found in non-compliance. These three components have been treated separately in many papers, but little work has been done to handle these components jointly. Notable exceptions are Russell et al. (1986), Russell (1987) and Harrington (1988).

The relationship between detection and penalties are of particular interest in this case.

As mentioned the industrial process for pollution control is likely to have some variation around the targeted value. Thus if the regulatory agency were to penalize all violations of the emission standard and the penalties levied were prohibitively strict, the firm would set a target below the standard to ensure violations did not occur. Assuming the standard is optimal for society, suboptimal firm behavior would be the rule (Førsund and Strøm, 1980). The agency must therefore allow minor violations, but on the average, no major violations should occur. More specifically the agency must decide what constitutes an acceptable violation.

Russell et al. (1986), Russell (1987) and Harrington (1988) have all developed principal-agent models of compliance to environmental standards where stochastic emissions have been incorporated to some degree. None of these papers are explicit in determining the optimal standard. As mentioned in the literature review, these models do not incorporate all of the following aspects: a penalty function which allows for stochastic emissions and induces compliance for all emission levels above the acceptable limit, and a dynamic principal-agent model. The first objective of this chapter is to develop such a model. Second, a formal analysis of the proposed scheme as a RAM is undertaken. Of particular interest in this connection are the properties of incentive compatibility and SBPO.

The next section gives an outline of the proposed dynamic model for pollution control. In the succeeding section a single-period model for inducing compliance is presented. From this model analytical results can be derived. These results will enhance the understanding of the dynamic multi-period model developed in the following section. Finally the dynamic principal-agent model for pollution control is evaluated using the criteria for RAMs developed in chapter three.

## 5.1 An Outline of the Proposed Model for Pollution Control

The model proposed here follows the main principles of Greenberg's (1984) model for "avoiding tax avoidance". It differs from the Greenberg model and the above mentioned environmental enforcement models in three important aspects; (i) more emphasis is placed on creating a monitoring and enforcement scheme which meets the requirements of RAMs, (ii) the model incorporates stochastic monitoring errors on behalf of the principal (the regulatory agency) and stochastic emission errors on behalf of the agents (the firms), and (iii) escape from group three (firms with repeated non-compliant behavior) is possible without losing the intended incentives for compliance.

The principles of the model are:

(1) Firms in group one (habitual compliers) don't pay monitoring costs, and are monitored less frequently. If caught in violation of the environmental standard, the firm is moved to group two, and assessed a fine according to the pre-specified penalty function.

(2) Firms in group two remain there until they are monitored. If they

are caught violating the standard with the allowed justifications made for monitoring errors and variability in the pollution control process, they are moved to group three and fined as indicated by the penalty function. Otherwise they are moved to group one. Their monitoring probability does not exceed that of group one, and they pay the costs of being monitored.

(3) Firms in group three are monitored more often, and remain there until they have complied with the regulations in K consecutive monitoring periods. They are then moved to group two. As for firms in group two, group three firms pay their monitoring costs, and are fined in the same way.

In the typical principal-agent model, the principal seeks to derive rules to maximize some known objective function, subject to available information about the objectives of the agent(s) (Rasmusen, 1989). With respect to pollution control this means that the regulatory agency (the principal) develops a monitoring scheme and a penalty structure for violations that minimize the damages (maximize the benefits) from pollution, given the individual firms' (the agents') objective of maximizing profits.

When the measurement of emissions and the actual emission levels are stochastic, the regulatory agency must allow for minor violations to avoid firms choosing targeted emission levels that are sub-optimal. One of the problems facing the agency is therefore choosing an adjustment factor, $\alpha$, to obtain a non-punishable emission level in excess of the pre-monitoring optimal emission level.

Thus the regulatory agency's choice variables are $\alpha$, which denotes the allowed variability in emissions above the nth firm's target level for emissions, $z_n^*$ , the monitoring probability in group g, $\rho^g$ , the penalty function, and K, the number of successive time periods a firm in group three has to comply before it is moved to group two.

## 5.2 A Single-Period Principal-Agent Model for Inducing Compliance to Environmental Standards

It is generally difficult to obtain analytical solutions to the multi-period dynamic game of pollution control. However, it is possible to obtain these results for the single-period game. The nature of these analytical results carries over to the dynamic multi-period game, and gives valuable insights regarding the multi-period game.

The assumptions made in section 3.1 about the firms' behavior and their production technologies with and without externalities apply throughout this chapter.

Let $Z^*$ denote the optimal aggregate level of one pollutant in the economy when the costs of environmental enforcement are not included. $Z^*$ could, for instance, have been found by the method suggested in chapter four. Each firm has a quota, $z_n^*$ , such that $\Sigma_{n\in N} z_n^* = Z^*$ . The individual firm quota, $z_n^*$ , is assumed to be the optimal emission level for each firm when the aggregate emission level $Z^*$ is not exceeded.

Under no constraints on the individual firm emissions, each firm emits $z_n'$ , where $z_n'$ is the solution of (3.4). Assume that $\Sigma_{n\in N} z_n' = Z'$ $> Z^*$ . With no monitoring and no penalty for violating the emission quota, $z_n^*$, it is assumed that the firms could increase their profits by emitting $z_n'$.

In the deterministic setting it is trivial to achieve compliance. By making the penalty of any violation severe enough, no violations will occur. This is known as the "hanging the criminal with probability zero" proposition (Becker, 1968). As mentioned in section 2.3, Shavell (1987) shows that when the enforcing authority has imperfect information, penalties will be levied. Under imperfect information Shavell therefore suggests that the penalties should be proportional to the harm done.

In the pollution control principal-agent model, the regulatory agency seeks the emission level that maximizes net benefits, while the firms are assumed to maximize their profits. The purpose is to induce firms to comply with their allowed emission level $z_n^*$, by modifying the firms' profit functions. Using Shavell's result, one way of modifying the profit function is to add a penalty function, $h(\bullet)$, and to monitor each firm with the probability $\rho$.

In order not to violate the privacy preserving requirement, the agency's imperfect information takes the form that the agency knows which technology, $\theta$, produces the most output for a given level of emissions, but the agency cannot observe the type of technology each firm uses, j. Most industrial processes, including those for pollution control, do not function perfectly; there is a tendency for variation, $\sigma_\theta$, around the targeted value, where $\theta \subset J$. By the same reasoning, for the variation in emissions around the targeted value, one would also expect some variation in the measurement of the emissions, $\sigma_M$. As the errors in the monitoring process and the control procedure of emissions are independent, the overall variance around a target value for emissions is $\sigma^2 = \sigma_\theta^2 + \sigma_M^2$. For simplicity assume that the distributions of the emission control errors and the measurement errors are normal. Consequently the overall errors are normally distributed, and the allowed emission level, $z_n^U$, depends on how strict the agency is in setting the standard. More specifically:

$$z_n^U = z_n^* (1 + z_{1-\alpha} \sigma) \tag{5.1}$$

where $\alpha$ indicates the percentile for not violating the standard.

Obviously $\alpha$ is a choice variable for the agency in the depicted stochastic emissions model. (5.1) also gives some assistance in specifying the penalty function, $h(\bullet)$, as only $z_n > z_n^U$ constitutes a violation. A profit maximizing firm solves the first order conditions of the profit function to obtain the profit maximizing level of output. Hence the penalty function must be increasing in the violation to deter large violations. Jones (1989) shows that in order to induce compliance over the whole range of potential emission levels for the firm, the penalty function, $h(\bullet)$, must be increasing at an increasing rate in the severity of the violation, i.e. $\partial h(\bullet)/\partial z_n > 0$ and $\partial^2 h/\partial z_n^2 < 0$. The profit maximizing output is also a function of the product price, p, such that $\partial y/\partial p > 0$. One penalty function, $h(z_n;p)$ which satisfies the above criteria is:

$$h(z_n;p) = \omega(p) \; [\mathrm{MAX}(0, z_n^2 - z_n^{U\,2})] \tag{5.2}$$

where $\omega(p)$ is a constant for a certain price such that $\partial\omega/\partial p > 0$.

All the pieces in setting up a principal-agent model for the stochastic emission control problem have now been gathered. The agency seeks to maximize societal welfare subject to firms maximizing a revised profit function. The following figure illustrates the game tree of the single-period principal-agent model to the above problem:

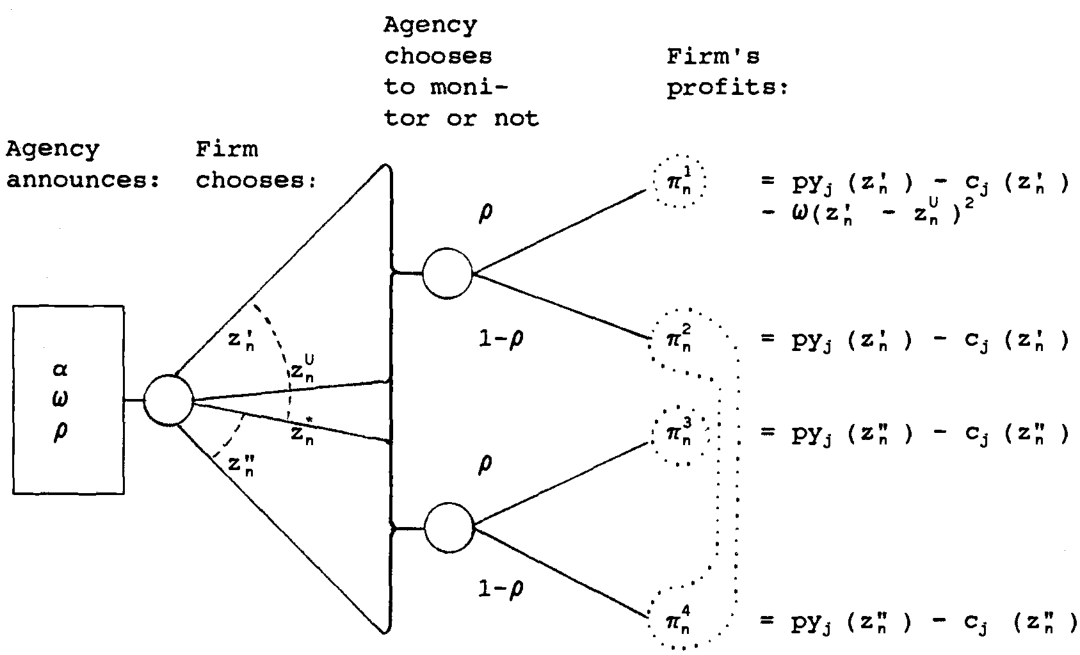


Figure 6: The game tree of the single-period principal-agent model[16], where $\pi^1_n < \pi^3_n = \pi^4_n < \pi^2_n$ , and

$z'_n$ is the firm's emission level, intending not to comply

$z''_n$ " " " " " , intending to comply

$\pi^1_n$ profits under intended cheating when caught

$\pi^2_n$ " " " " " not caught

$\pi^3_n = \pi^4_n$ profits under intended compliance.

[16] Areas bounded by dotted lines represents the agency's information sets.

The game tree in Figure 6 shows the order in which the regulatory agency and the firms make their decisions. When the agency does not monitor, it does not know if the firm cheated or not. Consequently $\pi_n^2$ and $\pi_n^4$ constitute one information set for the agency.

Mathematically the model becomes:

Regulatory agency: $$\max_{\alpha,\rho,\omega} \{B(Z,p,X;p^\circ \cdot Z^\circ) - \rho N C_m\} \qquad (5.3)$$

st.

Firms $$\left\{ \begin{array}{l} \max_{z_n} \pi_{jn} = py_j(z_n) - C_j(z_n) \\ \quad - \rho\omega(p)\text{MAX}[0, (z_n(1+e_j))^2 - (z_n^*(1+z_{1-\alpha}\sigma))^2] \end{array} \right. \qquad (5.4)$$

where $B(\bullet)$ is a pre-estimated benefit function in monetary terms (3.11),

$C_m$ is the cost of monitoring, and

$e_j$ is the variation in emissions for technology j.

(5.4) is necessarily not continuously twice differentiable in $z_n$. It may therefore not be appropriate to solve (5.4) for the firm's profit maximizing emission level using the first order conditions. An alternate approach is to formulate (5.4) as a constrained optimization problem, using a Kuhn-Tucker formulation. The firm's maximization problem then becomes:

$$\left. \begin{array}{ll} \max_{z_n} & \pi_{jn} = py_j(z_n) - C_j(z_n) \\ \text{st. (i)} & [z_n(1+e_j)] \leq [z_n^*(1+z_{1-\alpha}\sigma)] \\ \text{(ii)} & \rho\omega(p)[z_n^*(1+z_{1-\alpha}\sigma)]^2 \leq \rho\omega(p)[z_n(1+e_j)]^2 \end{array} \right\} (5.5)$$

where either constraint (i) or (ii) is met, i.e. they cannot be met simultaneously.

In this case of pollution control, constraint (ii) is the most interesting as it depicts a situation in which the firm could increase its profits by emitting more than its allowed level, $z_n^U$. The solution to (5.5) using constraint (ii) is:

$$z_n \geq z_n^* \quad \frac{(1 + z_{1-\alpha}\sigma)^2}{(1 + e_j)^2} \tag{5.6}$$

$$\lambda_{ii} = [2z_n \rho\omega(p)(1 + e_j)^2]^{-1} [p\, \partial y_j / \partial z_n - \partial C_j / \partial z_n] \geq 0 \tag{5.7}$$

where $\lambda_{ii}$ is the Lagrangian multiplier for constraint (ii). From (5.6) it follows that if $|e_j| < z_{1-\alpha}\sigma$, the firm's optimal emission level is more likely to exceed $z_n^*$, and conversely if $|e_j| > z_{1-\alpha}\sigma$. Thus if the agency chooses an $\alpha$ which allows for a large variation around the agency's target for the individual firm's emissions, the following occurs:

a) The likelihood of getting an aggregate emission level above the exogenously desired level, $Z^*$, increases.

b) The number of firms being caught in violation is reduced.

From (5.7) it follows that

$$\partial\lambda_{ii} / \partial\rho < 0 \text{ for all } e_j \tag{5.8}$$

and

$$\partial\lambda_{ii} / \partial\omega(p) < 0 \text{ for all } e_j \tag{5.9}$$

(5.8) and (5.9) show that cheating becomes less desirable as $\rho$ or $\omega$ is increased.

As (5.4) may not be twice continuously differentiable, first order conditions may be inappropriate to obtain the firm's emission level, $z_n$. This is a common problem in principal-agent models. Grossman and Hart (1983) therefore suggest obtaining the necessary conditions for compliance (the appropriate choice of $\rho$ and $\omega(p)$) by finding the conditions for the expected profits in the revised profit function (5.4) to exceed those of the unconstrained profit function (3.4). Let $z_n'$ denote the profit maximizing solution of (3.4). Without loss of generality assume that the unconstrained emission level exceeds the allowable emissions, that is $z_n' > z_n^* (1 + z_{1-\alpha}\sigma)$. In this single-period principal-agent model for emission control, this yields:

$$\rho(\alpha) = \frac{[p\, y_\theta (z_n') - C_\theta (z_n')] - [p_t\, y_\theta (z_n^*) - C_\theta (z_n^*)]}{\omega(p)[z_n'^2 - (z_n^* (1 + z_{1-\alpha}\sigma))^2]} \qquad (5.10)$$

Obviously (5.10) confirms the previously mentioned inverse relationship between the monitoring probability and the penalty. More interesting in this case is that the monitoring probabilities and the necessary fine are conditional upon $\alpha$. Choosing an $\alpha$ which allows for large variations around the targeted emission level increases the monitoring probability or the fine needed to induce compliance.

Another important insight coming from this single-period model is that the exogenously determined aggregate emission level, $Z^*$, may no longer be optimal. This can be seen by examining (5.3), the agency's objective function, as an increased monitoring probability increases the overall monitoring costs, thus reducing overall societal welfare.

## 5.3 A Dynamic Model of Firm Behavior and Regulatory Agency Response

The assumptions in the previous section about the firms and the regulatory agency still apply, as does the specification of the penalty function, $h(z_{nt}; p_t)$ (5.2). The single-period profits of a j type firm in group g can then be written as:

$$\max_{Z_{nt}} \pi^g_{jnt} = p_t\, y_j\,(z_{nt}) - C_j\,(z_{nt}) - \rho^g\,[h(\bullet) + C^g_m] \tag{5.11}$$

where $C^g_m$ is the monitoring costs such that $C^1_m = 0$, $C^1_m > 0$ for $g = 2$ or $3$, and

all other terms remain as specified in the profit function (3.4) for the single-period model presented earlier.

Let $C_\theta\,(\bullet)$ be the cost function for the $\theta$ technology. The single period profit function for any firm is viewed by the regulatory agency as:

$$\max_{Z_{nt}} \pi^g_{\theta t} = p_t\, y_\theta\,(z_{nt}) - C_\theta\,(z_{nt}) - \rho^g\,[h(\bullet) + C^g_m] \tag{5.12}$$

For simplicity and without loss of generality, assume that the firm's and the agency's time horizon coincide, i.e. $t \in \{0,1,\ldots,T\}$. Denote this set $T$. The form of the multi-period principal-agent model does not differ much from the single-period model:

Regulatory agency:

$$\max_{\alpha,K,\omega,\rho^g} \Sigma_{t\in T}\ \beta^t\ \{B(Z_t, p_t, X_t; p^\circ\,{}^\prime Z^\circ) - \Sigma^3_{g=1}\,\rho^g f^g N\, C_m\} \tag{5.13}$$

st.

Firms

$$\left\{ \begin{array}{l} \max_{\{z_{nt}\}} \Sigma_{t\in T}\ \pi_{jnt} \\ = \Sigma_{t\in T}\ \beta^t\ \{p_t\, y_j\,(z_{nt}) - C_j\,(z_{nt}) \\ -\ \rho\omega(p_t)\mathrm{MAX}[0,\ (z_{nt}\,(1 + e_j))^2 - (z^*_{nt}\,(1 + z_{1-\alpha}\,\sigma))^2\,]\} \end{array} \right. \tag{5.14}$$

where $\beta$ $= (1 + r)^{-1}$ is the discount factor and $r$ is a risk free nominal interest rate,

$f^g$ is the fraction of firms in group $g$, $g \in G$, and

$B(\bullet)$ is defined by (3.11).

Incentive compatibility of the suggested scheme, (5.13) and (5.14), can be achieved in many ways. The reason for this is that the agency has more choice variables than it has equations to solve, while the individual firm seeks to maximize one equation, (5.14). The first problem is therefore to find the agency's most efficient combined choice of parameter values. More specifically, this involves choosing a vector, $\lambda = [\alpha, K; \rho^g, \omega]$, $g \in G$, such that (5.13) is maximized.

According to the first simple single-period model, equations (5.3) and (5.4), there are several tradeoffs which can be made with respect to the choice of the policy parameters. Examples of these tradeoffs are monitoring probabilities and penalties, the allowed variability (the agency's choice variable is $\alpha$) and the monitoring probabilities, and the allowed variability and expected monitoring costs. Solving (5.13) and (5.14) analytically is not easy. Such a task may even prove to be impossible. Thus obtaining the optimal combination of the agency's choice variables numerically, fixing some parameter(s), and doing a grid-search are suggested. Even this may not be trivial. The procedures of the suggested solution path are as follows: (i) choose $\alpha$ and K, (ii) choose $\rho^3$ such that single-period compliance[17] in group three is achieved for a given $\omega$, (iii) choose $\rho^2$ such that multi-period compliance[18] in group two is achieved for the same $\omega$ and K, (iv) choose $\rho^1$

[17] Single-period compliance means that compliance is the dominant strategy of the firm irrespective of the dynamic nature of the model.

[18] Multi-period compliance means that compliance is the dominant strategy of the firm when the consequences of current actions on future expected profits are considered.

such that multi-period compliance in group two is achieved for the same $\omega$ and K, (v) find the Markov-stationary fractions of firms in each group, $f^g$, expressed as function of the monitoring probabilities, $\rho^g$, and (vi) calculate the expected value of (5.13) for various $\lambda(\alpha,K;\omega,\rho^g)$, $g \in G$.

One important difference between the single-period and the multi-period model is worth noting; the j-type firm's multi-period optimal emission level needs to incorporate the probability of moving from one group to another, as the expected profits in each group varies. Determining compliance in one time period, t, is equivalent to testing the hypothesis $H_0 : z_{nt} \leq z^*_{nt}(1 + z_{1-\alpha})$, against the alternative hypothesis $H_1 : z_{nt} > z^*_{nt}(1 + z_{1-\alpha})$. The probability of the nth firm staying in group g, g = 1, 2 or 3, after having been monitored once, equals the sum of the probability of a type I error (falsely rejecting $H_0$ when it is true) plus the probability of a type II error (wrongly accepting $H_0$ when it is false). These probabilities can be expressed in terms of the values of the power function, $\phi(\alpha,z_{nt})$. As will be demonstrated when investigating Markov-stationarity, this notation is very convenient. The power function is defined as the value of falsely rejecting $H_0$ when it is true and the value of falsely accepting $H_0$ when it is false (Freund and Walpole, 1980). By (5.14) the j type firm chooses $z_{nt}$ to maximize its expected profits. Obviously this emission level must incorporate the probabilities of being moved from one group to another.

It is also important to recall that the agency does not know the fraction of the firms using technology j, $j \in J$, nor does it know the individual firm's choice of technology. Substituting $\theta$ for j, the agency is able to figure out the optimal emission level for a $\theta$-type firm, expressed as a function of the policy parameter vector $\boldsymbol{\lambda}$ = $[\alpha,K;\omega,\rho^g]$, under various scenarios. Denote this emission level $z^x_{\theta t}$, where x denotes the chosen scenario.

5.3.1 Single-Period Compliance in Group Three

Intuitively the larger the proportion of firms in groups one and two, the greater the savings in monitoring costs. As will be demonstrated later, single-period compliance in group three induces multi-period compliance for firms in groups one and two without having excessive penalties for violation of the emission standard.

Due to institutional factors, Harrington (1988) suggests there is a maximum penalty for a given violation that can be implemented without costly litigation or years spent "horse-trading" in the legislature. Denote this penalty $\omega^*$, and assume it is known. As indicated for the single-period model, there is a tradeoff between the monitoring probability and the penalty (5.10). Given $\omega^*$ it is therefore possible to obtain the necessary monitoring probability for single-period compliance for the multi-period model (5.14). Once again using the solution procedures suggested by Grossman and Hart (1983), comparing the expected profits for a $\theta$-type firm in group three which intends to comply versus one that intends to cheat, one can solve for the necessary monitoring probability, $\rho^3$. As before, let $z^*_{\theta t}$ denote the compliant emission level and let $z^?_{\theta t}$ denote the unconstrained (non-compliant) profit maximizing emission level for a single-period game. Using the same functional form for the penalty function (5.2), the optimal $\rho^3$ given $\alpha$ and $\omega^*$ yields:

$$\rho^3(\alpha) = \frac{[p_t\ y_\theta(z'_{\theta t}) - C_\theta(z'_{\theta t})] - [p_t\, y_\theta(z^*_{\theta t}) - C_\theta(z^*_{\theta t})]}{\omega^*(p_t)\ [z'^2_{\theta t} - (z^*_{\theta t}(1 + z_{1-\alpha}\sigma))^2] + C_m} \qquad (5.15)$$

Let $\rho^3_\theta$ denote the solution of (5.15).

### 5.3.2 Multi-Period Compliance in Group Two

In the previous section the condition for single-period compliance in group two was established. This result can now be used to obtain the necessary $\rho^2$ for multi-period compliance in group two, for a given $\alpha$ and a given K, a known $\omega^*$ and $\rho^3_\theta$. The condition for multi-period compliance in group two is that the expected discounted profits of a firm intending to comply in group two must be larger than the same profits for a firm intending to cheat while in group two.

The probability of being monitored in group g, $\rho^g$, is uniformly distributed. Thus the expected time before being monitored in group g is the solution of:

$$\tfrac{1}{2} = (1-\rho^g)^{T_g},\ g \in G \qquad (5.16)$$

For simplicity assume that $T_g$ is an integer.[19] $\rho^3_\theta$ is chosen such that single-period compliance in group three is the dominant strategy for the firm. Therefore the condition for multi-period compliance in group two is that the expected profits for compliance in group two for the

[19] One way of getting around $T_g \in N_+$ is to solve for $\kappa$ in $(1-\kappa)\Im(T_g) + \kappa[\Im(T_g) + 1] = T_g$, where $\Im(T_g)$ is a function returning the integer part of $T_g$. The discrete time discounted maximization in group i is then equivalent to $\Sigma^T_{t=0}\, \beta^t(\bullet) + \kappa\beta^{T+1}(\bullet)$.

expected time without monitoring ($G_2$ c^m) plus its compliant profits when monitored ($G_2$ cm) must exceed the sum (a) through (d).

(a) the expected non-compliant profits of the expected time in group two without monitoring ($G_2$ n^m),

(b) the profits of detected non-compliance in the last time period in group two ($G_2$ nm) (before being moved to group three),

(c) the profits of compliance while in group three without being monitored ($G_3$ c^m), and

(d) the same profits minus the cost of being monitored in group three ($G_3$ cm) (before being moved to group two).

Mathematically this becomes:

$$\left.\begin{array}{ll}
\sum_{t=0}^{T-1} \beta^t \pi_\theta (Z_{\theta t}^*) + & (G_2 \text{ c\^{}m}) \\
\beta^T [\pi_\theta (Z_{\theta T}^*) - C_m] > & (G_2 \text{ cm}) \\
\sum_{t=0}^{Ta} \quad \beta^t \pi_\theta (Z_{\theta t}') + & (G_2 \text{ n\^{}m}) \\
\beta^{Ta+1} \; [\pi_\theta (Z_{\theta Ta}^*) - C_m] + & (G_2 \text{ nm}) \\
\sum_{k=1}^{K} \sum_{t=Tb}^{Tc} \; \beta^t \pi_\theta (Z_{\theta t}^*) + & (G_3 \text{ c\^{}m}) \\
\sum_{k=1}^{K} \beta^{Tc+1} \; [\pi_\theta (Z_{\theta Tc+1}^*) - C_m] & (G_3 \text{ cm})
\end{array}\right\} \quad (5.17)$$

where Ta = $0,1,\ldots,T_2 -1$,

Tb = $Ta + (k+1) + (k-1)T_3$ ,

Tc = $T_a + k(T_3 +1)$,

k = 1,2,...,K, where K is number of successive periods in group three found in compliance,

T = Tc + 1, where k = K,

$T_g$ is defined in (5.16),

$\pi_\theta$ has the form of (3.4), $\theta$ replacing j, and terms in brackets to the right indicate group, compliance or non-compliance and monitored or not, as previously defined.

Obviously (5.17) must be solved numerically, as $\rho^2$ enters in both the profits equation and in some of the boundary conditions on the time. A suggested starting value for $\rho^2$ is $(1/x)\rho_\theta^3$ , x > 2, as cost savings over a single-period compliance model implies $\rho^2 < \rho_\theta^3$ . Let $\rho_\theta^2$ denote the solution of (5.17).

5.3.3 Multi-Period Compliance in Group One

Having found the condition for multi-period compliance in group two, it is possible to establish the same condition for group one. The approach follows that of group two. Multi-period compliance in group one implies that the expected profits under compliance for the expected time without monitoring in group one ($G_1$ c^m) plus the expected profits under compliance for the expected time of monitoring ($G_1$ cm) must exceed the sum (a) through (d).

(a) the expected profits under non-compliance for the expected time without monitoring while in group one ($G_1$ n^m),

(b) the expected profits of non-compliance in the expected last time period in group one ($G_1$ nm) (before being moved to group two),

(c) the expected profits of compliance of the expected time without being monitored while in group two ($G_2$ c^m), and

(d) the same profits minus the cost of being monitored in the expected last time period in group two ($G_2$ cm) (before being moved back to group one).

As group one firms do not pay monitoring costs, compliance under the expected time without and with monitoring can be treated jointly. Let ($G_1$ c) denote this case. Mathematically this becomes:

$$\left.\begin{array}{ll} \Sigma_{t=0}^{T} \quad \beta^t \pi_\theta (z^*_{\theta t}) > & (G_1\ c) \\ \Sigma_{t=0}^{Ta} \quad \beta^t \pi_\theta (z^*_{\theta t}) + & (G_1\ n\hat{\ }m) \\ \beta^{Ta+1} \quad [\pi_\theta (z^*_{\theta Ta+1}) - C_m] + & (G_1\ nm) \\ \Sigma_{t=Ta+2}^{Tb} \quad \beta^t \pi_\theta (z^*_{\theta t}) + & (G_2\ c\hat{\ }m) \\ \beta^T \quad [p_T\, y_\theta (z^*_{\theta T}) - C_\theta (z^*_{\theta T}) - C_m] & (G_2\ cm) \end{array}\right\} \quad (5.18)$$

where Ta $= T_1 - 1$,

Tb $= Ta + 1 + T_2$,

T $= Tb + 1$,

$T_g$, is defined in (5.16), and

terms in brackets to the right indicate group, compliance or non-compliance and monitored or not.

As was the case for (5.17), (5.18) must be solved numerically, as $\rho^1$ enters in both the equation for the profits and in some of the boundary conditions on the time. The suggested starting value for $\rho^1$ is $\rho^2_\theta$. Let $\rho^1_\theta$ denote the solution of (5.18). Reduced monitoring costs imply that $\rho^1_\theta < \rho^2_\theta$.

Depending upon the relative profits in group one under non-compliance and group two under compliance, the necessary monitoring probability in group one, $\rho^1_\theta$, may exceed $\rho^2_\theta$. If this is the case, there is no reduction in monitoring costs by having group one. This group should then be dropped, and the model reduces to a two-group scenario (with groups two and three). To maintain the property of individual rationality, group two firms should then not pay their own monitoring costs.

### 5.3.4 Obtaining the Fractions of Firms in the Various Groups

The agency has already found the monitoring probabilities needed in group one, two and three for the $\theta$ technology, conditional on $\omega^*$ for various levels of $\alpha$ and K, $\rho_\theta^g(\alpha,\omega^*,K)$, $g \in G$.

The Markov-transition matrix for the $\theta$ technology can now be expressed as:

| | $G_1$ | $G_2$ | $G_3$ |
|---|---|---|---|
| $G_1$ | $1-\phi(\alpha,z_{\theta_n})\rho_\theta^1$ | $\phi(\alpha,z_{\theta_n})\rho_\theta^1$ | 0 |
| $G_2$ | $(1-\phi(\alpha,z_{\theta_n}))\rho_\theta^2$ | $1-\rho_\theta^2$ | $\phi(\alpha,z_{\theta_n}))\rho_\theta^2$ |
| $G_3$ | 0 | E | 1-E |

where $G_g$, $g \in G$, in the left column indicates the starting group, and the row $G_g$, $g \in G$, indicates resulting group, and E is the probability of escaping group three, conditional on $\omega$ and K. E becomes:

$$E = (1-\phi(\alpha,z_{\theta_n}))^K \rho_\theta^3 \tag{5.19}$$

Markov-stationarity implies that the number of firms entering and exiting between two groups must be equal. This is equivalent to solving the following system of equations:

$$\left.\begin{array}{lr} f^1\phi(\alpha,z_{\theta_n})\rho_\theta^1 = f^2(1-\phi(\alpha,z_{\theta_n}))\rho_\theta^2 & \text{exit 1 = entry 1} \\ f^2\phi(\alpha,z_{\theta_n})\rho_\theta^2 = f^3\ E\ \rho_\theta^3 & \text{exit 3 = entry 3} \\ \Sigma_{g=1}^3 f^g = 1 & \text{sum of fractions is one} \end{array}\right\} \tag{5.20}$$

Denote the solution of (5.20) $f^g(\alpha,K,\omega^*;\rho_\theta^g)$, $g \in G$.

## 5.4 An Evaluation of the Suggested Monitoring Scheme as a RAM

The desired properties of a RAM (section 3.4) are:

(i) individual rationality,

(ii) informational viability and efficiency,

(iii) incentive compatibility, and

(iv) second-best Pareto-optimality.

An additional desirable property of the proposed scheme for inducing compliant behavior is that the regulatory agency should be self-financed. This means that the revenues the agency generates from monitoring fees and fines levied should cover its expenses. This property is important because it provides incentives for the agency to catch violators and makes the agency independent of public funds. In a deterministic setting this criterion is easily met. Myerson (1979) showed that in a situation where the percentage of violators varies stochastically, this criterion has to be relaxed to that on the average the regulatory agency is self-financed.

### 5.4.1 Individual Rationality

The requirement that the proposed RAM is individually rational is not satisfied as firms' profits would be higher if they could emit freely. By modifying this property to apply to all firms that intend to emit less than the proposed pollution standard, these firms would not be worse off. This modified property however is of great importance. Suppose the proposed RAM is not individually rational for some hypothetical firms that abide by the stated emission standards. These firms would deem it unfair that they would have to suffer for any adjustments other firms would have to undertake. It is even possible that the proposed RAM would never materialize if the industry as a whole could show that all firms would suffer as a result of the actions of a few firms.

Under this definition of individual rationality, the proposed scheme is individually rational by construction as no firm in group one pays its monitoring costs. Thus any firm intending to comply is equally well off under the proposed monitoring and penalty scheme as they would be under no monitoring.

### 5.4.2 Informational Viability and Efficiency

The proposed scheme is also informationally viable by construction. From (5.13) and (5.14), the information needed by each firm to make a rational output decision is: (i) their own cost relationship, $C_j(z_{nt})$, (ii) their own emission limit, $z^*_{nt}$, (iii) their own variability, $e_j$, around their emission limit (iv) the prescribed allowed deviation in emissions, $z_{1-\alpha}\sigma$, (v) the probabilities of being monitored, $\rho^g$, $g \in G$, (vi) the penalty for violations, (vii) the time spent in group three under compliance before being returned to group two, K, and (vii) the product price, $p_t$. This information space is finite and privacy preserving from the firms' perspective. Comparing (5.11) and (5.12), the difference between the information space of the firm and the agency is the cost function. The firm's cost function, $C_j(z_t)$, is replaced by

$C_\theta(z_t)$. Thus the privacy preserving requirement is satisfied. As long as the number of firms is finite, the agency's information space is also finite by construction.

From the individual firm's perspective the proposed scheme is informationally efficient. In any system of environmental control, each firm needs to know its own abatement costs. All other necessary information (the monitoring probability in each group, the number of consecutive monitoring periods in group three and the specification of the penalty function) are provided at little or no costs from the agency.

The agency's costs of establishing the appropriate monitoring probabilities and penalties are also needed in any monitoring scheme. The costs of keeping past records of the firms, i.e. which group each firm belongs to, is assumed negligible. Thus the proposed scheme is informationally efficient from the viewpoint of the regulatory agency.

### 5.4.3 Incentive Compatibility

Sections 5.3.1 through 5.3.3 establish the conditions for the expected profits of compliance to exceed the expected profits of non-compliance. The proposed scheme thus satisfies the property of incentive compatibility.

### 5.4.4 Second-Best Pareto-Optimality

A true welfare comparison of various monitoring schemes would include comparing societal welfare of these schemes, i.e. a joint consideration of the reduction in emissions and the monitoring costs incurred. This would be equivalent to investigating SBPO.

Let $\{Z_t'\}_{t\in T}$ denote the emission level resulting from the policy parameter vector $\boldsymbol{\lambda}^*$. Moreover, let $\{Z_t''\}_{t\in T}$ be the emission level resulting from any other monitoring scheme at its optimal vector of policy parameters, $\boldsymbol{\mu}^*$. From definition 3.4, replacing $V(\mathbf{p},X_i)$ with the net benefit function, $B_i(Z,\mathbf{p},X_i;\mathbf{p}^\circ,Z^\circ)$ (3.11), the proposed scheme is SBPO over any other scheme if:

$$\left.\begin{array}{l} \{\sum_{t\in T} \beta^t \{B(Z_t,\mathbf{p}_t,X_t;\mathbf{p}^\circ \cdot Z^\circ) - \sum_{i=1}^{3} \rho^g f^g N\, C_m\}\} \,|\boldsymbol{\lambda}^* > \\ \{\sum_{t\in T} \beta^t \{B(Z_t,\mathbf{p}_t,X_t;\mathbf{p}^\circ \cdot Z^\circ) - E(C_M(\bullet))\}\} \,|\boldsymbol{\mu}^* \end{array}\right\} \qquad (5.22)$$

where $E(C_M(\bullet)$ is the expected monitoring costs for any alternate scheme,

holds. Obviously, it is difficult to obtain any analytical results from (5.22). As mentioned earlier, the incentive compatibility constraints may cause $\{Z_t'\}_{t\in T}$ to differ substantially from the pre-monitoring optimal levels $\{Z_t^*\}_{t\in T}$. There may exist cases where these large deviations are not acceptable, for example on ethical grounds.

An alternate way of comparing the various schemes is therefore to set a prescribed level of aggregate emissions. Let $\{Z_t'\}_{t\in T}$ denote these emission levels. Moreover let $\boldsymbol{\lambda}'$ be a parameter vector of the proposed scheme yielding $\{Z_t'\}_{t\in T}$. Now the question is if there exists any other scheme which achieves $\{Z_t'\}_{t\in T}$ at less cost. The expected monitoring costs of the proposed scheme is

$$E(C_M) = \Sigma_{g \in G} \rho_\theta^g f^g(\lambda^*) C_m N \qquad (5.23)$$

(5.23) will be compared with the expected monitoring costs of a single-group model.

#### 5.4.4.1 Comparison of the Expected Monitoring Costs: The Single-Group Model

In the single-group model, the firms' strategies will be based on single-period compliance, as the only consequence of exceeding the standard is a fine. Assume that $\omega^*$, the maximum penalty coefficient in the penalty function (5.2) and the penalty function itself are the same for the single-group scheme and the proposed model. Obviously the necessary monitoring probability for a given level of compliance in the single-group model, $\rho_\theta$, equals the monitoring probability in group three in the proposed scheme. Provided there exists a monitoring probability in group two in the multi-group model that is less than the monitoring probability in group three, i.e. $\rho_\theta^2 < \rho_\theta^3 = \rho_\theta$, the proposed scheme has lower monitoring costs than the single-group model. Clearly then:

$$\Sigma_{g \in G} \rho_\theta^g f^g(\lambda^*) C_m N < \rho_\theta C_m N \qquad (5.24)$$

#### 5.4.4.2 The Expected Societal Welfare for a Given Vector of the Agency's Choice Variables

Maximizing societal welfare is equivalent to maximizing (5.13) choosing $\alpha$. For each $\alpha$ there exists a policy parameter vector $\lambda(\alpha)$ =

$[K,\omega,\rho^g]$, $g \in G$, by the results indicated by (5.15) through (5.19) such that Markov-stationarity holds, and $\Sigma_{g=1}^{3} f^g = 1$. Evaluating (5.13) for various $\alpha$ and consequently for $\lambda(\alpha) = [K,\omega,\rho^g]$ is done numerically.

The results for the simple single-period model, equations (5.6) through (5.10), give some insights into choosing $\alpha$. The most important result in this connection is that choosing an $\alpha$ that reduces the needed monitoring probabilities and fine level to induce compliance, is likely to increase the variability in the firms' emission levels and thus the variability in the aggregate emission level, $Z_t$. In other words $Z_t$ may exceed the optimal aggregate emission level when compliance is not considered, $Z_t^*$. This is not a surprising result. The reason for this is that the incentive compatibility constraints of the principal-agent model may yield an outcome that is not Pareto-optimal (Laffont, 1988).

The optimality of the suggested monitoring scheme may be challenged on the grounds that the regulatory agency uses the $\theta$ technology in deriving the policy parameter vector $\lambda^*$, instead of the firms' actual technologies, j, $j \in J$. As mentioned before, allowing the agency this information violates the privacy preserving requirement needed for informational viability. Thus any informationally viable monitoring scheme will initially display this characteristic. An interesting question in this connection is whether this problem can be corrected.

Over time the agency may be able to learn the individual firm's true type, j, and thus the distribution of the J technologies among the firms. More specifically this learning process will include using Bayesian statistics, where the agency's prior of any firm's technology is $\theta$. As data on each firm's actual emission decisions become available

through the monitoring process, assuming that each firm chooses an emission level that maximizes its profits under technology j, the discrepancies between the observed emission level under the unknown j, and the expected emission level under $\theta$, makes it possible for the agency to figure out j or a technology arbitrarily close to j, j', for each firm. Once this is done, the agency knows the fractions of firms using the various technologies. Then the agency can revise the monitoring probabilities and the penalty needed to induce compliance, with the possibility of reducing the welfare loss due to excess monitoring.

There are two difficulties in applying the above Bayesian approach to get at the actual distribution of the J technologies:

(i) The existence of emission quotas induces a switch in technologies towards the $\theta$ technology, and potentially the search for technologies that allow even greater output for a given emission level. Thus it may be difficult for the agency to obtain the actual distribution of technologies at a given time.

(ii) Suppose the agency (despite (i)) was able to obtain the Bayesian posterior distribution of technologies among the firms. Adjusting the monitoring probabilities and the penalties needed for compliance may not bring about the desired effects, as these adjustments increase the volatility in the firms' environment, thus calling for frequent shifts in the firms' actions. Cyert and deGroot (1987) are explicit: adjustments are costly. Consequently the agency should consider these costs and the resulting loss in efficiency before changing the policy parameter vector, $\lambda = [\alpha, K, \omega, \rho^g]$, $g \in G$.

### 5.4.5 Balancing the Budget for the Regulatory Agency

In chapter three a balanced budget for the regulatory agency was mentioned as a desirable property. In this sub-section it will be demonstrated that this property is generally not possible if one also wants to satisfy incentive compatibility and SBPO.

A balanced budget for the agency implies that the aggregate monitoring costs in each time period, $f^1 \rho^1 C_m$, plus the agency's single period fixed costs (F) equal the generated revenues. These revenues consist of the collected fines, which are functions of $\alpha$, $\omega^*$ and K. In general one cannot expect these sums to be equal. Adjusting $\alpha$, $\omega^*$ or K will change the monitoring probabilities as well as the Markov-stationary fractions of firms in the different groups. Assuming that the values for these parameters and variables are those that maximize (5.14), requiring the agency's budget to balance may cause an overall loss of welfare.

## 5.5 The Optimality of Emission Quotas

As noted earlier, the pre-monitoring optimal emission levels, $\{Z_t^*\}_{t \in T}$, are generally not attainable. More specifically, setting an $\alpha$ that only allows for small variations around the targeted emission level increases the number of firms caught in violation, and consequently the expected monitoring costs as more firms are moved to groups two or three. From the proposed scheme as well as the models of Greenberg (1984), Russell et al. (1986) and Russell (1987), increased compliance comes at the cost of increased monitoring. One may therefore talk about an optimal level of non-compliance, $\epsilon > 0$.

Another interesting question regarding the optimality of quotas is raised by Dahlman (1979). His point is that an existing externality may be optimal if there exists no way of reducing the externality level that increases efficiency. To see this more clearly, consider the condition for SBPO (5.22). Again let $\{Z_t^*\}_{t\in T}$ denote the optimal emission level under the proposed monitoring scheme, i.e. the choice of the parameter vector $\lambda$ that maximizes (5.14). Let $\{Z_t^0\}_{t\in T}$ denote the emission levels resulting from no pollution control. Clearly these emission levels are SBPO if:

$$\Sigma_{t\in T}\ \beta^t\ \{B(Z_t^*) - \Sigma_{g\in G}\, \rho^g\, f^g\, N\, C_m\} < \Sigma_{t\in T}\, B(Z_t^0) \qquad (5.25)$$

Thus the emission levels $\{Z_t^0\}_{t\in T}$ are not Pareto-relevant if (5.25) holds.

## 5.6 Conclusions

The dynamic principal-agent model for monitoring compliance with emission quotas developed in this chapter deals with the class of pollution control problems where the regulatory agency does not have full information about the cost structures of the individual firms, and emissions are stochastic around some target emission levels. In the design of the scheme, the properties of individual rationality, informational viability and efficiency are satisfied by construction. An approach for solving for the incentive compatible policy parameter vector, $\lambda = [\alpha, K; \omega^*, \rho^g]$, $g \in G$ is derived. The starting point of finding $\lambda^*$, the optimal policy parameter vector, is to choose $\omega^*$, the scale parameter in the penalty function (5.2). The next step in finding $\lambda^*$ is to choose $\alpha$, the parameter indicating the allowed emission level above the pre-monitoring optimal emission level for each firm, $z_n^*$. Choosing the correct $\alpha$ is crucial to obtain an optimal outcome. The conditions to evaluate SBPO of the incentive compatible policy vector, $\lambda$, are established.

The expected monitoring costs of the suggested three group model are shown to be less than that of the single group model, provided the monitoring probabilities in groups one and two are less than the monitoring probability for single-period compliance in group three for given levels of emissions, $\{Z_t^0\}_{t \in T}$.

Finally the proposed approach to pollution control yields increased understanding of the feasibility of reduced emissions. The first important insight given by the model is that in general the pre-monitoring optimal emission levels, $\{Z_t^*\}_{t \in T}$, are not attainable, as the gains from reduced emissions to $Z_t^*$ are offset by high aggregate monitoring costs. Second, the suggested scheme makes it possible to evaluate whether the current emissions are Pareto-relevant. If the discounted benefits derived from the sequence of emissions under no pollution control exceeds those under pollution control, the emissions under no pollution control are not Pareto-relevant.

# CHAPTER 6

# SUMMARY AND CONCLUSIONS

This dissertation has addressed two issues in pollution control; (i) the optimal level of emissions, and (ii) the design of a system to induce compliance with this emission level at minimum costs. The starting point for this research is that the public, represented by a regulatory agency, does not know the individual firm's pollution abatement costs, and that firms are generally reluctant to reveal these costs.

Viewing the market for emission permits and the pollution control system as resource allocation mechanisms, it has been emphasized that the proposed mechanisms satisfy the properties of individual rationality, informational viability and efficiency, incentive-compatibility and second-best Pareto-optimality. Individual rationality, informational viability and efficiency are met by construction. The conditions for incentive compatibility have been found, and it is demonstrated that among the class of known incentive compatible pollution control mechanisms, the proposed schemes are SBPO, provided that the benefit (or damage) function entails both direct and indirect effects from emissions. This latter point is of extreme importance, and appears to have been neglected in the literature.

The optimal level of emissions in an atemporal setting is inferred from comparing the inferred price from the marginal damage function, with the price of emission permits in a market for tradeable emission quotas. If the inferred price is higher than the permit price, the social marginal damage from emissions is higher than the social marginal cost of reducing emissions, implying that the level of emissions is above the social optimum. By buying permits from the firms for retirement, the overall emission level can be reduced until it reaches its optimum value. This occurs where the price in the permit market equals the inferred price from the damage function.

With the insights gained from the atemporal model, an intertemporal model is developed. In this setting, each firm is awarded an initial emission level. This level of emissions is equivalent to a property right, where the firm can buy or sell the rights to emit. Unlike the atemporal model, buying a permit is now an investment. The resulting emission permit price at any aggregate emission level, is therefore the price that maximizes the expected profits of the firms at this emission level. Consequently the appropriate criterion for the optimal emission level is that the inferred price equals the permit price times the cost of capital, i.e. the interest rate.

One problem with the suggested model for obtaining the optimal aggregate emission level is that there is nothing in the model that induces firms to comply with their pre- or ex-trade emission levels. A mechanism is therefore needed that induces each firm to comply with their emission level. In chapter five an atemporal and an intertemporal principal-agent to induce compliance are developed, when there are stochastic variations in the firms' targeted emission levels.

The atemporal model is developed to illustrate some of the difficulties that arise when emission levels are stochastic. If the regulatory agency views any emission level above the individual firm's emission quota as a violation, and the penalty structure is such that the expected profits from violations are less than those under compliance, sub-optimal emission levels will result. Consequently the agency needs to choose an allowed emission level above the pre-monitoring optimal emission level, such that SBPO is achieved.

Jones (1989) showed that a necessary criterion for compliance at all emission levels, is that the penalty function for violations must increase at an increasing rate. One such penalty function is presented (equation 5.2). Given the allowed emission level (equation 5.1), and the scaling parameter in the penalty function (equation 5.4), the agency now chooses a monitoring probability such that the expected profits of intended compliance exceed those for any level of intended cheating. The atemporal model shows that there is an inverse relationship between this scaling parameter and the monitoring probability needed to induce compliance.

With these insights, a dynamic model is constructed. Initially all firms are in group one, where monitoring is less frequent. If caught in violation, they are moved to group two. If monitored and found in compliance, the firm is moved back to group one. Conversely, if monitored and found in non-compliance, the firm is moved to group three, where they remain until they have been monitored and found in compliance K consecutive periods. Given the scale parameter, and the allowed variability in targeted emissions, the monitoring probability in group three is chosen such that single-period compliance is induced.

While in groups two or three, the firms themselves cover the costs of being monitored.

The monitoring probability in group two is chosen such that, given the penalty scale parameter, the allowed variability in emissions and the number of consecutive monitoring periods in group three, K, the expected profits of complying in group two, exceed the expected profits of non-compliance, and consequently being moved to group three.

Firms would prefer to be in group one, since they would not pay monitoring costs. The monitoring probability in group one is now chosen such that, given the other parameters in the model, the expected profits of multi-period compliance in group one exceed those in group two. Generally the monitoring probability in group one is less than that in group two, which is less than that in group three. Consequently the proposed model induces compliance with the allowed emission level, at lesser costs than would result from a one group model, where single-period compliance is needed to reach the same degree of compliance.

Two important insights are gained from the model for inducing compliance. The first of these insights is that for each firm there exists an optimal allowed emission level, (equation 5.1), that is generally higher than the optimal emission quota, derived in chapter four. Indirectly the regulatory agency chooses the allowed emission level by determining the allowed variability in emissions above the optimal emission quota. Choosing the right variability is detrimental to achieving an optimal outcome. The second insight follows directly from the first; the ex post monitoring optimal emission level is likely to differ from the ex ante monitoring optimal emission level, and generally the former exceeds the latter. The model for obtaining the pre-monitoring optimal emission levels and the model for inducing compliance, are therefore constructed such that they can be used together, thus achieving a SBPO aggregate emission level, which is enforceable. Jointly these models constitute a set of new institutions for pollution control that are informationally feasible and less costly to operate than previously described approaches.

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# APPENDIX

# APPENDIX

# EXPLANATION OF NOTATION AND SYMBOLS

## A.1 Special Characters

| | |
|---|---|
| $\alpha$ | the variability scale factor |
| $\in$ | an element in a set |
| $\subset$ | a subset of |
| $\succsim_i$ | the ith consumer's preference ordering |
| $\rho^g$ | the monitoring probability in group g, $g \in G$ |
| $\theta$ | the technology yielding the most output per unit emissions, $\theta \subset J$ |
| $\sigma_M^2$ | the variance in the regulatory agency's emission level measurement |
| $\sigma_\theta^2$ | the variance in the emission level around the targeted emission level for technology $\theta$ |
| $\sigma^2$ | the total variance around the targeted emission level |
| $\omega$ | the scale factor in the penalty function |

## A.2 Symbols

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|---|---|
| E | the probability of escape from group 3 |
| $f^g$ | the fraction of firms in group g |
| i | an index, indicating the ith consumer, $i \in I$ |
| $I$ | the index set of all consumers |
| j | an index, indicating the jth technology, $j \in J$ |
| $J$ | the index set of known technologies |

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|---|---|
| K | the number of successive time periods in group 3 without violation before being moved to group 2 |
| m | an index, indicating the mth price or product, $m \in M$ |
| $M$ | the index set of goods |
| n | an index, indicating the nth firm (producer), $n \in N$ |
| $N$ | the index set of all firms (producers) |
| $\mathbf{p}$ | the output price vector, the product price vector |
| $\mathbf{q}$ | the input vector |
| $Q(\mathbf{y})$ | the input requirement set |
| $\mathbf{v}$ | the input price vector |
| $X_i$ | the ith consumer's budget (= labor income + stock dividends + endowments) |
| $\mathbf{X}$ | a vector of all consumer incomes |
| $Y$ | the production possibility set / the consumption set |
| $Y^*$ | the producible set |
| $Y_i(Z')$ | the ith consumer's constrained consumption set |
| Z | an emitted public good, a pollutant |
| $\mathbf{Z}$ | a vector of public goods/emissions |
| $z_n^U$ | the nth firm's upper level of emissions before being penalized |

## A.3 Functions

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|---|---|
| $\pi_{jn}$ | the nth firm's profit function with the jth technology |
| $B(Z,p,\mathbf{X};p^\circ \cdot Z^\circ)$ | the benefit function from pollution |
| $C^I(\bullet)$ | informational costs |

| | |
|---|---|
| $C_j(z_n)$ | the nth firm's cost function (in the emission level) |
| $C_M$ | monitoring costs |
| $c_n(\mathbf{y}_n, \mathbf{v})$ | the nth firm's cost function (in output and input prices) |
| $h(z_n; p)$ | the penalty function for emissions |
| $M_i(\mathbf{p}, X_i; \mathbf{p}^\circ)$ | the ith consumer's money metric utility function |
| $M_i(\mathbf{p}, X_i; \mathbf{p}^\circ \mid Z')$ | the ith consumer's constrained money metric utility function |
| $M(\mathbf{p}, \mathbf{X}; \mathbf{p}^\circ)$ | the aggregate money metric utility function |
| $M(\mathbf{p}, \mathbf{X},; \mathbf{p}^\circ \mid Z')$ | the aggregate constrained money metric utility function |
| $U_i(\mathbf{y}_i)$ | the ith consumer's (direct) utility function |
| $V_i(\mathbf{p}, X_i)$ | the ith consumer's indirect utility function |
| $V_i(\mathbf{p}, X_i \mid Z')$ | the ith consumer's constrained indirect utility function |
| $W(\mathbf{y})$ | Bergson-Samuelson general Social Welfare Function (general form) |
| $W(\mathbf{p}, \mathbf{X}, \boldsymbol{\beta})$ | Bergson-Samuelson weighted Social Welfare Function (additive in weighted utilities) |
| $\phi(\alpha, z_{\theta_n})$ | the power function of $\alpha$ and $z_{\theta_n}$ |

## A.4 Abbreviations

| | |
|---|---|
| AMMU | Aggregate Money Metric Utility |
| CAC | Command And Control |
| CAMMU | Constrained Aggregate Money Metric Utility |