FACTORS THAT DETERMINE THE EFFICIENCY RANKING OF SECOND-BEST INSTRUMENTS FOR ENVIRONMENTAL REGULATION

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ABSTRACT

Cost-effective policies allow minimizing the compliance costs associated to reaching a desired environmental quality target. However cost reductions associated to the use of these policies are not always significant. In this paper a conceptual model is developed to analyze explicitly the interaction among the factors that determine the compliance costs under two market based policies (the optimal ambient permit system, APS, and an emission permit system, EPS) and two CAC policies (equal percentage reduction, PER and a uniform concentration standard of emissions, STD). Considering a non-uniformly mixed pollutant the model incorporates explicitly the number of polluting sources; the size, in terms of emissions, of each process; the marginal costs of abatement for each process; the concentration of the emitted pollutant at the source; the transfer coefficient that relates emissions at each location with the impact on environmental quality at the receptor; and the desired environmental quality target. A first question addressed using the model. is how each of these factors affects compliance costs under each policy and as a result how the costs of sub-optimal policies compare with those of the optimal policy. The model shows that each factor affect the relative efficiency of each suboptimal policy quite differently. A second issue addressed is the efficiency ranking of second-best instruments under plausible values of each factor. It is shown that (1) APS is significantly less costly than the suboptimal policies in 45% of the cases; (2)EPS is very efficient in 75% of the cases, particularly when sources are clustered around the receptor; (3) a uniform standard performs well in many common situations; and PER is also efficient in some specific cases; (4) there is a high dispersion of results for cost quotients in some specific cases; and (5) relative compliance costs for PER and STD show extreme variations becoming very inefficient in some cases. Extreme values of the cost quotient for EPS are much lower.

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I. INTRODUCTION

Market based incentive policies, in particular spatially differentiated marketable permits and fees have been shown to be cost effective in theory [Baumol and Oates, 1971; Montgomery, 1972]. Simulation studies have established that cost reductions can be significant using these instruments [Tietenberg, 1985; O'Ryan, 1996]. However the efficiency gains of the optimal policy[1], are not always substantial. For example in a study for the Los Angeles area the cost effective policy was only 12 percent less costly than command and control (CAC) policies [Hahn and Noll, 1982]. Considering the potential difficulties in implementing an optimal instrument, a low cost advantage may warrant the use of second-best instruments[2] in many specific cases. The question is then whether to apply a suboptimal uniform tax or emission permit system (EPS) or a CAC instrument. There is no formal model that allows comparing systematically the specific factors that determine when each instrument can be expected to perform well, i.e. result in compliance costs similar to the optimal instrument, and when very poorly.

From a detailed review of eight empirical simulations Tietenberg [1985] identifies the general factors that determine the compliance costs under each policy for the case of non-uniformly distributed pollutants. Four factors are key:

(1) The heterogeneity of firms. This includes both differences in the amount of emissions and the variation in relative marginal costs of abatement among firms;
(2) the number of polluting firms of each type;
(3) the degree of clustering around the receptor that requires the largest improvements (location); and
(4) the stringency of the ambient standard relative to the level of uncontrolled emissions.

In this paper a model is developed to examine how each of these factors influences the compliance costs of reaching a desired environmental quality standard at a unique receptor location under alternative policies. The model considers the more general case of a non-uniformly distributed pollutant.

Russell [1986] developed a formal model to compare the efficiency ranking of two second-best policies. In a simple setting, he obtained the conditions under which a uniform percentage reduction is more efficient than a uniform charge for a non-uniformly mixed pollutant[3]. He considered two point sources emitting from different locations having to reach a given standard at a unique receptor location. The model developed in this paper builds on Russell's results in various ways. First, it considers explicitly the amount of emissions (or "size") of the sources. Second it includes the number of polluting firms. Third, the model allows evaluating the importance of the degree of clustering around the receptor location on the cost effectiveness of each policy. For example, the impact on the

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[1] "optimal" will be used in the limited sense of cost-effective in this paper.

[2] Transaction and implementation costs are potential problems. See Bohm and Russell (1985) for a discussion of dimensions relevant to the choice of instruments other than cost-effectiveness.

[3] See also Nichols [1984] and Kolstad [1987] that develop a similar comparison in an optimizing framework, i.e. considering simultaneously the cost and damage functions;

relative compliance costs of few high emitters close to the receptor as opposed to many high emitters far from the receptor. These differences allow comparing the compliance costs of policy instruments under a more general setting than Russell's simple model where only two sources of the same size are considered.

The model also considers a uniform concentration standard as an alternative policy. Finally, the effect of the stringency of the policy is incorporated. As is well known, the cost gains from an optimal policy instrument are not significant when low (i.e. close to zero) reductions are required, or conversely when very high reductions are required. This latter result is due to the fact that in this case most sources will have to apply the same control technology.

Two questions are addressed using the model. First, how does each factor affect the relative compliance cost of each of the suboptimal policy instruments? Second, under what combination of the factors is the optimal policy much better than the other policies, and conversely, when are second best policies a good choice? Considering values common for each of the parameters of the model we examine the relative compliance costs of three different second best policies. Some interesting regularities are obtained that inform the choice of policy instruments.

The second section presents the model developed. In the third section the model is used to determine the analytic expression for compliance costs under each policy considered. Section four examines the importance of each factor in determining the efficiency gains of the optimal policy when compared to second-best policies. Section five examines the efficiency ranking of alternative second-best policies for different combination of values of each factor. The final section presents the main conclusions.

II. The Model

This section presents the basic elements of the model developed to establish the compliance costs for different environmental quality targets considering multiple heterogeneous firms located at different distances from a unique or dominant receptor location[4]. The general case of a non-uniformly distributed pollutant is considered.

First, it will be useful to group similar sources into categories called processes. Two sources of similar technology, fuel type, emissions (size), abatement cost and located near each other will be considered "identical" processes. As a result, there can be many sources that correspond to a single process. For example, in a given city there may be N diesel powered, relatively old, industrial boilers that are medium sized emitters (i.e. that emit one to two tons of a given pollutant), and close to the receptor location. This simplification allows focusing on the differences that actually matter to determine the costs of each policy, and gloss over small differences that are not relevant[5].

The following are the key parameters of the model:

n: number of different processes;

N_i: number of sources for each process i, $i=1...n$;

a_i: slope of the marginal cost curve for process i, $i=1...n$;

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[4] Solving for more than one receptor location requires the use of linear programming techniques. It becomes extremely cumbersome to obtain meaningful stylized conclusions.

[5] This distinction also makes sense from a policymakers' perspective, that needs to decide what type of instrument to focus on in a specific case, without having to model all sources in detail.

M_i: total emissions or "size" of process i, $i=1...n$;
α_i: transfer coefficient that translates emissions from process i, $i=1...n$, to concentrations at the receptor location.
G_i: Concentration of emissions at the source for process i, $i=1...n$;
Q_0: original environmental quality at the receptor location;
Q^*: the desired environmental quality goal to be reached at the unique receptor.

Any process i is characterized by its marginal cost curve a_i, total emissions M_i -the "size" of the emitting process-, its concentration of emissions G_i, and its location relative to the receptor, summarized in parameter α_i.

The form of the marginal cost curve is presented in figure 1 for two processes. Each curve has a constant slope a_i up to M_i. Beyond this point, no further reductions are possible, or, equivalently, marginal costs of reduction are vertical. This formulation captures the fact that in practice the slope of the marginal cost curves are not constant but after a point grow exponentially[6], and that each process can reduce a maximum of M_i units of emissions because it is applying the best technology available.

From figure 1, if a tax is set at a value (t_1) greater than C_1, or the price of permits rises above this value (to P_1), emission reductionsby process 1 will reach a maximum of M_1, and emission reductions by process 2 will reach m% of M_2.

The transfer coefficient α_i characterizes the impact of each process i on the receptor location[7].. Each unit of emissions by process i contributes to ambient concentrations at the receptor location by α_i. The further to the receptor, the lower the value of this parameter. Without loss of generality it can be assumed that processes type 1 are the closest to the receptor and in this case $\alpha_1=1$. Of course in the case of a uniformly distributed pollutant, since location does not matter, $\alpha_i = 1$ for all i.

Total initial emissions by any process i are M_i*N_i. Consequently, total emissions (TE) by all n processes is :

$$TE = \sum_{i=1}^{n} M_i * N_i \qquad (1)$$

The total costs of abating m% of emissions by any process i, $TC_i(m)$, will be the area under the marginal abatement cost curve, precisely up to m (area A_2 in figure 1). As a result of the simple formulation of the model, $TC_i(m)$ can be determined by the following expression[8]:

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[6] An even better approximation to an exponential marginal cost curve can be obtained by assuming that some reductions can be made at zero cost. This has been done, however the resulting formulation is somewhat messy and does not introduce interesting insights.

[7] Note that two otherwise identical processes that have different transfer coefficients are treated as different processes.

[8] Simplifying assumptions made are: (i) The abatement cost function is continuous and begins at zero cost; (ii) it is possible to abate 100% of emissions for each exponential marginal cost curve can be obtained by assuming that some reductions can be made at zero cost. This has been done, however the resulting formulation is somewhat messy and does not introduce interesting insights.

[8] Note that two otherwise identical processes that have different transfer coefficients are treated as different processes.

$$TC_i(m) = (\frac{a_i}{2})*(m*M_i)^2 \qquad (2)$$

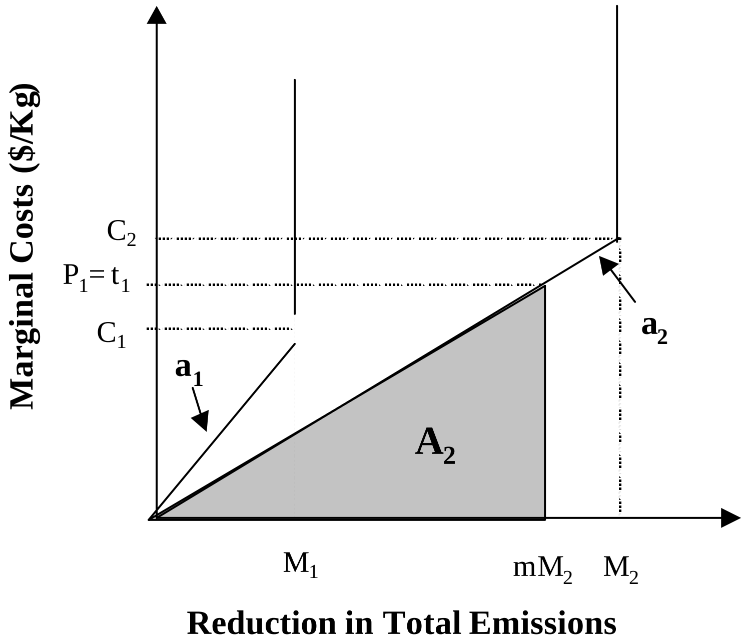

Figure 1: Marginal Cost for Two Processes

III. COMPLIANCE COSTS UNDER DIFFERENT POLICIES FOR *n* PROCESSES

In this section the model is used to determine compliance costs for the optimal ambient based permit system (APS), and three suboptimal policies: equal percentage reduction (PER), identical emission concentration standard (STD), and a spatially undifferentiated emission permit system (EPS). It is straightforward to see that the results for EPS and APS are equivalent, from an efficiency perspective, to using a unique charge and spatially differentiated charges respectively.

Under APS it is assumed that compliance costs are minimized, i.e., trades among sources are based on the impact of the trade on the concentration at the receptor location. As a result the cost per unit of concentration reduced at the receptor location will be equated across processes. An emission permit system (EPS) allows that all sources trade on a one to one *emission* basis, an as a result, in equilibrium, the marginal abatement costs of each unit of emission (not concentration at the receptor) is equated across processes. This, of course, is not optimal for non-uniformly mixed pollutants. Under PER all sources are required to achieve identical percentage reductions m, and under STD all sources must comply with a maximum concentration standard g measured at the source.

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[8] Simplifying assumptions made are: (i) The abatement cost function process; (iii) marginal costs grow at a constant rate.

The initial environmental quality Q_0 at the receptor location is given by the following expression:

$$Q_0 = \sum_{i=1}^{n} N_i * M_i * \boldsymbol{a}_i \qquad (3)$$

As a result of this formulation, total compliance costs of each policy instrument to reach a desired environmental quality goal Q^* are presented in the following table as a function of all known parameters. The derivations are presented in appendix 1.

Table 1: Compliance costs under each policy of reaching the desired air quality standard Q^*

Policy Instrument	**Total compliance cost of Reaching Q^* based on known parameters**	**Additional Parameters**
APS	$TC(Q^*) = \frac{1}{2}\sum_{i=1}^{q} M_i^{\,2} * N_i * a_i + \frac{1}{2}\sum_{i=q+1}^{n} \frac{N_i * P_i(Q^*)^2}{a_i}$ **(4)** **Note: To comply with Q^* there are q processes that reduce emissions 100% and n-q processes that each reduce a fraction of their emissions.**	$P_i(Q^*) = \boldsymbol{a}_i \frac{\sum_{i=q+1}^{n}(M_i * N_i * \boldsymbol{a}_i) - Q^*}{\sum_{i=q+1}^{n} \frac{M_i * N_i * \boldsymbol{a}_i^{\,2}}{a_i}}$ **Note: $P_i(Q^*)$ is the permit price per unit of emission reduced for each location i.**
EPS	$TC(Q^*) = \frac{1}{2}\sum_{i=1}^{q} M_i^{\,2} * N_i * a_i + \frac{P(Q^*)^2}{2} \sum_{i=q+1}^{n} \frac{N_i}{a_i}$ **(5)** **Note: To comply with Q^* there are q processes that reduce emissions 100% and n-q processes that each reduce a fraction of their emissions.**	$P(Q^*) = \frac{\sum_{i=q+1}^{n} M_i * N_i * a_i - Q^*}{\sum_{i=q+1}^{n} \frac{N_i * \boldsymbol{a}_i}{a_i}}$ **Note: $P(Q^*)$ is the unique permit price per unit of emission reduced.**
STD	$TC(Q^*) = \frac{1}{2}\sum_{i=1}^{l} (1 - \frac{g(Q)}{G_i})^2 * a_i * M_i^{\,2} * N_i$ **(6)** **Note: It is assumed that under STD only l<=n processes actually reduce emissions given the standard g required to comply with Q^***	$g(Q^*) = \frac{Q^* - \sum_{i=l+1}^{n} M_i * N_i * \boldsymbol{a}_i}{\sum_{i=1}^{l} \frac{N_i * M_i * \boldsymbol{a}_i}{G_i}}$
PER	$TC(Q^*) = \frac{1}{2}(1 - \frac{Q^*}{Q_0})^2 \sum_{i=1}^{n} N_i * M_i^{\,2} * a_i$ **(7)**	

These equations allow comparing the costs of abatement under PER, STD, EPS and APS policies respectively. Assuming five different processes a comparison of total compliance costs for different reduction targets is given in figure 2. The parameters chosen for the example are not meant to be representative, but suggest the type of cost relations that can result. These results resemble those obtained from simulation models applied to real cities (see for example Atkinson and Tietenberg (1982) and O'Ryan (1996)).

As expected, APS is the cost-effective policy. All other policies are more costly. The cost differential can be significant between APS and the other instruments. For example STD is 3 times more expensive than APS for reaching a 30% reduction target. However, as the required reduction target increases, all policies tend to the same total cost.

The efficiency ranking of the suboptimal policies depends on the level of required abatement. STD is the most inefficient policy for low values of required abatement. However, at approximately 55 percent required abatement, PER becomes the most inefficient policy. Finally, PER actually performs better than EPS at low levels of required abatement, i.e. in this range, a suboptimal market-based scheme is less efficient than a CAC policy.

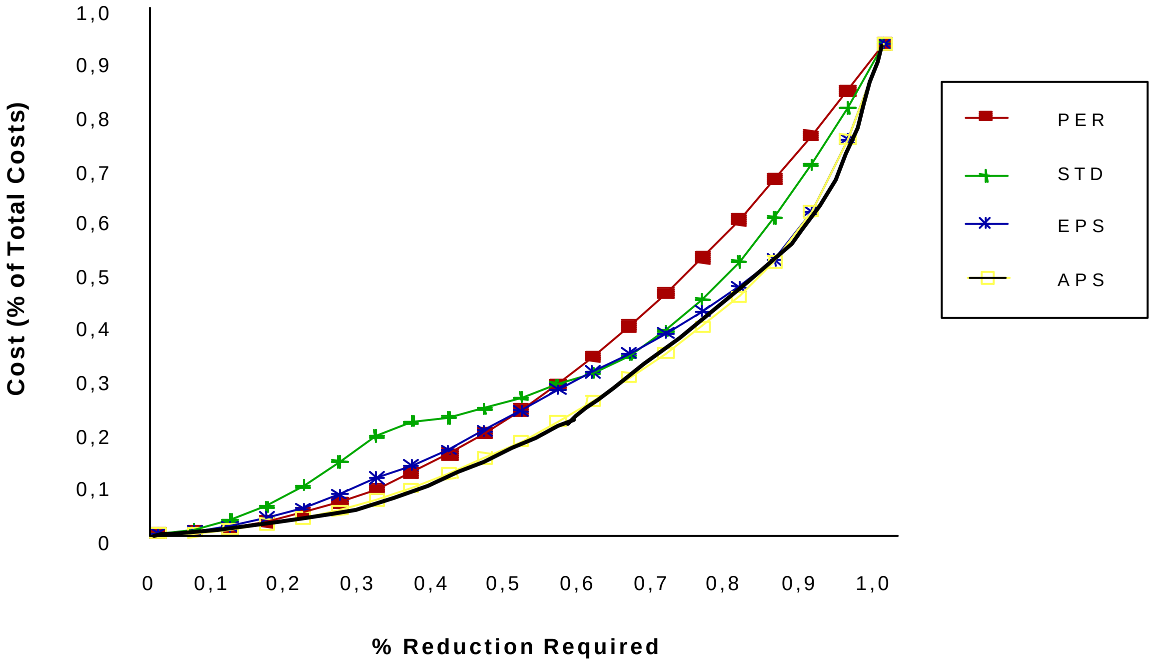

Figure 2: Cost Comparison of Different Instruments Used to Improve Environmental Quality

IV. OPTIMAL POLICY VS SECOND BEST POLICIES: IMPORTANCE OF EACH FACTOR IN DETERMINING THE EFFICIENCY GAINS

This section discusses the importance of each factor -number of sources per process, heterogeneity of processes, i.e. size and abatement costs, location, stringency of the target environmental quality- in determining the potential efficiency gains of the optimal APS policy compared with the three suboptimal EPS, PER and STD policies.

Using the results from table 1, the compliance costs of the non-optimal policies are compared with those of the optimal policy considering only two processes[9]. This allows obtaining simple analytical

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[9] The model allows considering n processes, however only two are needed to examine how each factor affects relative compliance costs. The way the model is set up allows however to consider many emitting sources, because there are N1 sources of process type 1 and N2 sources of process type 2.

expressions for the corresponding cost ratios.

Figure 3 presents an example of the cost ratios for different policies considering the whole range of possible reduction targets. As in the previous case, the example is simply illustrative of the types of results that are possible. As expected the ambient permit system is always better than the non-optimal policies, and as a result the cost ratio is greater than one for all cost comparisons.

The form of each curve as the required abatement increases is of interest. For all policies there is a first range of values for which the cost ratio is constant. This is the result of assuming constant slopes for the marginal abatement cost curves. In this constant range the relative efficiency of the policies is invariant and as a result cost comparisons are robust. In this example, the cost-effective APS policy is 40 percent less costly than EPS, 50% less costly than STD and 2.5 times more efficient than PER. However, these results depend critically on the specific values of the parameters chosen for the example. As will be seen in the following sections, changing the parameters can reverse the efficiency rankings and change the magnitude of the ratio significantly.

As required abatement increases, there are critical values of abatement or switch points above which all policies begin to converge to APS. These last results are in accord with what is normally obtained from simulation models. Appendix 2 discusses the importance of the stringency of the desired environmental quality goal in detail.

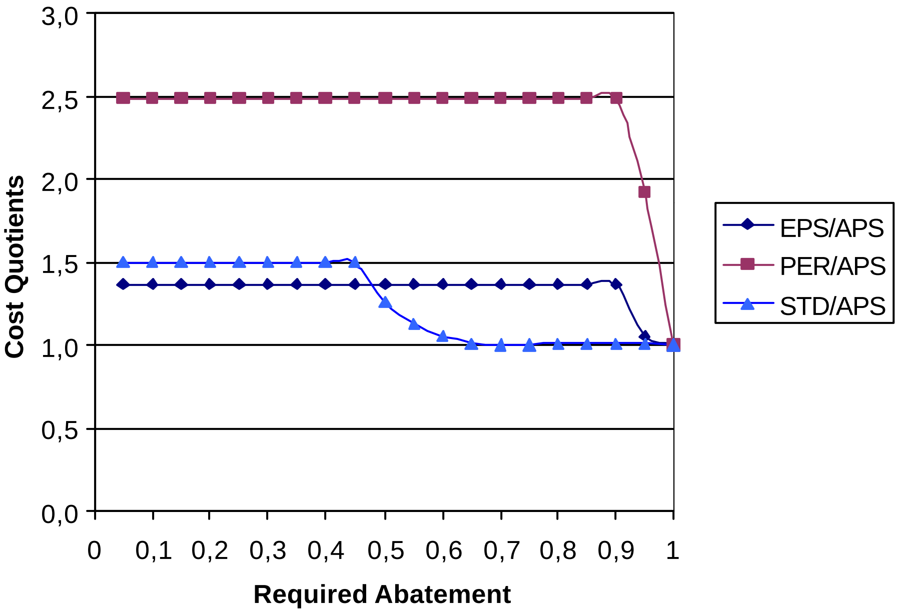

Figure 3: Cost Comparison of Different Policies

(a) Cost ratios to compare the relative efficiency of each policy instrument

It is of interest to examine the influence of each parameter on the relative cost-effectiveness of each second best policy. The following cost ratios will be useful for this:

$$R_0 = \frac{\text{Total Cost under Equal Percentage reduction}}{\text{Total Cost under an Ambient Permit System}} = \frac{PER}{APS}$$

$$R_1 = \frac{\text{Total Cost under Equal Concentration Standard}}{\text{Total Cost under an Ambient Permit System}} = \frac{STD}{APS}$$

$$R_2 = \frac{\text{Total Cost under Emission Permit System}}{\text{Total Cost under an Ambient Permit System}} = \frac{EPS}{APS}$$

If a cost ratio tends to 1, then the second best policy is relatively cost effective, since compliance costs will be similar to APS. Conversely, if a cost ratio is very high the policy is extremely inefficient. Each cost ratio will be estimated using the cost functions from Table 1. To simplify matters we explore the zones where these ratios are constant. This allows examining how the factors interact to determine the magnitude of the cost ratio, independently of the required reduction.

Finally, it is convenient to define the following quotients:

$M = M_1/M_2$	relative size of both processes;
$a = a_1/a_2$	relative slope of marginal cost curves for each process;
$\alpha = \alpha_1/\alpha_2$	relative transfer coefficients between processes;
$N = N_1/N_2$	relative number of sources between processes;
$G = G_1/G_2$	relative pollutant concentrations at the source, for both process.

These parameters summarize the main factors identified as key to the efficiency gains of optimal policies: *M* and *a* are a measure of the heterogeneity of processes and *N* together with α of the degree of clustering around the receptor.

N, *M*, *a* can be greater, equal or less than one. If these parameters are all greater (smaller) than 1, then the process type 1 that is close to the receptor has relatively *many* (few) sources ($N>1$), is a relatively *large* (small)emitter ($M>1$), and has a relatively high (low) slope of the marginal cost curve ($a>1$) or is "*high cost*" (low cost).

As a result, the following expressions can be obtained for each of the relevant cost ratios:

$$R_o = \frac{(M^2 * N * a + 1)(\alpha^2 * N + a)}{a(M * N * \alpha + 1)^2} \qquad (8)$$

$$R_{1a} = 1 + \frac{a}{N\alpha^2} \qquad (G > 1) \qquad (9a)$$

$$R_{1b} = 1 + \frac{N\alpha^2}{a} \qquad (G < 1) \qquad (9b)$$

$$R_2 = \frac{(N+a)(\boldsymbol{a}^2 * N + a)}{(N * \boldsymbol{a} + a)^2} \qquad (10)$$

It is clear to see that the cost ratios depend on all the parameters: N, M, a, G and α. The behavior of these costs ratios as the value of these parameters change is explored in the following section.

(b) Significance of each parameter in the efficiency comparison of policy instruments

Table 2 presents the cost ratios when each of the following parameters tends to extreme values:

Table 2: Influence of extreme values of parameters in cost effectiveness of second best policies

Parameter	**Tends to**	**PER/APS** **R_0**	**STD/APS (G>1)** **R_{1a}**	**STD/APS (G<1)** **R_{1b}**	**EPS/APS** **R_2**
Location: ***a***					
	1	$1+\frac{N(Ma-1)^2}{a(MN+1)^2}$	$1+\frac{a}{N}$	$1+\frac{N}{a}$	1
	+∞	$1+\frac{1}{M^2Na}$	1	+∞	$1+\frac{a}{N}$
Number of Sources per Process: *N*	0	1	+∞	1	1
	1	$1+\frac{(Ma-a)^2}{a(Ma+1)^2}$	$1+\frac{a^2}{a}$	$1+\frac{a}{a^2}$	$1+\frac{a(a-1)^2}{(a+a)^2}$
	+∞	1	1	+∞	1
Amount of Emissions: *M*	0	$1+\frac{a^2N}{a}$	$1+\frac{a}{a^2N}$	$1+\frac{a^2N}{a}$	$\frac{(N+a)(a^2*N+a)}{(N*a+a)^2}$
	1	$1+\frac{N(a-a)^2}{a(aN+1)^2}$	$1+\frac{a}{a^2N}$	$1+\frac{a^2N}{a}$	$\frac{(N+a)(a^2*N+a)}{}$
	+∞	$1+\frac{a}{a^2N}$	$1+\frac{a}{a^2N}$	$1+\frac{a^2N}{a}$	$\frac{(N+a)(a^2*N+a)}{}$
Marginal Compliance Costs: *a*	0	+∞	1	+∞	1
	1	$1+\frac{N(a-M)^2}{(aMN+1)^2}$	$1+\frac{1}{Na^2}$	$1+N\boldsymbol{a}^2$	$1+\frac{N(a-1)^2}{(Na+1)^2}$
	+∞	+∞	+∞	1	1

For each policy, there are values of the parameters that make the cost quotients go to one, indicating that the suboptimal policy is as efficient as APS. For example EPS is cost-effective (i.e. $R_2 = 1$) when

α tends to 1. This result is expected since $\alpha = 1$ means that the pollutant is uniformly distributed.

PER is as cost effective as APS when three conditions hold: α=a=M=1. In this case all sources are the same so the efficient solution requires that all reduce in exactly the same percentage their emissions. An interesting result from equation (8) is that for $Ma = \boldsymbol{a}$, PER is as also efficient, for any value of the other parameters. Multiplying by m on both sides and rewriting this expression we obtain the following relation: $(m*M_1)a_1/\alpha_1= (m*M_2)a_2/\alpha_2$, that states that marginal reduction costs per unit of concentration at the receptor will be equal in this case, the well known rule for cost effectiveness! Finally, this result is a generalization of Russell's (1986) model that establishes that PER is efficient for $\alpha=a$. However that model implicitly assumes that M=1. It is clear to see that for any other value of M this result will not hold.

The cost ratios can also take intermediate values and in some cases very high values. For example, when marginal compliance costs are very different (the quotient a is zero or tends to infinity) PER is very inefficient. The reason for this is that PER imposes similar reduction efforts on both processes even though the efficient policy would require that the low cost process make the largest reduction effort.

Now the influence of each parameter on the relative cost-effectiveness of each second best policy is examined. When N is large, EPS, PER and STD (for G>1)[10] are as efficient as APS even if the processes considered are heterogeneous. The reason for this is that any policy will have to impose most of the weight of the reduction on these numerous sources that are close to the receptor. In particular, since G>1 in this case, i.e. , sources close to the receptor have higher concentration of emissions, an efficient solution would require that these sources bear the brunt of the reduction. This is what happens when STD is applied. However when N is low, indicating that there are many sources type 2 (i.e. far from the receptor, with low concentration of emissions), STD becomes highly inefficient. In this case, an efficient solution would require that reductions be undertaken by type 2 sources, without requiring significant reductions from sources type 1 that are few and that consequently are not too relevant for the concentrations at the receptor location[11]. However STD imposes that sources type 1 with high concentration of emissions reduce first. Since this is ineffective because they are few, significant reductions from sources type 2 are also required. This results in a high relative cost for this policy.

The relative size of sources M only influences the cost quotient R_0 (PER/APS), not R_1 (STD/APS) or R_2 (EPS/APS). The reason for this is that the size of the process only affects the reductions undertaken as a result of PER policy because only this percentage depends on the initial emissions. For APS, EPS and STD, the reduction required will be independent of the relative size M in the constant range of the cost ratio being considered here, so the cost quotient is not affected by the size of the emitters[12].

The relative slope of the marginal abatement cost curves a affects the cost ratios differently. PER

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[10] We assume the case G>1 from now on, to simplify the exposition of results.

[11] High concentrations of emissions (G_i) is not the same as high emissions (M_i). A source can have high concentration of emissions but emit a small amount if it operates few hours per day, or has a low gas flow.

[12] This must not be confused with the fact that larger processes impose higher total emissions as well as larger total costs of reduction. However the cost quotients compare the relative costs of each policy. In this case APS and all the suboptimal policies are more costly.

becomes very inefficient whenever there is a large difference in relative abatement costs, i.e., for both low and high values of a. STD is fairly efficient for low values of a, but very inefficient for high values.

The inefficiency of PER at both low and high values of a results from the fact that in each case the policy moves away from the optimal solution: equating marginal cost of each unit of concentration reduced at the receptor. The explanation of the result for STD is different. Any standard imposed will affect more the high concentration of emissions type 1 sources, requiring that they reduce a higher proportion of their emissions than type 2 sources. If sources type 1 have the lower marginal cost, i.e. a is small, this behavior comes close to what would be done under an optimal policy, so the cost quotient tends to one. However, if type 2 sources have the lower marginal costs (a is large), the optimal result would require that type 2 sources abate more, exactly the opposite of the result applying STD, consequently this policy becomes very inefficient.
As the relative transfer coefficient α increases, indicating a more non-uniformly mixed pollutant, an equal concentration standard policy (STD) becomes increasingly efficient. For large values of the transfer coefficient the optimal policy would require strong reductions from process type 1 sources, close to the receptor. This is precisely what STD does.

In summary, the value of these parameters determine how close or far from being cost effective each policy will be, and the effect of each parameter on the cost effectiveness of each policy instrument is significantly different.

V. EFFICIENCY RANKING OF SECOND-BEST POLICIES

Using the model, we now address the following issue: under what combination of the factors is the optimal policy much better than the suboptimal policies and when are second best policies comparable in terms of efficiency, with the optimal instrument. A related question is what is the efficiency ranking of the suboptimal policies?

As in the last section, the case for two processes is considered. To examine cases of interest to policymakers, we will use values of the parameters observed in practical cases. The parameter α has been defined as greater or equal to one. Specifically it will be assumed that α can take a low (between 1 and 2) value[13] indicative of a uniformly mixed pollutant, or sources clustered around the receptor location, an intermediate (between 2 and 5) value and a high (between 5 and 50) value. This latter corresponds to a strongly non-uniformly mixed pollutant.

It is assumed that each of the other parameters (N, M, a) can be greater or less than one, consequently, there are eight possible cases for each value of α:

Case 1: many, small, low cost sources close to the receptor.
Case 2: many, small, high cost sources close to the receptor.
Case 3: many, large, low cost sources close to the receptor.
Case 4: many, large, high cost sources close to the receptor.
Case 5: few, small, low cost sources close to the receptor.
Case 6: few, small, high cost sources close to the receptor.

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[13] For example in air for Santiago, for every one kilometer the transfer coefficient falls approximately 10%. Sources separated by a distance of 5 kilometers from the receptor would have a transfer coefficient of 2.

Case 7: few, large, low cost sources close to the receptor.
Case 8: few, large, high cost sources close to the receptor

Based on empirical observations, each of the parameters (N, M, a) is allowed to vary within the following range of plausible values[14]:

The relative number of sources: $N \varepsilon$ [10,100] for $N>1$ and [0.01,0.1] for $N<1$;
The relative size of sources: $M \varepsilon$ [50,500] for $M>1$ and [0.0002, 0.02] for $M<1$;
The relative slopes of the marginal cost curves: $a \varepsilon$ [5,20] for $a>1$ and [0.05,0.2] for $a<1$.

Two hundred values were generated randomly for each of the parameters and for each of the three values of α[15]. They were combined to obtain 200 plausible cases of the cost quotients for each value of α. The results are presented in Table 3. They include the four cost quotients, estimated for each of the above eight cases, considering three possible values of α. The mean value of each quotient is presented together with the standard deviation. In gray are the most cost-effective options for each case[16].

The results are very informative. Overall, APS is "much better" than the suboptimal policies – defined as a cost quotient greater than two- in only 45% of the randomly generated cases. In particular APS is much better than EPS only in 17% of the cases, and in a significant 53% of the cases for both STD and PER. In general, there is a strong case for preferring APS over CAC instruments, but not necessarily over EPS.

Second best policies are almost as good as APS (gray cells) in 41% of the cases. As expected, the best performance is by EPS that in 75% of the cases performs very well. When sources are clustered around the receptor (low values of α) EPS performs very well. However, EPS becomes relatively inefficient at high values of α.

STD and PER perform very well in 33% of the cases. If the regulator has information that allows establishing that sources close to the receptor have relatively higher concentrations of emissions, then, surprisingly, for high α the standard performs very well in six of the eight possible cases, with costs very similar to APS! EPS and STD are thus interesting options in specific cases. The result for STD gives support to the extensive use of standards when the pollutant is non-uniformly mixed.

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[14] See for example O'Ryan (1996), Atkinson and Tietenberg (1982) and Nichols (1984) for ranges of values of N, a and M.

[15] A uniform distribution is assumed for these values.

[16] Assumed as the cases in which the cost quotient is less than 1.1.

Table 3: Efficiency ranking of suboptimal policies for the eight possible cases

Transfer coefficient a	**Cases**	**PER/APS**		**STD/APS**		**STD/APS**		**EPS/APS**	
		R0		**R1a**		**R1b**		**R2**	
		Average (Std. Dev.)		**Average** (Std. Dev.)		**Average** (Std. Dev.)		**Average** (Std. Dev.)	
Low a	Case 1	**371,05**	(376,12)	**1,00**	(0,00)	**1613,78**	(1513,04)	**1,00**	(0,00)
	Case 2	**4,19**	(3,70)	**1,19**	(0,27)	**16,19**	(13,64)	**1,02**	(0,01)
	Case 3	**1,00**	(0,00)	**1,00**	(0,00)	**1613,78**	(1513,04)	**1,00**	(0,00)
	Case 4	**1,19**	(0,27)	**1,19**	(0,27)	**16,19**	(13,64)	**1,02**	(0,01)
	Case 5	**2,33**	(0,98)	**2,18**	(0,81)	**2,33**	(0,98)	**1,05**	(0,04)
	Case 6	**1,01**	(0,01)	**128,29**	(97,67)	**1,01**	(0,01)	**1,00**	(0,00)
	Case 7	**1,89**	(0,62)	**2,18**	(0,81)	**2,33**	(0,98)	**1,05**	(0,04)
	Case 8	**109,18**	(78,38)	**128,29**	(97,67)	**1,01**	(0,01)	**1,00**	(0,00)
Intermediate a	Case 1	**851,79**	(1001,28)	**1,00**	(0,00)	**9416,78**	(9422,69)	**1,00**	(0,00)
	Case 2	**8,91**	(10,07)	**1,04**	(0,07)	**89,43**	(84,78)	**1,10**	(0,03)
	Case 3	**1,00**	(0,00)	**1,00**	(0,00)	**9416,78**	(9422,69)	**1,00**	(0,00)
	Case 4	**1,04**	(0,07)	**1,04**	(0,07)	**89,43**	(84,78)	**1,10**	(0,03)
	Case 5	**8,43**	(6,01)	**1,23**	(0,18)	**8,48**	(6,06)	**1,40**	(0,17)
	Case 6	**1,07**	(0,05)	**26,20**	(22,06)	**1,07**	(0,06)	**1,04**	(0,03)
	Case 7	**1,16**	(0,14)	**1,23**	(0,18)	**8,48**	(6,06)	**1,40**	(0,17)
	Case 8	**24,20**	(19,55)	**26,20**	(22,06)	**1,07**	(0,06)	**1,04**	(0,03)
High a	Case 1	**2859,84**	(4740,76)	**1,00**	(0,00)	**475539,32**	(601216,59)	**1,00**	(0,00)
	Case 2	**28,86**	(45,37)	**1,00**	(0,01)	**4640,01**	(5899,34)	**1,25**	(0,23)
	Case 3	**1,00**	(0,00)	**1,00**	(0,00)	**475539,32**	(601216,59)	**1,00**	(0,00)
	Case 4	**1,00**	(0,01)	**1,00**	(0,01)	**4640,01**	(5899,34)	**1,25**	(0,23)
	Case 5	**442,16**	(468,16)	**1,02**	(0,06)	**466,17**	(499,75)	**2,63**	(0,90)
	Case 6	**5,58**	(5,33)	**3,48**	(6,70)	**5,86**	(5,70)	**3,85**	(2,68)
	Case 7	**1,01**	(0,04)	**1,02**	(0,06)	**466,17**	(499,75)	**2,63**	(0,90)
	Case 8	**3,33**	(6,09)	**3,48**	(6,70)	**5,86**	(5,70)	**3,85**	(2,68)

STD and PER have high standard deviations, showing a high dispersion of the cost quotient. In these cases, e.g. case 7 for intermediate α where Ro is the lowest cost quotient (PER is best) and case 6 for high α where R1a is the lowest (STD is best), there are however many combinations of values of the parameters where these result do not hold, i.e. the other instruments are of lower cost. With high standard deviations, it is advisable that the regulator use more elaborate simulation models before deciding what instrument to apply.

Finally it is important to note that for low and intermediate values of α, STD and PER can be extremely inefficient. In cases 1, 2 and 8 PER is extremely inefficient, and similarly STD is extremely expensive in cases 6 and 8: values of the cost quotient go into the hundreds and even thousands. The cost quotient for command and control is extremely sensitive to the parameters. The cost quotient under EPS does not present such extreme variations as the other two policy instruments, reaching a maximum value of 4.

VI. CONCLUSIONS

A model has been developed to determine total compliance costs of reaching an environmental quality goal under different policies. It incorporates explicitly the number of different polluting sources per process; the size, in terms of emissions, of each process; the marginal costs of abatement for each process; and the transfer coefficient that relates emissions at each location with the impact on environmental quality at the receptor. The model also incorporates the stringency of the desired environmental quality goal.

The model permits analyzing explicitly the role of each of the factors that determine the compliance costs under different policies. The basic results show that:

> (i) As expected, APS is more efficient than all second-best policies. However the magnitude of the efficiency gains depend crucially on each of the factors.
> (ii) The relative number of sources N is key to the cost quotients. When N is large, EPS, PER and STD are as efficient as APS even if the processes considered are heterogeneous. However when N is low, STD becomes highly inefficient and PER and EPS are efficient.
> (iii) The relative size M of sources is relevant only when comparing PER to APS. Depending on the value of M, equal percentage reduction can be very inefficient or fairly efficient.
> (iv) The relative slope of the marginal abatement cost curves a affects the cost ratios differently. PER becomes very inefficient whenever there is a large difference in relative abatement costs. STD is fairly efficient for low values of a, but very inefficient for high values. EPS performs well for both low and high values, but is inefficient at intermediate values.
> (v) Depending on the value of the relative transfer coefficient α any policy can be optimal. An equal concentration standard policy (STD) becomes increasingly efficient as α increases. EPS is optimal if α is equal to 1. PER is optimal if $\alpha = Ma$.

These results permit concluding that even though an optimal market-based APS incentive policy is cost effective, there are situations under which second best policies can be expected to perform well also. Considering plausible values for each of the relevant parameters, important regularities emerge in the cost quotients. First, APS is significantly better than any other policy in only 45% of the total cases. In all the other cases, the use of suboptimal policies should be considered seriously by the regulator. In particular, it is shown that in 75% of the cases in which it is applicable, EPS has costs that are less than 10% greater than APS. It is extremely cost-effective for values of $\alpha < 2$. STD and PER are efficient in 33% of all possible cases where they apply. However, for high values of α, STD is a fairly cost effective policy in 6 of the eight cases. EPS and STD are thus very attractive options for the regulator when the optimal APS policy has high implementation or transaction costs.

In some cases some suboptimal policies are fairly efficient when the average cost quotient is considered. However a high standard deviation of the quotient shows that even though the average is better, there are many combinations of values of the parameters where this result does not hold. When there is high dispersions in the result, t is necessary for the regulator to use simulation models to determine the best suboptimal instrument.

Finally the cost quotients for PER and STD have much more extreme variations than EPS. For plausible values of the parameters, both command and control policies can be 10, 100 or even higher times more costly than the optimal policy. The cost quotient variations are much less extreme under EPS.

The results obtained are useful for examining policy options for a variety of non-uniformly mixed pollutants. The model presents a systematic way to examine how the different factors will interact to determine the costs under each policy in specific contexts. The simulations inform the policymaker about when a specific instrument can be expected to be cost-effective, and when very inefficient.

APPENDIX 1
Derivation of the cost functions for each policy instrument

This appendix presents the derivation of the compliance cost functions for each of the four policy instruments considered.

(a) Equal percentage reduction (PER)

Under this policy all sources are required to achieve identical percentage reductions m. As a result from equation (2), the total cost of reduction is given by :

$$TC = \frac{m^2}{2}\sum_{i=1}^{n} a_i * M_i * N_i \qquad \text{(a)}$$

However, m is related to the desired environmental quality Q^* by the following relation:

$$Q^* = (1-m) * Q_0 \qquad \text{(b)}$$

as a result:

$$m = 1 - \frac{Q^*}{Q_o} \qquad \text{(c)}$$

Substituting (6c) in (4a) gives the expression for total costs for PER based on known parameters:

$$TC(Q^*) = \tfrac{1}{2}(1-\frac{Q^*}{Q_0})^2 \sum_{i=1}^{n} N_i * M_i{}^2 * a_i \qquad \text{(d)}$$

(b) Identical source concentration standard (STD)

Under this policy all sources are required (at least) the same concentration standard g measured at the source. This standard is such that, as a result, the desired air quality is obtained at the receptor. To incorporate the concentration standard it is necessary to relate emissions by process to concentration of emissions by process. This is done through the following relationship:

$$M_i = G_i * H_i * F_i \qquad \text{(e)}$$

where:

M_i = Total emissions from process i (Kg/day)
G_i = Concentration of the pollutant at the source for process i (kg/m^3)
H_i = Hours of operation per day for process i (hr/day)
F_i = Per hour flow of the gas that contains the pollutant to be controlled, from process i (m^3/hr)

Not all sources will reduce the same percentage of their emissions (m_i) as a result of imposing g. It may be the case that, initially, some sources are below the required concentration standard and as a result are not required to reduce emissions at all. Without loss of generality, it can be assumed that there are *l* sources affected by the standard and *n-l* not affected. Each of the *l* processes affected will reduce emissions by m_i, and the others zero. Moreover, total emissions after applying the standard must reach the desired air quality goal. As a result, final air quality is given by the following relation:

$$Q^* = \sum_{i=1}^{l} N_i * M_i * \boldsymbol{a}_i * (1 - m_i) + \sum_{i=l+1}^{n} N_i * M_i * \boldsymbol{a}_i \qquad \text{(f)}$$

The first term in the right hand side is the weighted emissions of the *l* sources that reduce for a given standard. The second term is the weighted emissions of the *n-l* sources that do not reduce. The weight in each case is the transfer coefficient relating total emissions (N_i $M_i(1\text{-}m_i)$ and M_i N_i) at location i with ambient concentrations at the receptor location.

Also, the resulting concentration at the source for each process $(1\text{-}m_i)*G_i$ must equal the allowed standard *g*, i.e:

$$m = 1 - \frac{g}{G_i} \qquad \text{i = l + 1, ..., n} \qquad \text{(g)}$$

Substituting (10) into (9), and after some manipulation gives the following expression for *g* based on known parameters:

$$g = \frac{Q^* - \sum_{i=l+1}^{n} N_i * M_i * \boldsymbol{a}_i}{\sum_{i=1}^{l} \frac{N_i * M_i * \boldsymbol{a}_i}{G_i}} \qquad \text{(h)}$$

Finally, to determine total abatement costs under STD only those *l* processes that actually reduce emissions must be considered. As a result, from (2).

$$TC(m) = \tfrac{1}{2} \sum_{i=1}^{l} m_i^2 * a_i * M_i^{\,2} * N_i$$

or, as a function of g and G_i:

$$TC = \tfrac{1}{2} \sum (1 - \frac{g}{G_i})^2 * a_i * M_i^{\,2} * N_i \qquad \text{(i)}$$

(c) Emission permit system (EPS)

If an EPS is used, it will be the case that in equilibrium the price of the permits will be unique, i.e., marginal costs of abatement will be equal across sources. For non-uniformly mixed pollutants this is not a cost-effective policy.

Two types of processes can be distinguished: those that at the unique price P of permits reduce 100% of their emissions, and those that only reduce a fraction. Figure 1 illustrates this situation for two processes. At price P processes of type 1 abate 100% of their emissions. Assuming there are N_1 sources of this type, total abatement is N_1 M_1. Processes of type 2 abate m_2. Note that m_2 is equivalent to P/M_2a_2. As a result, the total amount abated by the N_2 sources of type 2 at price P> 0 is N_2 * (P/a_2) .

Generally, it can be assumed that the first q processes will reduce 100% and the other n-q will reduce a fraction m_i of their total emissions. As a result, final environmental quality will be the result of emissions from the n-q sources that emit:

$$Q^* = \sum_{i=q+1}^{n} N_i * M_i * \boldsymbol{a}_i * (1 - m_i) \qquad \text{(j)}$$

$P(Q^*)$ can be obtained from equation (j) and the fact that m_i is equivalent to P/a_i as:

$$P(Q^*) = \frac{\sum_{i=q+1}^{n} N_i * M_i * \boldsymbol{a}_i - Q^*}{\sum_{i=q+1}^{n} \frac{N_i * \boldsymbol{a}_i}{a_i}} \qquad \text{(k)}$$

And, finally, total costs under EPS are given by :

$$TC(Q^*) = \tfrac{1}{2} \sum_{i=1}^{q} N_i * M_i^{\,2} * a_i + \frac{p^2}{2} \sum_{i=q+1}^{n} \frac{N_i}{a_i} \qquad \text{(l)}$$

In this case q, the number of processes that are reducing all their emissions, also depends on the specific parameters of the problem.

(d) Ambient permit system (APS)

If an ambient permit system is used, compliance costs will be minimized, i.e. the result will be cost-effective. In equilibrium, the cost per unit of concentration reduced at the receptor $\gamma(Q^*)$ is equated across processes, i.e.:

$$\frac{MC_1(Q^*)}{\boldsymbol{a}_i} = \frac{MC_2(Q^*)}{\boldsymbol{a}_2} = \ldots\ldots\ldots = \frac{MC_n(Q^*)}{\boldsymbol{a}_n} = g(Q^*) \qquad \text{(m)}$$

The equilibrium price for a unit of emission reduced by any process i is $P_i = MC_i$. From (m) $P_i = \alpha_i * \gamma$, i.e the equilibrium price of each unit of emission depends on the transfer coefficient. If the transfer coefficient is high, the price will be high, reflecting that a source that is close to the receptor must undertake a larger reduction effort than a similar one far from the receptor.

As in the case for emission permits, two types of processes can be distinguished: *q* processes that at the equilibrium reduce 100% of their emissions, and *n-q* processes that only reduce a fraction m_i. The desired environmental quality that results from the n-q processes that emit is:

$$Q^* = \sum_{i=q+1}^{n} N_i * \alpha_i * (M_i - \frac{P_i}{a_i}) \qquad \text{(n)}$$

From equations (n) and (m) the equilibrium price for each unit of concentration at the receptor for a given Q^*, $\gamma(Q^*)$, is obtained:

$$\gamma(Q^*) = \frac{\sum_{i=q+1}^{n} N_i * M_i * \alpha_i - Q^*}{\sum_{i=q+1}^{n} \frac{N_i * \alpha_i^2}{a_i}} \qquad \text{(o)}$$

From which $P_i = \alpha_i * \gamma$ can be obtained based on known parameters.

Finally total costs are given by :

$$TC(Q^*) = \tfrac{1}{2} \sum_{i=1}^{q} N_i * M_i^2 * a_i + \tfrac{1}{2} \sum_{i=q+1}^{n} \frac{N_i * P_i^2}{a_i} \qquad \text{(p)}$$

APPENDIX 2
Importance of the level of required abatement

From figure 3 the cost ratio is constant for all policies in an initial range. For EPS and APS this corresponds to a required abatement low enough so that neither of the two processes has reduced 100 percent of its emissions. For STD, the requirement is such that only the high concentration process needs to abate. The fact that the ratio is constant in this range results from the assumption of constant slopes for the marginal abatement cost curves.

However as the level of required abatement increases, all curves have a critical or switch point (from now on denoted r^*) above which the cost ratio is no longer constant. This switch point can be determined for each cost ratio curve. For example a switch point occurs for PER vs APS when, under APS, one of the sources reaches an abatement level of 100% [17]. In this case:

$$r^* = \frac{(\alpha * M * N + \frac{a^*}{\alpha})}{(\alpha * M * N + 1)}$$

Clearly r^* depends on all the parameters in the model. For large values of α the switch point tends to one and the constant range of the cost ratio is large. Thus the conclusions of the previous section hold for a wide range of abatement values. However, if sources type 1 are low cost (a is small) and are relatively few (N is small), then r^* is close to zero, and the previous conclusions are limited to low values of abatement.

In this example, beyond r^* the cost ratio R_0 depends on the desired air quality Q^* and the original air quality Q_0. Defining $q=Q^*/Q_0$, then:

$$R_o = \frac{(1-q)^2 (N * a + 1)}{(N * a + (1 - q(N * a + 1))^2}$$

i.e., as the desired air quality becomes more stringent (Q^* tends to zero), R_0 tends to one, as expected.

The cost ratio is not as straightforward in the case of EPS and STD. In both cases there is more than one switch point, i.e. more than one point at which the cost ratio varies. For example for STD a first switch point is reached when source 2 begins abating under an equal standard. A second point is reached when under APS source 1 reaches its abatement limit[18]. The relative concentration of emissions G plays a role in this case determining where the switch points are located.

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[17] The switch point for STD vs Aps in the example is: $r^* = \alpha MN(g - 1)/(g(\alpha MN + 1))$
The switch point for EPS vs APS is: $r^* = \alpha MN(a + 1)/(a(\alpha MN + 1))$

[18] This second switch point is at : $r^{**} = (\alpha MN + a/\alpha)/(\alpha MN + 1)$

Finally, for all policies the cost ratios tend to one after the first switch point, i.e., they tend to behave like APS[19]. This is expected because at high levels of required abatement all policies impose the same abatement technologies.

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[19] However, at high values of required abatement STD may actually perform relatively worse, before beginning to tend towards the cost under APS.

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