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Optimal Design of a Politically Feasible Environmental Regulation*

Jongmin Yu** · Seokjong Ryu***

This paper discusses the optimal environmental regulation model that considers the political support of the regulated agents. We suggest a hybrid emission control policy pair, which combines a price (penalty) and a quantity control (emissions cap), and is efficient from the regulator's perspective. Regulated companies choose one of the lowest-cost policy options within the pool of efficient hybrid policy pairs, and the regulator also prefers the most popular policy option with the smallest political resistance from the industry. This theoretic analysis provides an opportunity for policymakers to design acceptable regulation structures.

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I. Introduction

Price vs. quantity control in regulating pollution has been a longstanding argument, and related discussions are primarily focused on the efficiency of different policy instrument choices. Weitzman (1974) shows the conditions under which instruments are deemed efficient by comparing relative slopes between marginal benefits and the cost of abatement. Pizer (2002) shows that pure price control outperforms pure quantity control in his general equilibrium model.

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** Corresponding and First Author, Assistant Professor, Department of Economics, Hongik University, 94 Wausan-ro, Mapogu, Seoul, 121-791, Korea, Phone: 82-2-320-1750/ Email: yucono@hongik.ac.kr

*** Second Author, Assistant Professor, Department of Economics, Shanghai University of Finance and Economics No.111, Wuchuan Rd, Yangpu District, Shanghai, 200433, China.

However, Stavins (1996) argues that, in terms of the political attractiveness of quantity control, a hybrid policy can be a suitable alternative to pure price control. This is because a hybrid policy provides welfare improvement compared with pure quantity control and demonstrates the same welfare improvement when compared with price control.

According to Roberts and Spence (1976), mixing price control and quantity control makes the regulation system more flexible than pure price control or pure quantity control. Thus, the policy mix can approximate the private sector's marginal cost curve to the social planner's damage function. Jacoby and Ellerman (2004) raise a general concern that adding a significant penalty, which would be levied when the quantity control level is exceeded, may increase expected pollutant emissions beyond the quantity cap.

A few studies have designed an optimal hybrid system that maximizes welfare by determining a price and quantity instrument simultaneously so that one policy instrument works with the other. Grafton and Ward (2008) estimate welfare loss when price or quantity rationing policy is used for household water supply at Sydney. Webster et al. (2010) show that optimal price control does not depend on the quantity cap, which is based on the assumption that marginal damage from emissions is constant. Burtraw, Palmer, and Kahn (2010) note that the asymmetry of an instrument (a single-sided safety valve) adopted by most countries can cause a negative impact on investment. Stranlund and Moffitt (2014) present an optimal hybrid policy that can achieve the social optimum by relaxing the assumption of a flat marginal damage curve. They characterize optimal hybrid policies as those that produce the expected emissions level and maximize social welfare when emissions are stochastic. Maeda (2012) also discusses specific hybrid policy pairs that eliminate the need to consider uncertainty and highlights the relative effectiveness of two policy instruments under uncertainty. Moreover, Yu and Mallory (2015) look beyond previously studied single compliance period models and extend this model to an optimal hybrid policy model with multiple compliance periods.

Despite the abovementioned findings, no study has identified a policy mix that considers the preference of regulated agents. This differs from the economic efficiency issue of the hybrid policy discussed in previous papers. Stavins (1996) notes that the political feasibility of introducing regulations should be considered using a set of efficiency criteria. Mixing price and quantity emission controls have a long history, but no study has identified which hybrid policy is preferred by the regulated industry among the efficient hybrid policy sets that provide a socially optimal outcome. The present study defines the optimal combination of price control (penalty) and quantity control (emissions cap) from an industry perspective within the pool of efficient hybrid policy pairs. All policy candidates offer differing compliance costs to the industry, although we know the efficient hybrid policy pairs that induce the best abatement. Thus, the industry would politically support the policy candidate that minimizes compliance costs. Regulators also prefer the most popular policy option because it may bring the least political resistance from the industry. A regulation that is preferred over others would be politically feasible and implementable. Therefore, the research question presented is as follows: what is the preferred environmental regulation if multiple policy pairs are suggested?

This study defines political feasibility as the willingness of regulated agents to conform to one specific regulation over other regulations. Policy makers consider alternative toolkits to achieve a certain policy objective. Among several traditional policy evaluation criteria, such as environmental effectiveness, fairness, cost-effectiveness, efficiency, distribution of welfare, incentive compatibility, notions of justice, administrative burdens, incentives of technological change, and political feasibility, political feasibility is a key factor for the successful establishment of the regulatory system. Researchers define this factor as the low share of regulatory burden (Hahn, 1990; Goulder and Parry, 2008; Rhodes and Jaccard, 2013; Carley, 2011; Kim, 2013; Urpelainen, 2015, Urpelainen, 2015; Jun, Cho, Park, 2015; Lamperti, Napoletano, and Roventini, 2016; Anouliès, 2017). Bovenberg and Goulder (2001) compare the regulatory burdens of emitters under the free allocation and auctioning regimes of emission permits and Oh and Kim (2016) demonstrate the political difficulties in adopting a new environmental regulation, that is, the emission trading scheme in Korea. Stavins (1996, 2009) notes that the hybrid policy has been designed with the consideration of political resistance to environmental regulation, and policymakers may need to consider the political aspect once they have multiple, efficient policy candidates.

The numerous hybrid policy pairs are all deemed efficient from the regulator's perspective, and the most politically feasible choice among them is the one that produces the highest expected profit (or the lowest compliance costs) for firms. Therefore, regulated agents can choose policy pairs after the regulator proposes the policy menu. This process does not hurt the efficiency of the pollution control policy but rather respects the financial interests of regulated firms. Therefore, identifying the preferred policy among all of the efficient policies serves the original purpose of a hybrid policy.

This paper proceeds as follows. Section 2 defines the regulated firms and regulator models, and derives the most politically feasible policy pairs. Section 3 analyzes the comparative statics of policy equilibria to gain insights from the model. This section also calibrates the model that illustrates the process of how the best policy is chosen when both parties have different expectations regarding emissions. Section 4 presents our conclusions.

II. Model

1. Representative Firm's Problem

We model the economy with a single representative firm that aggregates the entire industry's emissions and abatements, as done by Seifert, Uhrig-Homburg, and Wagner (2008) and Yu and Mallory (2015). This assumption enables us to focus primarily on an optimal hybrid policy design with a parsimonious model rather than the allocation or trading of emissions permits across multiple firms. "Free rider" or "hold-up" problems would give disproportionate weights to particular firms if multiple regulated firms with different preferences for emission regulations exist. Thus, we aggregate the industry's preferences, because many industries have their own associations in the real world to present their unified positions and lobby their governments.

The objective function in terms of the regulated representative firm minimizes total compliance costs. The total compliance cost in Equation (1) consists of two parts: the abatement cost for compliance, $C(u)$, and the expected penalty payment when the firm fails to comply with an emissions cap, $Z(u;P,e,y)$. The representative firm chooses the desired abatement level, u_f, which minimizes the sum of the abatement costs and the expected penalty payment. We define y as business as usual (BAU) emissions in the absence of an emissions regulation given that the amount of the emissions, y, is uncertain. From a set of hybrid emission control regulations that the firm must consider, two types of policy instruments are presented: the emissions cap, e, which is free up to the grandfathered limit, and a penalty rate, P.

The regulated firm's payoff is the sum of the abatement costs necessary to reduce emissions in addition to penalty expenditures if abatement is insufficient. The objective function is to derive an abatement level, u_f, that minimizes expected values of the sum. Many environmental studies have modeled cost minimization issues instead of welfare maximization, assuming that firms do not modify their output decisions based on policies imposed by environmental regulations (Rubin, 1996; Schennach, 2000; Kling & Rubin, 1997; Leiby *et al.*, 2001; Stranlund *et al.*, 2014; Yu *et al.*, 2015). Initially, they make profit-maximizing output decisions, followed by abatement and emission permit purchase decisions to comply with regulations.[1]

$$TC = \underset{u_f}{\text{Min}}\, E[C(u) + Z(u \mid P, e, y)] \tag{1}$$

[1] This example may describe a coal-fired electric plant that bases kilowatt hour electric output decisions on macroeconomic conditions and consumer demands and then installs scrubbers or purchases emission permits to achieve compliance.

Equation (1) shows that the only control variable is the amount of emission abatement, $u_f(\geq 0)$. Individual firms can determine how much of their emissions permits to use under the exogenously given emissions cap, $e(\geq 0)$. Our model assumes a homogeneous representative firm that can reflect all the firms' activities. We do not have control variables of tradable permits, because the net purchase amount for permits is zero. The assumption on the timing of actions is as follows. The regulator has its own information on the probability distribution over the stochastic emissions to be realized. This information is used as the regulator proposes an optimal policy option to the firm. Firms must first determine the abatement efforts given the probability distribution of emissions. The amount of realized emissions over the free permit limit determines the penalty payment amount.

From the first-order condition of the firm's objective function, which aims to minimize compliance costs, Equation (1), with respect to u_f, is expressed as

$$\frac{\partial C(u)}{\partial u} + E\frac{\partial Z(u;P,e,y)}{\partial u} = 0 \tag{2}$$

$$\therefore \quad u_f^* = u_f(P,e,E(y)). \tag{3}$$

2. The Regulator's Problem

This section defines the regulator's desired abatement level, u_s, as that which minimizes the regulator's costs. Therefore, the model allows the regulator to choose two policy instruments, a free emissions cap or quota, e, and a penalty rate, $P(\geq 0)$, so that the firm's optimal choice of abatement, u_f, becomes equal to the socially optimal abatement amount, u_s. In the regulator's problem, the three cost components are enforcement costs, environmental damage, and the firm's compliance costs. The regulator aims to minimize the social costs consisting of the three cost components.

Montero (2002) and Arguedas (2008) note that, when compliance is deficient, the regulator incurs extra costs for regulation enforcement, which presents the choice between emissions tax and emissions trading. Stranlund and Moffitt (2014) argue the possibility of designing a hybrid policy with an enforced, explicit price cap to achieve full compliance. Thus, our model also assumes full compliance. Therefore, we explicitly incorporate an enforcement cost term in the regulator's objective function. Most enforcement costs are monitoring costs to ensure compliance. We define this enforcement cost term as the function of abatement, $M(u)$. This follows the fact that a strict abatement requirement can incentivize noncompliance, because the opportunity cost of compliance also increases when more abatement is required. Thus, the regulator must increase monitoring costs to guarantee full compliance.

Regarding environmental damage, cumulative pollutant emissions, Q, cause damage to society. This social cost should be seen by the social planner (the environmental regulator), but firms may not care about this environmental damage, because they only focus on minimizing their monetized costs for abatement or compliance in their balance sheet. We define the damage function as $D(Q+y-u)$. The term Q represents the accumulated emissions during past periods. The amount of newly added emissions is net emissions, $y-u$, which is BAU minus the amount of abatement. This environmental damage term is strictly increasing in Q and $y-u$ and is convex (or is at least weakly convex).

Regarding the firm's compliance costs, only abatement costs, $C(u)$, can be included as social costs, because the expected penalty payment when the firm fails to comply with an emissions cap, $Z(u;P,e,y)$, becomes the regulator's revenue. Thus, penalty payment is not a cost from the perspective of the regulator. However, the firm's expenditures toward reducing emissions can be counted as social costs.

The regulator's payoff is the sum of abatement costs incurred from the regulated firm and the total environmental damage. The objective function is to minimize their expected values. The regulator's objective function is defined below and determines its own optimal abatement level, u_s.

$$TC_s = \underset{u_s}{\mathrm{Min}}\, E[M(u)+D(Q+y-u)+C(u)] \tag{4}$$

From the first-order condition of the regulator's objective function, we can minimize the total social costs with respect to abatement, u_s, using the equation

$$0 = \frac{\partial M(u_s)}{\partial u_s} + \frac{\partial D(Q+y-u_s)}{\partial u_s} + \frac{\partial C(u_s)}{\partial u_s}. \tag{5}$$

High amounts of abatement may increase monitoring and abatement costs but decrease environmental damage, but this optimal abatement level balances the costs from this environmental regulation program against pollution damage caused by emissions. From the optimization process, we can determine the optimal abatement level from social perspectives, u_s^*. The regulator optimally sets a penalty rate for excessive emissions and a quantity cap, (P,e), which induces the industry to abate an optimal amount of emissions, u_s.

We can derive a unique abatement level, u_s^*, but a set of hybrid policies yields the same amount of abatement. In this case, combining two policy instruments provides a degree of freedom with regards to the regulator's problem. For example, in order to maintain the abatement level, a strict emissions cap can be offset by a lenient penalty level and vice versa. A single policy parameter in traditional tax or quantity control systems equalizes the marginal abatement costs to the marginal damage of emissions (Weitzman, 1974).

The regulator achieves abatement targeting by equating the firm's optimal abatement, u_f^*, with the predetermined socially optimal abatement, u_s^*, which is computed using the equation

$$u_s^* = u_f^*(P, e, E(y)). \tag{6}$$

By combining Equations (3) and (6), the social planner has a policy mix (P, e) that induces the firm to abate the same amount required by the regulator, u_s^* (u^* afterward)

$$P = f(e \mid u^*, E(y)), \tag{7}$$

which characterizes the indifference curve of the regulator, $I(P, e \mid u^*, E(y))$ in the (P, e) phase.

3. Most Politically Feasible Policy Pairs

The firm and the regulator have different objective functions; thus, each prefers a different policy mix. The regulator aims to have the policy mix in Equation (7) that satisfies u_s^* and minimizes the loss of social welfare. Further, the firm only wants to minimize its compliance costs. The previous section models a string of policy combinations, (P, e), that the regulator can use to induce the firm to undertake the same level of pollution abatement. However, this efficient policy mix does not consider the total expected compliance costs for the firm because each can cause a different level of compliance costs to the firm. The regulator suggests various hybrid policy options that incur the same social costs, but the firm has different preferences for suggested policy candidates. We plug in the policy pair from Equation (7), which induces the u^* back to the total compliance cost function in Equation (1). Thus, the firm should satisfy the regulator's need for abatement by following the policy pair, and the firm can pursue compliance cost minimization. Equation (8) thus shows the equation for expected compliance costs

$$TC = E_y[C(u) + Z(u; f(e \mid u^*, E(y_s)), e, y_f)]. \tag{8}$$

The next topic of discussion has to do with the implications of choosing a single policy mix over all others on the efficient policy locus from a firm's perspective. In this case, the regulator is impartial to policy pairs on its locus, but each pair of policies renders a different level of compliance costs to the firm. Therefore, some hybrid policy pairs may be highly politically acceptable even if the environmental effects of every policy option are the same. If the regulator allows the firm to choose the policy pair (P,e), the firm can minimize its compliance costs by optimizing Equation (8) with respect to one of the policy instruments, e. To minimize compliance costs, we differentiate Equation (8) with respect to e,

$$\frac{\partial TC}{\partial e} = \frac{\partial E_y[Z(u \mid f(e \mid u^*, E(y_s)), e, y_f)]}{\partial e} = 0, \tag{9}$$

after which we derive $e^*(u^*, E(y_s), E(y_f))$. We plug Equation (9) back into Equation (7) and derive $P^*(u^*, E(y_s), E(y_f))$. The solution $(P^*(u^*, E(y_s), E(y_f)),$ $e^*(u^*, E(y_s), E(y_f)))$ now represents a set of efficient policy pairs that simultaneously achieves the socially optimal abatement, u_s^*, and the minimization of compliance costs for the firm, TC. This policy pair is the most efficient and politically feasible regulation option.[2]

III. Analyzing the Comparative Statics with the Calibrations

We attempted to analyze comparative statics and calibrations to extract policy implications from the equilibrium results. For calibration, we assume functional forms of objective functions and parameter values to derive a simplified closed form solution.

1. Comparative Statics

The price and quantity instruments incorporated in the emissions control system are defined in Equation (10). The firm should pay P rate of penalty per additional unit of emission over the sum of the emissions cap and abatement, $(e+u)$. A non-linear penalty program can be a generalized functional form, but our model uses the marginally linear per-unit penalty, as is the case for most environmental regulations in the real world. This scheme is the most commonly used quantity regulation by command-and-control, which imposes a certain rate of over-emissions beyond a certain free-quota. The current paper focuses on how to simultaneously determine the penalty rate with the amount of free-quota (or

[2] The ordering of optimization does not affect the solution. We solve simultaneous equations with two problems (the social planner and the representative) and two unknowns (P,e). The answers are not affected by the order of solution.

emission cap) to be socially optimal as is usually designed in the optimal "fixed" Pigouvian tax rate.

Moreover, we must define a probability distribution regarding uncertainty in emissions, y. For simplicity, we assume a uniform probability density function with an upper limit, $U[0,\bar{y}]$.[3] The assumption that emissions levels are uncertain—rather than specifically chosen by the firm—is equivalent to assuming that firms do not control their output decisions, but rather decide on their emission abatement based on the policies imposed by environmental regulations. The problems defined by stochastic abatement or stochastic emissions are isomorphic to one another; we chose stochastic emissions following Seifert *et al.* (2008) and Maeda (2012). Uncertain emissions cause uncertainty in environmental damage, and uncertain abatement causes uncertainty in abatement costs.[4]

$$Z(u;P,e,y) = P\max[0, y-(e+u)] \tag{10}$$

We assume these functional forms and attempt comparative statics of the equilibria by deriving the closed form solution. Appendix A contains additional details on the differentiability of this penalty payment term. Table 1 shows that the penalty rate increases as a lenient emissions cap is applied to maintain the level of abatement. Moreover, the policy equilibria (P^*, e^*) tend to decrease when $\bar{y}_f$ is higher than certain criteria, whereas the equilibria increase when $\bar{y}_f$ is lower than certain criteria.

The relationship between the penalty rate and the free emissions quota is straightforward in its interpretation. To maintain the same level of regulation or socially requested abatement amount, u^*, lenient price control should accompany restrictive quantity control and vice versa, that is, $\frac{de(u^*)}{dP(u^*)} > 0$, which is illustrated in the next section.

Regarding the preferred penalty rate, the firm pays tax or penalty at a fixed rate per emission unit, as defined in Equation (10). Under the uniform distribution, then the firm could pay a penalty equal to the over-emitted amount. The results show that the firm seeks a lower penalty rate as the probability of over-emitting increases, $\frac{dP}{d\bar{y}_f} < 0$, which can happen even if the free emissions quota level decreases from the first result, $\frac{de(u^*)}{dP(u^*)} > 0$. Hence, the firm is willing to give up the free emissions quota tantamount to a low-level per-unit penalty rate that would minimize compliance costs.

[3] We assume that both representative players are risk-neutral; thus, the qualitative results are not affected by the different probability distributions of stochastic emissions. Furthermore, this specification allows for the model tractability of the different assumptions regarding the probability density function of emissions.

[4] This assumption does not affect the results of our study, because both uncertainties contribute to the emissions stock in the same way.

[Table 1] Comparative Static Results

Condition	Changes in equilibrium
u^*	$\dfrac{de(u^*)}{dP(u^*)} > 0$
$\overline{y}_f \geq (u^* + e)$	$\dfrac{dP^*}{d\overline{y}_f} < 0$
$\overline{y}_f < (u^* + e)$	$\dfrac{dP}{d\overline{y}_f} > 0$

Note: Penalty rate increases as a lenient emissions cap is applied to maintain the level of abatement. The preferred level of the penalty rate, P^* (and with e^*), depends on the comparative level of maximum emissions, $\overline{y}_f$. If the firm pays a penalty because it emits more than the compliance instrument dictates, $y_f > (u^* + e)$, the firm always prefers a low level of (P^*, e^*) as y_f increases. However, if a penalty becomes unnecessary because the maximum emissions, $\overline{y}_f$, are less than the maximum set in the compliance instrument, then the firm always prefers to have a high emissions cap and accordingly a high penalty rate.

Conversely, if the maximum level of emissions, $\overline{y}_f$, is lower than compliance $(u^* + e)$, then the firm cannot pay anything by uncertainty in emissions. The firm then prefers a high penalty rate even with a high probability of over-emitting, $\frac{dP}{d\overline{y}_f} > 0$. Thus, the firm focuses more on obtaining free quotas to assure full compliance, that is, $\overline{y}_f < (u_s^* + e)$.

The next section calibrates the model to compare the results with the comparative statics we derived in the current section.

2. Calibration

To specify the functional forms of objective functions, we follow the assumptions regarding the functional form of abatement costs, parameter values, and the probability density function for emission uncertainty, which Yu et al. (2015) used in their work. The assumption regarding the abatement cost function is to obtain the quadratic functional forms so that the marginal abatement costs are linear (Mendelsohn, 1986; Ha-Duong, Grubb and Hourcade, 1997; Byström, 1998; Hoel and Karp, 2002; Webster, 2002; Hart, 2003; Karp and Zhang, 2005, 2006; Du, Hanley, Wei, 2015). The marginal functions are linear in the explanatory variables, as previous studies have assumed.

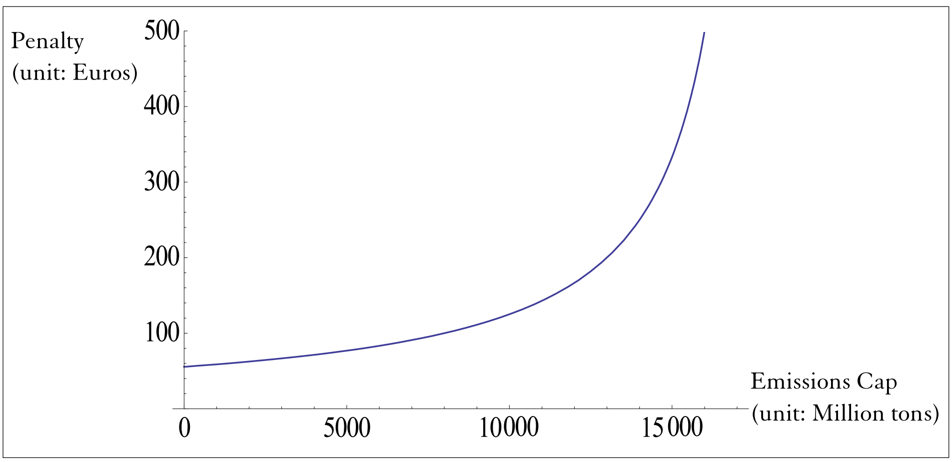
$$C(u) = \frac{1}{2}cu^2 \tag{11}$$

We use the parameters of the climate policy in EU for calibration purposes contained in Table 2. The European Council has declared that the EU aims to reduce its greenhouse gas emissions at least 20 percent lower than the 1990 level by 2020. Because the total emissions amount during Phase II was approximately 9,665 million tons of CO_2 equivalents, we assume the abatement goal parameter to be 20% of the actual emissions, or 2000 million tons. The upper limit of emissions is based on the regulator's information, $\overline{y}_s$, so we assume the parameters of the expected value of emissions, $E(\overline{y}_s)$, to be the same as the actual emissions amount during Phase II. Because we use the uniform distribution for calibration purposes, $\overline{y}_s$ is assumed to be roughly equal to 20 billion tons of CO_2 equivalents.

[Table 2] Parameters chosen to plot hybrid policy pairs

Parameters	Values
Marginal abatement costs per ton of emissions, c	0.025
Optimal abatement amount, u^*	2,000
Stochastic emissions upper limit, $\overline{y}_s$	20,000

[Figure 1] Indifferent hybrid policy pairs of the social planner (given u_s^*)

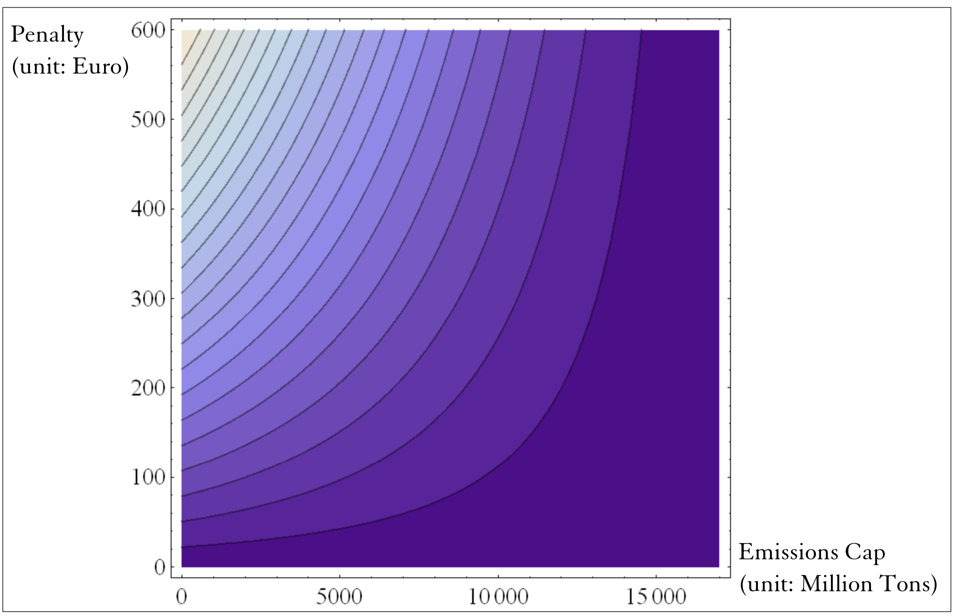


Note: Figure 1 depicts the optimal locus of policies, (P, e) when u_s^* is secured. The area above the locus represents policy pairs that encourage the firm to abate more than the optimal amount, whereas the area below the locus represents policy pairs that incentivize the firm to abate less than the optimal amount.

Figure 1 depicts the locus of policy pairs, (P, e), in the calibrated model as described in the regulator's model set forth in equation (7). Once the regulator decides on the optimal abatement level, u^*, the policy pairs in Figure 1 induce the firm to abate the same amount as the regulator's plan, u^*. We can call the regulator's indifference curve the *iso-abatement* curve. This means that all policy options would bring about the same environmental effect by achieving the same emission abatement level. The calibrated results correspond to the results of the comparative statics in the previous section as well as the results of other studies (Jacoby and Ellerman, 2004): a per-unit penalty raises the regulator's abatement, and the quantity cap reduces the regulator's abatement, $(\partial u^* / \partial P > 0, \partial u^* / \partial e < 0)$.

In addition to the regulator's iso-abatement curve, the firm has its own indifference curves. In Figure 2, we illustrate the indifference curves where the regulated firm has the same expected compliance costs; thus, we call the firm's indifference curve the *iso-cost* curve. In other words, within the same curve, the firm is indifferent to any combination of the emissions cap and penalty. Similar to the regulator's indifference curve, the penalty rate increases the firm's abatement, and the quantity cap reduces the firm's abatement, $(\partial u^*(B|P,e) / \partial P > 0, \partial u^*(B|P,e) / \partial e < 0)$. Of course, the firm's iso-curve is not guaranteed to cause the same level of environmental protection, u^*, meaning that all policy pairs represent the same compliance costs but can generate different levels of emissions abatement.

[Figure 2] Contour set of the firm's hybrid policy pairs (different levels of compliance costs)

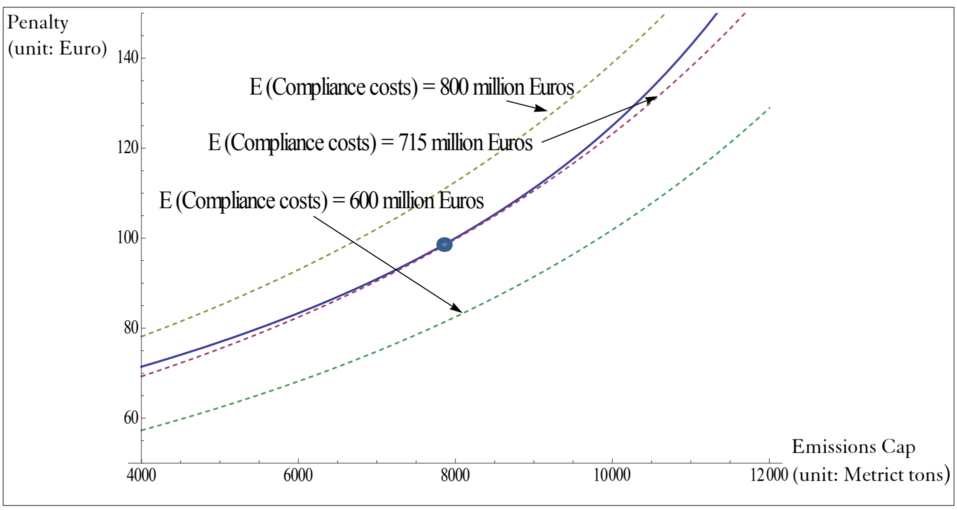


Note: Figure 2 depicts optimal loci of policies, (P, e) with each representing a different level of compliance costs. A policy locus with a higher penalty rate and a lower emissions cap has higher compliance costs.

Therefore, the point that results in expected minimal compliance costs is the point at which the iso-curve of the firm is tangential to the iso-abatement curve of the regulator. Once the firm finds its optimal hybrid policy, the industry may lobby congress to choose that policy bundle, and the regulator would likely be inclined to accept this political pressure because any policy choice among the optimal sets would be inconsequential to the government's environmental goal.

For calibration purposes, it is important to assume comparative sizes for $(\bar{y}_s, \bar{y}_f)$. In a real-world policy environment, the regulated agent hides the accurate information regarding its BAU from the regulator, and the regulator does not believe an industry's BAU as reported. Hence, we must consider how different expectations of the BAU, $E(y_s) \neq E(y_f)$, affect the policy mix in calibration. When the firm's expected emissions level is higher than the regulator's, that is, $E(y_s) \leq E(y_f)$, we assume two parameters to describe the upper limit, $\bar{y}_s$ and $\bar{y}_f$, where $\bar{y}_s < \bar{y}_f$. Likewise, $E(y_s) > E(y_f)$ can be described by assuming that $\bar{y}_s \geq \bar{y}_f$. The closed form solutions driven from functional assumptions are shown below, and they also correspond to the results of the comparative statics in Section 3.2.

[Figure 3] The most popular hybrid policy pairs (when $\bar{y}_s < \bar{y}_f$)



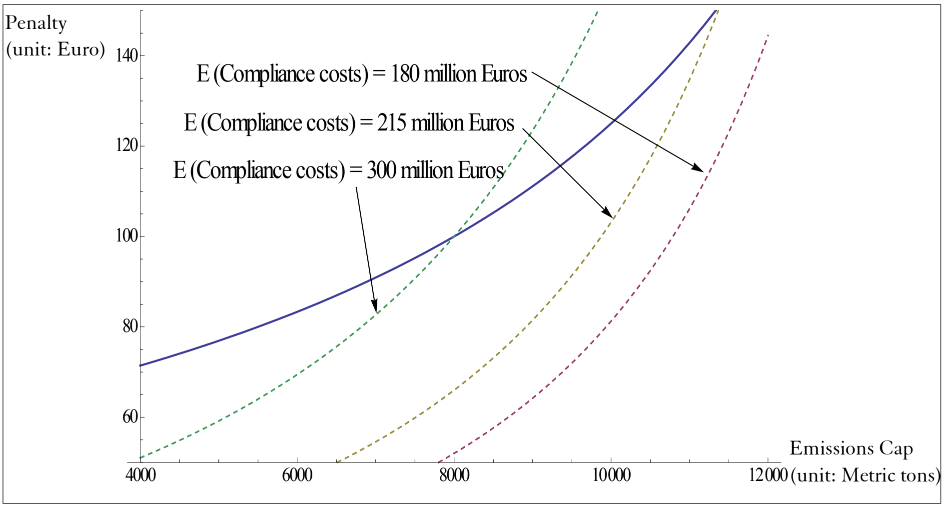
Note: Figure 3 illustrates a case where the firm can minimize expected compliance costs up to 715 million Euros by supporting (P=95, e=8000). The firm's indifference curve (indicated by a dashed line) is tangential to the regulator's indifference curve (solid line).

Figure 3 describes the case of $\bar{y}_s < \bar{y}_f$, where the regulator overestimates the actual emission levels .

$$(e^*(u^*, E(y_s), E(y_f)), P^*(u^*, E(y_s), E(y_f))) = \left(-u^* + 2\bar{y}_s - \bar{y}_f, \; {cu^*\bar{y}_s}\Big/{(\bar{y}_f - \bar{y}_s)} \right)$$

We see the firm's iso-cost curve become tangent to the iso-abatement curve of the regulator, which indicates a solution that satisfies the 1st and 2nd order condition. This calibration result is robust, regardless of parameters, if the condition, $\bar{y}_s < \bar{y}_f$, holds true.

[Figure 4] The most popular hybrid policy pairs (when $\overline{y}_s \geq \overline{y}_f$)



Note: Figure 4 presents a case where the firm's indifference curve (dashed line) is not tangential to the regulator's indifference curve (solid line). Thus, a corner solution with an infinite penalty rate is chosen.

Figure 4 shows the case in which the firm's iso-cost curve cannot be tangent to the regulator's iso-abatement curve, the corner solution.

$$(e^*(u^*, E(y_s), E(y_f)), P^*(u^*, E(y_s), E(y_f))) = \left(-u^* + \overline{y}_f, \; cu^*\overline{y}_s \big/ (\overline{y}_s - \overline{y}_f) \right)$$

Accordingly, the firm generates minimum compliance costs when the hybrid policy approximates the pure quantity regulation with an extremely high price rate and corresponding high quantity cap. This means that the pure quantity instrument becomes the politically preferred policy mix. Although a small amount of additional permit endowments causes a steep marginal increase in the per-unit penalty, the firm always prefers to have an additional emissions cap.

3. Policy implications

Figure 3 describes the case, $E(y_s) \leq E(y_f)$, where the firm knows its actual emissions are likely to be over the emissions cap, which makes the firm consider the potential of penalty payments for noncompliance. From the optimal policy string in Figure 1, the firm knows that the penalty rate marginally increases according to the increase in the emissions cap. Hence, the firm would not tolerate a steep increase in the penalty rate in exchange for a small increase in the emissions cap.

From the condition $E(y_s) > E(y_f)$, Figure 4 presents an uninteresting and straightforward corner solution – all price or all quantity. This assumption is not realistic. The industry typically exaggerates actual baseline emission numbers to induce favourable regulations from the government, which means the government's emissions estimates are generally lower than the firm's stated estimate. Furthermore, even if the $E(y_s) > E(y_f)$ assumption holds true, the result is not surprising or interesting because the firm wishes to avoid penalty payments for the highest emissions cap, regardless of the penalty amount. The firm knows that actual emissions would probably be lower than the regulator's forecast, and then the firm would choose the policy mix with a high (P, e) from the policy menu. When the firm follows the regulator's abatement goal, which might be overestimated by $E(y_s) > E(y_f)$, then the firm is less likely to emit over the cap and will not worry about paying the penalty for exceeding the emissions cap. Thus, the firm's priority is always extending the free emissions cap, regardless of the penalty level.[5]

IV. Conclusion

After a long history of research on price controls versus quantity controls on emissions, this is the first study to highlight the political feasibility of a regulation. We theoretically investigated the features of price-quantity control applied to environmental regulations while considering the perspective of the regulated agent. As a result, it becomes possible to make regulations more acceptable by permitting regulated agents to choose a specific option. Regulated agents can participate in the process of decision-making to reflect their positions as stakeholders. This can also facilitate voluntary compliance with the rules and decrease the incentives for noncompliance. Of course, not every regulator is indifferent to expected levels of noncompliance and sanctions, but this theoretic analysis will assist the regulator when considering a regulation structure in the future.

Theoretical simplifications such as the representative firm or the linear penalty system utilized in this article drive our primary message. In summary, the regulator and the regulated agent have different goals: minimizing social environmental costs and minimizing industry compliance costs. Hence, the government can suggest multiple price-quantity policy mixes to induce an environmental goal because the marginal effect from one instrument in a hybrid policy can be offset by the marginal loss from the other instrument. However, the firm may have different preferences on each policy mix.

Our analyses using comparative statics and calibrations provide insight regarding how the optimal politically feasible regulation can be chosen. Among suggested

[5] Note that when $\overline{y}_s \geq \overline{y}_f$, the tangent point that satisfies the second-order condition of optimization represents maximum compliance costs, not minimal costs.

policy options, there would be a unique policy pair preferred by the industry among the regulator's suggested policy options. Based on the proposed model, iso-cost curves with idiosyncratic slopes from the different policy preferences can lead to a unique solution.

As a possible extension, heterogeneity for multiple firms would be possible. Furthermore, it is worth assuming different risk attributes or functional forms of abatement costs and trying sensitivity analysis from different key assumptions. For example, if the firm is more risk-averse than the regulator, the firm would be more likely to avoid a high penalty rate, even though it would relinquish only a small amount of its permit endowment.

Appendix A

From the first-order condition in equation (2), we substitute a penalty payment term with equation (10) as below[6]

$$\frac{\partial(Cu^*)}{\partial u^*}+\frac{\partial P\cdot \max[0, y-(e+u^*)]}{\partial u^*}=0 \tag{12}$$

To see how the policy pair interacts while u_s^* is kept constant and compliance cost is minimal, we use the implicit function theorem with respect to e and P,

$$\left\{\frac{\partial^2 P\cdot \max[0, y-(e+u^*)]}{\partial u^*\partial e}\right\}de+\left\{\frac{\partial \max[0, y-(e+u^*)]}{\partial u^*}\right\}dP=0 \tag{13}$$

From the implicit function theorem that shows the relationship between variables as a functional form, equation (13) can be converted as below

$$\frac{de}{dP}=-\frac{\left\{\frac{\partial^2 E\max[0,y-(e+u^*)]}{\partial u^*\partial e}\right\}}{\left\{\frac{\partial P\cdot E\max[0,y-(e+u_s^*)]}{\partial u^*}\right\}} \tag{14}$$

The sign of the denominator, $\frac{\partial P\cdot E\max[0,y-(e+u^*)]}{\partial u^*}$, is always negative. Thus, we need to see the sign of the numerator, $\frac{\partial^2 E\max[0,y-(e+u^*)]}{\partial u^*\partial e}$, in order to see the sign of $\frac{de}{dP}$. By substituting $(e+u^*)$ for A, a differentiation with respect to u^* is expressed as

$$\begin{aligned}\frac{\partial\int_A^{\bar{y}}(y-A)dy}{\partial A}\cdot\frac{\partial A}{\partial u^*}&=\frac{\partial\left(\int_A^{\bar{y}}ydy-A\int_A^{\bar{y}}1dy\right)}{\partial A}\cdot\frac{\partial A}{\partial u^*}\\&=\frac{\partial\left(\frac{1}{2}(\bar{y}^2-A^2)-A\bar{y}+A^2\right)}{\partial A}\cdot 1=A-\frac{\bar{y}}{2}\end{aligned} \tag{15}$$

The second differentiation of equation (15) with respect to e is

[6] $u^*=u_f^*=u_s^*$.

$$\frac{\partial(A-\frac{\overline{y}}{2})}{\partial e}=1 \tag{16}$$

Therefore, we conclude that the sign of $\frac{de}{dP}$ should be positive, which means the penalty rate should always increase as a lenient emission cap is applied to keep the socially desirable abatement level constant; i.e., $\frac{de(u^*)}{dP(u^*)}>0$.

Then, we again apply the implicit function theorem to equation (12) with respect to $\overline{y}_f$ and P,

$$\left\{\frac{\partial^2 P(u^*)\cdot\max[0,y-(e+u^*)]}{\partial u^*\partial\overline{y}_f}\right\}d\overline{y}_f+\left\{\frac{\partial\max[0,y-(e+u^*)]}{\partial u^*}\right\}dP(u^*)=0 \tag{17}$$

$$\frac{d\overline{y}_f}{dP}=-\frac{\left\{\frac{\partial^2 P(u^*)\cdot E\max[0,y-(e+u^*)]}{\partial u^*\partial\overline{y}_f}\right\}}{\left\{\frac{\partial E\max[0,y-(e+u^*)]}{\partial u^*}\right\}} \tag{18}$$

Because we know the sign of denominator (+), we need to verify the sign of the numerator, $\frac{\partial^2 P(u^*)\cdot E\max[0,y-(e+u^*)]}{\partial u^*\partial\overline{y}_f}$. By substituting $(e+u^*)$ for A, the first-order condition is a differentiation with respect to u^*, as below

$$\begin{aligned}
\frac{\partial P(u^*)\cdot E\max[0,y-(e+u^*)]}{\partial u^*}&=P(u^*)\cdot\frac{\partial\int_A^{\overline{y}_f}(y-A)dy}{\partial u^*}+P'(u^*)\cdot\int_A^{\overline{y}_f}(y-A)dy\\
&=P(u^*)\cdot\frac{\partial\int_A^{\overline{y}_f}(y-A)dy}{\partial A}\cdot\frac{\partial A}{\partial u^*}+P'(u^*)\cdot\int_A^{\overline{y}_f}(y-A)dy\\
&=P(u^*)\cdot\frac{\partial\left(\int_A^{\overline{y}_f}ydy-A\int_A^{\overline{y}_f}1dy\right)}{\partial A}\cdot\frac{\partial A}{\partial u^*}+P'(u^*)\cdot\int_A^{\overline{y}_f}(y-A)dy\\
&=P(u^*)\cdot\frac{\partial\left(\frac{1}{2}(\overline{y}_f^2-A^2)-A\overline{y}_f+A^2\right)}{\partial A}\cdot 1+P'(u^*)\cdot\int_A^{\overline{y}_f}(y-A)dy\\
&=P(u^*)\cdot(A-\overline{y}_f)+P'(u^*)\cdot\int_A^{\overline{y}_f}(y-A)dy
\end{aligned} \tag{19}$$

The second-order condition is a differentiation with respect to the maximum level of a firm's emissions, $\overline{y}_f$, as below.

$$\frac{\partial P(u^*)\cdot(A-\overline{y}_f)+P'(u^*)\cdot\int_A^{\overline{y}_f}\left(y-A\right)dy}{\partial\overline{y}_f}$$

$$=P(u^*)+P'(u^*)\cdot\frac{\partial(\frac{1}{2}(\overline{y}_f^2-A^2)-A\overline{y}_f+A^2)}{\partial\overline{y}_f}$$

$$=\ P(u^*)+P'(u^*)\cdot(\overline{y}_f-A)$$

$$=P(u^*)+P'(u^*)\cdot(\overline{y}_f-u^*-e) \tag{20}$$

Because $(u^*)>0, P'(u^*)>0$, the sign depends on whether $\overline{y}_f > or < (u^*+e)$. Either of the optimal policy instruments should increase as the firm expects higher emissions, $\frac{dP}{d\overline{y}_f}<0$ and $\frac{de}{d\overline{y}_f}<0$ when $\overline{y}_f$ is greater than (u^*+e), whereas either of the optimal policy instruments should decrease as the firm expects lower emissions $\frac{dP}{d\overline{y}_f}>0$ and $\frac{de}{d\overline{y}_f}>0$ when $\overline{y}_f$ is less than (u^*+e) .This analysis focuses on ex ante, where the regulator is indifferent to the policy pairs made with different combinations between price and quantity, whereas they are certainly not indifferent ex post.

Appendix B

1. Strictly Convexity

From the perspective of the social planner, an indifference curve for any given u is:

$$P_s(e)=-\frac{cu\overline{y}_s}{e+u-\overline{y}_s}$$

1) First, $P_s(e)$ is strictly convex in e under the assumption of $e+u<\overline{y}_s$ because:

$$P_s''(e)=\frac{-2cu\overline{y}_s}{(e+u-\overline{y}_s)^3}>0$$

From the perspective of a firm, an indifference curve for any given u is:

$$P_f(e) = \frac{TC - 0.5cu^2}{-e - u + \frac{0.5e^2}{\overline{y}_f} + \frac{eu}{\overline{y}_f} + \frac{0.5u^2}{\overline{y}_f} + 0.5\overline{y}_f} = \frac{2\overline{y}_f(TC - 0.5cu^2)}{(e + u - \overline{y}_f)^2}$$

2) $P_f(e)$ is strictly convex in e under the assumption of $e + u < \overline{y}_s < \overline{y}_f$ and $TC - 0.5cu^2 > 0$ because:

$$P_f''(e) = \frac{12\overline{y}_f(TC - 0.5cu^2)}{(e_t + u - \overline{y}_f)^4} > 0$$

In conclusion, under the following 3 assumptions, $P_s(e)$ and $P_f(e)$ are strictly convex in e.

A1) $e + u < \overline{y}_s$
A2) $\overline{y}_s < \overline{y}_f$
A3) $TC - 0.5cu^2 > 0$

2. Uniqueness of the Tangent Point

The tangent point (e_t, P^t) of two indifference curves should satisfy the following conditions:

3) $P_s^t(e_t) = P_f^t(e_t)(*)$

4) At $e = e_t$, $\dfrac{dP_s^t}{de} = \dfrac{dP_f^t}{de}(**)$

The first condition $P_s^t(e_t) = P_f^t(e_t)$ implies the following:

$$\frac{2\overline{y}_f(TC - 0.5cu^2)}{(e_t + u - \overline{y}_f)^2} = -\frac{cu\overline{y}_s}{e_t + u - \overline{y}_s}$$

The second condition $\frac{dP_s^t}{de} = \frac{dP_f^t}{de}$ at $e = e_t$ implies the following:

$$\frac{cu\overline{y}_s}{(e_t + u - \overline{y}_s)^2} = -\frac{4\overline{y}_f(TC - 0.5cu^2)}{(e_t + u - \overline{y}_f)^3}$$

By using the first condition, the second condition is as below:

$$\frac{cu\overline{y}_s}{(e_t+u-\overline{y}_s)^2}=\frac{2cu\overline{y}_s}{(e_t+u-\overline{y}_f)(e_t+u-\overline{y}_s)}$$

This implies that:

$$2=\frac{e_t+u-\overline{y}_f}{e_t+u-\overline{y}_s}(***)$$

For any given u, when $\overline{y}_s \geq \overline{y}_f$, there is no $e_t > 0$ that satisfies the above equation, which implies that there is no tangent point (e^t, P^t) of two indifference curves in the case of $y_s^{bar} \geq y_f^{bar}$. In this case, only possible solution is e_t+u^* $-\overline{y}_f=0$ because a firm would like to increase the emission cap as much as possible.

Hence, $e_t=-u^*+\overline{y}_f$ and the corresponding P is determined by the social planner's indifference curve:

$$P=-\frac{cu\overline{y}_s}{e_t+u^*-\overline{y}_s}=-\frac{cu^*\overline{y}_s}{\overline{y}_f-u^*+u^*-\overline{y}_s}=-\frac{cu^*\overline{y}_s}{\overline{y}_f-\overline{y}_s}=\frac{cu^*\overline{y}_s}{\overline{y}_s-\overline{y}_f}$$

Now assume that $\overline{y}_s<\overline{y}_f$. By using $(***)$, we can find a tangent point $e=e_t$ such that:

$$e_t=2\overline{y}_s-\overline{y}_f-u^*$$

Furthermore, $P^t=P_s^t(e_t)=P_f^t(e_t)$ is calculate with $e=e_t$ as below:

$$P^t=-\frac{cu^*\overline{y}_s}{e_t+u^*-\overline{y}_s}=-\frac{cu^*\overline{y}_s}{2\overline{y}_s-\overline{y}_f-u^*+u^*-\overline{y}_s}=-\frac{cu^*\overline{y}_s}{\overline{y}_s-\overline{y}_f}$$

Therefore, we can conclude that, for any given $\overline{y}_s, \overline{y}_f$, and u^*, there is a unique (e_t, P^t) that satisfies the above equations, under the following assumptions:

A1′) $e_t+u^*<\overline{y}_s$

A2′) $\overline{y}_s<\overline{y}_f$

A3′) $TC-0.5cu^{*2}>0$

3. Comparison of Curvatures

For any function $y=f(x)$, the curvature κ at x is given by the following formula:

$$\kappa(x) = \frac{|f''(x)|}{(1+(f'(x))^2)^{\frac{3}{2}}} (\#)$$

We need to show $\kappa_s(e_t) > \kappa_f(e_t)$ where $\kappa_s(e_t)$ is the curvature of $P_s(e)$ at $e = e_t$ and $\kappa_f(e_t)$ is the curvature of $P_f(e)$ at $e = e_t$ to show that two indifference curves could only meet at the unique tangent point. We need following derivatives:

1) $P_s^{t'}(e_t) = \dfrac{cu^*\overline{y}_s}{(e_t + u^* - \overline{y}_s)^2} = \dfrac{cu^*\overline{y}_s}{(\overline{y}_s - \overline{y}_f)^2}$

2) $P_f^{t'}(e_t) = -\dfrac{4\overline{y}_f(TC - 0.5cu^{*2})}{(e_t + u^* - \overline{y}_f)^3} = \dfrac{4\overline{y}_f(TC - 0.5cu^{*2})}{(2\overline{y}_s - \overline{y}_f - u^* + u^* - \overline{y}_f)^2} = \dfrac{\overline{y}_f(TC - 0.5cu^{*2})}{(\overline{y}_s - \overline{y}_f)^2}$

$= P_s^{t'}(e_t)\ by\ (**)$

3) $P_s''(e_t) = \dfrac{-2cu^*\overline{y}_s}{(e_t + u^* - \overline{y}_s)^3} = \dfrac{-2cu^*\overline{y}_s}{(\overline{y}_s^{bar} - \overline{y}_f)^3}$

4) $P_f''(e_t) = \dfrac{12\overline{y}_f(TC - 0.5cu^{*2})}{(e_t + u^* - \overline{y}_f)^4} = \dfrac{12\overline{y}_f(TC - 0.5cu^{*2})}{16(\overline{y}_f - y_s^{bar})^4} = \dfrac{3\overline{y}_f(TC - 0.5cu^{*2})}{4(\overline{y}_f - \overline{y}_s)^4}$

However, by $(*)$,

$$TC - 0.5cu^{*2} = -\frac{cu^*\overline{y}_s(e_t + u^* - \overline{y}_f)^2}{2\overline{y}_f(e_t + u^* - \overline{y}_s)} = -\frac{4cu^*\overline{y}_s(\overline{y}_s - \overline{y}_f)^2}{2\overline{y}_f(\overline{y}_s - \overline{y}_f)} = \frac{2cu^*\overline{y}_s(\overline{y}_f - \overline{y}_s)}{\overline{y}_f}$$

This implies that:

$$P_f''(e_t) = \frac{3\overline{y}_f(TC - 0.5cu^{*2})}{4(\overline{y}_f - \overline{y}_s)^4} = \frac{2cu^*\overline{y}_s(\overline{y}_f - \overline{y}_s)}{\overline{y}_f}\frac{3\overline{y}_f}{4(\overline{y}_f - \overline{y}_s)^4} = \frac{3cu^*\overline{y}_s}{2(\overline{y}_f - \overline{y}_s)^3}$$

So,

4′) $P_f''(e_t) = \dfrac{3cu^*\overline{y}_s}{2(\overline{y}_f - \overline{y}_s)^3}$

By Plugging 1), 2), 3) and 4’) into $(\#)$, we can calculate the curvatures at $e = e_t$ as followings:

$$\kappa_s(e_t) = \frac{\frac{-2cu^*\overline{y}_s}{(\overline{y}_s - \overline{y}_f)^3}}{\left(1 + \left(\frac{cu^*\overline{y}_s}{(e_t + u^* - \overline{y}_s)^2}\right)^2\right)^{\frac{3}{2}}}$$

$$\kappa_f(e_t) = \frac{\frac{3cu^*\overline{y}_s}{2(\overline{y}_f - \overline{y}_s)^3}}{\left(1 + \left(\frac{4\overline{y}_f(TC - 0.5cu^{*2})}{(e_t + u^* - \overline{y}_f)^3}\right)^2\right)^{\frac{3}{2}}}$$

Therefore, by using $(**)$, $\kappa_s(e_t) > \kappa_f(e_t)$ if and only if:

$$\frac{-2cu^*\overline{y}_s}{(\overline{y}_s - \overline{y}_f)^3} > \frac{3cu^*\overline{y}_s}{2(\overline{y}_f - \overline{y}_s)^3}$$

$$\Leftrightarrow \frac{2cu^*\overline{y}_s}{(\overline{y}_f - \overline{y}_s)^3} > \frac{3cu^*\overline{y}_s}{2(\overline{y}_f - \overline{y}_s)^3}$$

This inequality always holds.

In conclusion, $\kappa_s > \kappa_f$ at $e = e_t$ under the following assumptions:

5) $e_t + u^* < \overline{y}_s$
6) $\overline{y}_s < \overline{y}_f$
7) $TC - 0.5cu^{*2} > 0$

Under the assumptions A1′), A2′), and A3′), by the strict convexities of $P_s(e)$ and $P_f(e)$, the unique tangent point (e_t, P^t), and $\kappa_s(e_t) > \kappa_f(e_t)$, we can conclude that two indifference curves only meet at (e_t, P^t), which is a unique tangent point for any given $\overline{y}_s, \overline{y}_f$, and u^*.

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