ESSAYS ON SECOND-BEST ECONOMIC POLICYMAKING WITH PRICE MAKERS

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Abstract

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The first essay of this dissertation analyzes the claim that a Marshallian total surplus optimum characterizes a second-best Pareto optimum in a general equilibrium model with price makers. The main result of this essay is that a Marshallian total surplus optimum corresponds to a second-best Pareto optimum when (i) the consumer's preferences are quasi-linear with respect to a numéraire, and (ii) for all other markets except the one under consideration, first-best (or Paretian) optimality conditions are satisfied.

The second essay characterizes the optimal regulatory policy for point-source pollution emissions when firms are competing in Cournot fashion in the product market and have private information about their own cost. It is shown that the optimal regulatory policy benefits from the strategic interaction between the firms in the output market even though the firms' private information is uncorrelated. The firms strategic interaction in the output market acts as an information correlation externality that mitigates the well-known *"rent-extraction efficiency"* trade-off. Each firms' opportunity to over-report their costs is reduced because the output market's strategic interaction reduces the profitability of infra-marginal units if they do. The main result shows that optimal environmental regulations discriminate between firms of given industry. Moreover, it is shown that if the regulator believes that firm A is always more likely to be efficient than firm B (in the sense of first-order stochastic dominance) and that both firms are equally efficient *ex post*, then firm A faces a higher marginal tax than its competitor. In light of this result, it is argued that the model provides theoretical foundations for grandfather clauses in environmental regulations.

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Dedication

À ma mère, ainsi qu'à la mémoire de mon père.

Chapter 1

Introduction

Since Dupuit (1844), economists have relied on partial equilibrium models to evaluate the welfare consequences of public projects and public policies. Indeed, in almost every field of economics, one often finds social welfare defined as the sum of consumers' and producers' surplus, or namely, 'total surplus'. Total surplus is most often regarded implicitly, and on some occasions explicitly,[1] as an appropriate *normative* social welfare objective function in order to conduct positive or normative welfare analysis of various distortions or government policies.[2] While the application of partial equilibrium welfare analysis in first-best (or, perfectly competitive) economies has theoretical foundations,[3] the theoretical justification for its application in second-best economies has not received the same attention. Yet, the most attractive feature of partial equilibrium welfare analysis truly lies in its ability to provide a reliable and tractable framework of analysis for economists and policymakers in complex second-best economies. This dissertation reconsiders two 'first-best' (or Paretian) traditional partial equilibrium approaches to economic

[1] See Besanko (1985a, p. 41) for such an explicit statement.

[2] Consumers' surplus is the area between the aggregate demand curve and a horizontal line determined by the price level. Producers' surplus is simply the economic profits of producers. Consumer surplus is frequently referred to as Marshallian consumer surplus (see Marshall (1920, p.811)), and occasionally as Dupuit-Marshall consumer surplus (see Blackorby and Donaldson (1999)). The use of the term 'total surplus' to represent the unweighted sum of consumers' and producers' surplus is made for greater clarity.

[3] See Mas-Colell, Whinston and Green (1995, Chap.10).

policymaking in the context of a second-best economy with price makers.[4]

In the second chapter of this dissertation it is shown that the traditional partial equilibrium analytical approach is appropriate in a second-best economy with price makers under restrictive assumptions about preferences and the competitiveness of a general equilibrium. Then, applying the result of the previous chapter, the third chapter of this dissertation shows that discriminatory regulations are optimal in a second-best economy where price making firms have private information about their costs. A corollary of this chapter provides theoretical justification for grandfathering regulations where an older firm faces a lower tax on pollution than a newer firm. The contribution of this dissertation is best understood in light of the following literature.

There is a plethora of examples in the industrial organization literature that implicitly assume that total surplus is an appropriate (or a reasonable approximation) social welfare objective function in order to perform "objective" positive or normative welfare analysis of distortions, externalities, and government policies.[5] Similar approaches are also found in the environmental economics (e.g. Roberts and Spence (1976), Adar and Griffin (1976)), the international trade (e.g. Brander and Spencer (1981)), and the tax incidence literature (e.g. Auerbach (1985)). But more importantly, there is such a practical and intuitive appeal to partial equilibrium welfare analysis that the concept has expanded naturally to—and is often most vigorously defended by practionners in—public policy circles.[6]

Still, because the empirical evidence and several other theoretical objections which

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[4]In this dissertation, price makers refers to imperfectly competitive producers as in Guesnerie and Laffont (1978).

[5]For example, see Baron and Myerson (1982), Waterson (1984), Braeutigam (1989), Shapiro (1989), Armstrong and Vickers (1993), and Wolinsky (1997).

[6]For example, endorsing the seminal antitrust contribution of Williamson (1968), the Canadian antitrust enforcement agency adopted a total surplus 'approach' to determine the overall welfare effects of an anticompetitive merger that yields technical efficiency gains (see Competition Bureau (1991, p.49)). Then, Sanderson (1997) and McFetridge (1998) among others argued that total surplus was the only adequate welfare measure even after the Canadian Competition Tribunal's decision in *Hillsdown* (1992) criticized and questioned the ability of 'total surplus' to adequately measure 'total welfare' on appropriate grounds.

suggest that partial equilibrium welfare analysis is not accurate nor reliable, it is quite remarkable how 'total surplus economics' has persisted apart from "dogma and sloppiness" (Hammond (1990)).[7] There appears to be two main arguments in defense of partial equilibrium welfare analysis.

In many-consumers economies, the argument often appears to rest on the application to partial equilibrium models of the second fundamental theorem of welfare economics. This theorem is widely interpreted as meaning that social welfare judgements can be made in abstraction of equity objectives because the issue of efficiency can be separated from redistribution when analyzing the effects of distortions or public policies. For example, Tirole (1988) relies on a public sector's institutional framework outlined by Musgrave (1959) where the distribution branch of government worries about wealth redistribution and the allocation branch of government deals with efficiency. Then, using the compensation principle (see Hicks (1940) and Kaldor (1939)), Tirole justifies the utilization of total surplus while recognizing that actual income distributions are not optimal even with optimal income taxes for real economies. This argument relies on the assumption that one can reach welfare conclusions on the basis that income redistribution from one consumer to another has no welfare effect.[8]

It is widely recognized that governments do not engage in lump-sum redistributions because they do not have the information required in order to implement such taxes in equitable manner. Given that taxes are inevitably distortionary, one must recognize that any policy that changes the distribution of endowments has an effect on the overall efficiency of the economy. Hence, efficiency and equity considerations cannot be separated.[9] Consequently, these somewhat incongruent arguments on the separation of efficiency and

[7]See Whalley (1975) and Kokoski and Smith (1987) for examples of an empirical assessment of partial equilibrium welfare measurement. Also, see Hausman (1981) and Slesnick (1998) for an empirical critique of consumers' surplus economics. See Chipman and Moore (1976) and Blackorby and Donaldson (1990), in particular, for theoretical and ethical objections to the use of consumer's and consumers' surplus.

[8]This implicitly assumes that the marginal social utilities of income are equalized across consumers after the implementation of costless lump-sum redistribution of wealth.

[9]See Stiglitz (1994, chap.4) for an excellent critique of the second fundamental theorem of welfare.

equity considerations in partial equilibrium may reflect more the need for seemingly scientific objectivity, analytical simplicity, and implementation practicality and tractability than for accuracy and consistency in making welfare evaluations of market-specific policy interventions. The appararent advantages of partial equilibrium welfare analysis appear to overide the reliability and rigour that other approaches (e.g. computable general equilibrium) may have for economic policy making. Indeed, these advantages are nowhere more important than in economic policymaking for second-best economies.

The second argument, in single-consumer economies, in defense of partial equilibrium welfare analysis is based on some extent to the claim that a consumer's "expenditure on any one thing [...] is only a small part of his whole expenditure," argued by Marshall (1920, p. 842).[10] Marshall's hypothesis implies that in order to analyze the welfare effect of a change in a specified commodity's price, one is assuming: (*i*) no income effect for the commodity, and (*ii*) the prices of all other commodities remain constant following the price change. Interestingly, more general results have supported Marshall's hypothesis.

Vives (1987) shows that income effects decrease with the square root of the number of goods in the economy in support of zero income effects. Given the large number of goods in the economy, the income effect on any single good would be sufficiently small. In addition, an appealing general equilibrium result can be argued instead of assuming that all other prices need to be constant in order to conduct partial equilibrium welfare analysis. Formally proving Hicks (1946), Blackorby and Donaldson (1999) show that the change in consumer surplus measured along the *equilibrium market demand curve* is equal to the sum of consumer and producer surplus in **all** markets. Yet, these more general theoretical findings share the same problem as the defense in many-consumers' economies: they are not likely to hold in second-best economies.

Specifically, Vives (1987) assumes the budget constraint of the consumer is linear, and

[10] When costless lump-sum transfers are feasible, a single-consumer economy is equivalent to a many-consumers economy.

Blackorby and Donaldson (1999) assume that all other markets than for the commodity under consideration satisfy first-best (or Paretian) conditions. Clearly, the reliability of their results are not likely to hold in real second-best economies. The presence of several nonlinear payment schedules (e.g. quantity discounts, nonlinear incentive labor payment schedules) and nonlinear income taxes, for example, has profound implications in economic theory and for the traditional neoclassical (Arrow-Debreu) paradigm. In second-best economies, not only can aggregate demand not equal aggregate supply but a competitive equilibrium driving profits to zero can also be shown not to be valid with imperfect information.[11]

The second chapter of this dissertation shows that it is possible to restore second-best Pareto efficiency in imperfectly competitive economies with an appropriate use of *optimal* taxes by a policymaker that maximizes total surplus. In other words, the results of this chapter show that partial equilibrium welfare analysis can be applied to second-best economies under restrictive assumptions about consumer preferences and distortions in the other sectors of the economy. Hence, the results of this chapter show that the general theory of second-best can be analyzed in the context of a tractable partial equilibrium analysis like the one undergone in the third chapter of this dissertation.

An example of a partial equilibrium traditional Paretian claim is that optimal taxes or regulations set by a policymaker that maximizes social welfare should not discriminate across firms among a given industry.[12] This tradition is best examplified in the public finance literature of tax incidence where the welfare analysis of an imperfectly competitive industry's corporate tax intuitively falls somewhere between the two polar cases of monopoly and perfect competition tax analysis.[13] One important feature of first-best economic policies is that they are non-discriminatory across firms because the marginal

[11]For other general statements, see Stiglitz (1994).

[12]See Laffont and Tirole (1994) for remarks on other possible explanations for this policy prescription.

[13]This partial equilibrium tradition appears to result from the intuition of that one gets from perfect competition or monopoly models of corporate taxation. See the discussion, for example, of tax theory in Tresh (1981), Harberger (1974), and Musgrave (1959).

costs are equalized to marginal rates of substitution in general equilibrium. Indeed, this reasoning underlies the thinking of some environmental economists who have been supporting market-based approaches to pollution abatement similar to the SO_2 tradeable pollution permits market created by the Clean Air Act Amendments of 1990 in the United States.

Designing piecemeal policies derived from partial equilibrium economic models without full considerations of economic interdependencies accruing for example of second-best constraints (e.g. imperfect competition, asymmetric information) generally results in suboptimal and inefficient policies.[14] In real world problems, where imperfect competition governs production in most sectors of the economy and prevents the attainment of first-best optima, the policy prescriptions for optimal pollution abatement control policies lose the simplicity and universality of Paretian policies.

Nevertheless, under the framework outlined in the second chapter of this dissertation, a partial equilibrium optimal policy in second-best economies are Pareto optimal. The third chapter of this dissertation applies this framework in order to derive optimal pollution emission tax/quotas for an imperfectly competitive industry where the firms have uncorrelated private information about their cost. It is shown that an optimal Pigouvian pollution tax discriminates between firms in a given industry even though the firms' costs are identical ex post. The strategic interaction between the firms in the market acts a private information correlation externality and a source of discipline against an efficient firm's ability to misreport its cost. Indeed, when the regulator recognizes the interdependence between a firm's private information (i.e. cost) and its production strategies, the strategic interaction between firms in a market becomes indirectly an instrument to extract information rents from efficient firms similar to nonlinear taxes. Hence, the results of this chapter provide a theoretical justification for optimal discriminatory pollution

[14]See Lipsey and Lancaster (1956), Guesnerie (1980), Hammond (1990), Blackorby (1990), Boadway (1994) for more explanations and examples on this.

regulations based on the regulator's independent prior belief about each firm's cost.

The two essays of this dissertation appear to provide theoretical evidence in support of the conclusions from the general theory of second-best in a partial equilibrium framework. And, following the arguments presented above, this would appear to be most relevant for economists and policymakers who have to design economic policy in the real world.

Chapter 2

Taxing Price Makers using Marshallian Surplus

2.1 Introduction

Welfare analysis in partial equilibrium models is widespread in economics. Generally, finding a Pareto optimum (or, welfare optimum) of an economy requires the maximization of some welfare function subject to the production constraints and various other second-best constraints. However, finding a Marshallian "total surplus" optimum subject to the same constraints raises the natural question: under what conditions is a "total surplus" optimum a Pareto optimum?

In the industrial organization and tax incidence literature, the policy-maker's problem is often represented by the maximization of the sum of Marshallian consumer's surplus and producer's profit (i.e. total surplus function) of a given market subject to various types of constraints (e.g. feasibility, budgetary, and incentive constraints). It has long been recognized that the approach is legitimate only if one is willing to assume: (i) prices of all the commodities other than the one under consideration remain fixed, and (ii) there are no income effect in the market under study. Given that such conditions are very restrictive and highly unrealistic, one often needs to rely on modest generalization of the approach in order to justify it.[1] Nonetheless, the appurtenance of the partial equilibrium welfare analysis in single consumer economies has been justified by mainly two arguments in the literature.

The first argument—often mentionned in the industrial organization literature—rests on the claim that zero income effects are sufficient for a partial equilibrium welfare analysis to characterize efficient allocations. Given the severe empirical implications imposed by this restriction on preferences, a stronger defense of the approach has been made recently by Vives (1987). He shows that income effects decrease with the square root of the number of goods in the economy and that, given the large number of goods in the economy, the income effect on any single commodity would be small. However, his finding only applies to first-best economies which limits the appeal of the result for policy-makers in second-best environments. For example, his result requires the linearity of the budget set of the consumers. In second-best economies where consumers often face nonlinear prices (e.g. quantity discounts) or taxes (e.g. income tax), the budget constraint of a consumer is more likely to be nonlinear which could invalidate this line of defense.

A second argument, which dates back to Hicks (1946) and recently proven by Blackorby and Donaldson (1999), claims that the change in consumer surplus measured along an *equilibrium market demand curve* for a single commodity is equal to the sum of Marshallian consumer surplus in all other markets and producer surplus in all markets. The weakness of this general equilibrium argument, however, is that it requires the economy to be perfectly competitive. Again, this necessary condition may fail to hold due to the wide variety of distortions present in real economies.

Consequently, it appears to be the convenience of partial equilibrium welfare analysis

[1]Mas-Colell et al. (1995, Chap. 10) provides a good exposition of some of these more general assumptions.

rather than its empirical relevance that would explain its traditional "popularity" among economists and policy-makers. Because one only needs to know, observe, or estimate the representative consumer's ordinary demand for a limited number of goods, it is generally considered easier to conduct applied welfare analysis with Marshallian total surplus than with alternative methods.[2] Moreover, it is generally argued (mainly Willig (1976)) that the Marshallian surplus function is a reasonable approximation of exact measures of welfare when the income effect resulting from the price change is small.[3] Hausman (1981) not only showed that when consumer surplus is calculated with goods with large income effect Willig's method was inaccurate(e.g. labor), but that Willig's method did not provide a good approximation of deadweight loss. Still, all these arguments rely on first-best characterizations of an economy.

Indeed, the ability of partial equilibrium welfare measure such as Marshallian total surplus to characterize second-best Pareto optima has not received much attention in the literature. Yet, the analytical convenience of Marshallian total surplus truly is one of the most obvious appeal to economists and policy-makers. Provided that the conditions for Marshallian total surplus function to characterize second-best Pareto optima are not too restrictive, then that would be of some comfort to most practioners of applied welfare economics in partial equilibrium analysis: A policy-maker's optimal policy could be derived separately from all other distorted sectors in the economy, and it would be proportional to a second-best Pareto optimal one. However, the likelihood of such a scenario has recently been compromised by Blackorby (1998).

Blackorby (1998) investigates the validity of the partial equilibrium procedure in second-best economies using a tax reform approach.[4] He models a second-best economy

[2]Other arguments have also been used to support consumer surplus. For example, see Harberger (1971). See Slesnick (1998) for a recent survey of empirical approaches to welfare measurement.

[3]It is important to note that Willig's argument does not apply when there are multiple price and expenditure changes (e.g. horizontal merger with differentiated products) because Marshallian consumer surplus is not single-valued in those circumstances

[4]Although this approach is valid only for policies that have small localized effects, it has the advantage that the optimality of policies are based on first-order optimality conditions. See Guesnerie (1995) for

by assuming that there exists a fixed wedge between the consumer and producer prices in a subset of markets other than the one where the Marshallian surplus function is defined. Then, assuming a perfectly competitive productive sector, he shows that the surplus optimum coincides with a Pareto optimum when (*i*) all the wealth effects are captured by a numéraire (i.e. restriction to quasi-linear preferences), and (*ii*) the Pareto optimum satisfies the Paretian conditions of optimality.[5] He then concludes that there are no well-behaved preferences such that the sum of Marshallian consumer surplus and producer surplus can lead the economy to its second-best Pareto optimum. That is, unless the second-best Pareto optimum satisfy the Paretian conditions of optimality, a partial equilibrium Marshallian total surplus optimum never characterizes a second-best Pareto optimum.

Clearly, this would be bad news for practitioners of applied partial equilibrium welfare analysis. If a partial equilibrium surplus analysis is valid only in first-best economies, even under strong restriction on preferences, then the usefulness of the approach is left to textbooks. It would not have any appeal to describe real-world economic policies even when there would be no income effect.

This essay considers the following question: Under what conditions does a partial equilibrium total surplus approach characterizes 'real' second-best Pareto optima? The essay characterizes optimal allocations that results from maximizing (i) a representative consumer's welfare, and (ii) a Marshallian total surplus function in a second-best general equilibrium economy where there exists one market where production is governed by price makers à la Guesnerie and Laffont (1978). Unlike Blackorby (1998), this essay explicitly models the distortion with an imperfectly competitive sector (Cournot) which leads the economy to a "true" second-best Pareto optimum and the methodology chosen does not

an illustration of the approach.

[5]He shows that when prices are not normalized no Marshallian consumer surplus function can lead the economy to a Pareto optimum.

limit the results to infinitesimal changes in policy instruments.[6]

Extending the Guesnerie and Laffont (1978) economy to an asymmetric Cournot price-making sector, it is shown that even if the policy maker's instruments include firm specific taxes, then the decentralization of a first-best Pareto optimum cannot be acheived. Then, the main result of this essay shows that a Marshallian total surplus optimum coincides with a second-best Pareto optimum if preferences are quasi-linear and all existing distortions are contained in the market used to define the Marshallian total surplus function.

Contrary to the claim made in Blackorby (1998), it is shown that there exist well-behaved preferences such that the Marshallian total surplus can lead the economy to a second-best Pareto optimum as long as all distortions are contained in the market used to define the Marshallian surplus function. The maximization of Marshallian consumer's surplus plus producer profits in a second-best economy may be an appropriate normative (i.e. welfare) objective if all second-best distortions are contained in the market under consideration and preferences of a representative consumer are quasi-linear.[7]

This essay is organized as follows: the next section describes the model before Section 3 revisits Guesnerie and Laffont (1978) using the Marshallian consumer's surplus function allowing for income change as the objective function. Section 4 characterizes second-best Pareto optima for an asymmeric Cournot oligopoly in a general equilibrium economy. Section 5 characterizes the surplus optimum and states the conditions under which the partial equilibrium Marshallian consumer's surplus function can lead the economy to its true second-best Pareto optimum found in Section 4. Finally, Section 6 summarizes the findings of the essay.

[6]Also, the essay does not assume that the planner controls the consumer prices directly. See Blackorby and Brett (1998) for a discussion on the effects of the choice of instruments.

[7]For example, Besanko (1985b, p.41) defines the sum of consumer surplus and producer profits as social welfare and claims that this is an appropriate normative objective.

2.2 The Model

Suppose that an economy consists of $N+1$ goods where good-0 is produced by price makers (i.e. monopoly, or oligopoly) and all the other goods are produced by a perfectly competitive sector. Let $\mathbf{q} = (q_0, \mathbf{q}_{-0})^\top$ be the consumer price column-vector with $\mathbf{q}_{-0} = (q_1, \ldots, q_N)^\top$, $\mathbf{p} = (p_0, \mathbf{p}_{-0})^\top$ be the producers' price column-vector and $\mathbf{t} = (t_0, \mathbf{t}_{-0})^\top = \mathbf{q}^\top - \mathbf{p}^\top$ the linear tax/subsidy column-vector. Also, assume the policy-maker's instruments include a 100% tax on profits and lump-sum transfers to consumers.

To abstract from distributional issues, assume there is only one consumer who has well-behaved preferences represented by an indirect utility function $V : \mathbb{R}_+^{N+1} \times \mathbb{R}_{++} \mapsto \mathbb{R}$.[8] Let V be twice continuously differentiable, strongly quasi-convex, increasing in income, decreasing in prices, and homogeneous of degree zero in all its arguments. From Roy's theorem, the ordinary demand function for good j is:[9]

$$d_j = D_j(\mathbf{q}, m) = -\frac{V_j(\mathbf{q}, m)}{V_m(\mathbf{q}, m)}, \quad j = 0, 1, \ldots, N. \tag{2.1}$$

The indirect utility function, V, is related to the expenditure function $E(\mathbf{q}, u)$ by the identity

$$u = V(\mathbf{q}, m) \Longleftrightarrow m = E(\mathbf{q}, u)$$

where E is increasing in u, non-decreasing in $\mathbf{q}$, and homogeneous of degree 1 in $\mathbf{q}$.

From Sheppard's lemma, the compensated (or Hicksian) demand functions are given by

$$h_j = H_j(\mathbf{q}, u) = \frac{\partial E(\mathbf{q}, u)}{\partial q_j}, \quad j = 0, \ldots, N, \tag{2.2}$$

and, the Hessian of the expenditure function is of rank N which implies

$$\mathbf{q}^\top \nabla_{\mathbf{q}}^2 E(\mathbf{q}, u) = 0$$

[8]This model extends easily to a many-consumer economy with individual lump-sum transfers. Note that a lack of distributional concern is embedded in the Marshallian surplus function (see Dupuit (1844) and Marshall (1920)).

[9]The following notation is used: $V_j \equiv \partial V / \partial q_j$ for $j = 0, \ldots, N$, and $V_m \equiv \partial V / \partial m$.

or equivalently

$$\sum_{j=0}^{N} q_j \frac{\partial^2 E(\mathbf{q}, u)}{\partial q_j \partial q_k} = 0, \quad k = 0, \ldots, N. \tag{2.3}$$

The competitive sector's technology, given by the profit function $\Pi(\mathbf{p}_{-0}) : \mathbb{R}^N \mapsto \mathbb{R}_+$ is assumed increasing, strongly convex, and linearly homogeneous.[10] The net supply of the competitive sector is given by:

$$y_j(\mathbf{p}_{-0}) = \Pi_j(\mathbf{p}_{-0}), \quad j = 1, \ldots, N.$$

Note that the above assumptions imply that the rank of the Hessian of Π is $N-1$, and therefore,

$$\mathbf{p}_{-0}{}^{\top} \nabla^2_{\mathbf{p}_{-0}} \Pi(\mathbf{p}_{-0}) = \mathbf{0}_N,$$

or

$$\sum_{j=1}^{N} p_j \frac{\partial y_j(\mathbf{p}_{-0})}{\partial p_k} = 0, \quad k = 1, \ldots, N. \tag{2.4}$$

The imperfectly competitive sector is composed of F price-making firms.[11] Let each firm's technology be represented by a cost function $C^f(\mathbf{p}_{-0}, x_0^f) : \mathbb{R}^N_{++} \times \mathbb{R}_+ \mapsto \mathbb{R}_+$ where good-0 is the single final product. Assume C is twice-continuously differentiable, increasing in x_0^f, non-decreasing in $\mathbf{p}_{-0}$, and homogeneous of degree one, and concave in $\mathbf{p}$. The demand for inputs by the sector-0 firms is given by:

$$\eta_j^f(\mathbf{p}_{-0}, x_0^f) = \frac{\partial C^f(\mathbf{p}_{-0}, x_0^f)}{\partial p_j}, \quad j = 1, \ldots, N; \ f = 1, \ldots, F. \tag{2.5}$$

The assumptions on the cost function imply that the Hessian of the cost function is of rank $N-1$, or equivalently:

$$\mathbf{p}_{-0}^{\top} \nabla^2_{\mathbf{p}_{-0}} C^f(\mathbf{p}_{-0}, x_0^f) = \mathbf{0}_N,$$

[10] Since this sector is perfectly competitive, there is no loss of generality in assuming a single profit function.

[11] For clarity, when the imperfectly competitive sector is a monopolist the superscripts f are dropped.

or

$$\sum_{j=1}^{N} p_j \frac{\partial \eta_j^f}{\partial p_k} = 0, \quad k = 1, \dots, N. \tag{2.6}$$

Moreover, assume the (N, N) matrix A with elements defined by

$$a_{jk} = (\frac{\partial y_j}{\partial p_k} - \frac{\partial \eta_j}{\partial p_k}) \tag{2.7}$$

is of rank $N - 1$. As in Guesnerie and Laffont (1978), this is simply a local regularity condition.

From (2.1), the net Marshallian consumer surplus in market-0, allowing for income (m) change, is defined by

$$S_0(\mathbf{q}, m) = \int_{q_0}^{\bar{q}_0} D_0(\chi_0, \mathbf{q}_{-0}, m) d\chi_0 + m \tag{2.8}$$

where $\bar{q}_0 \equiv \inf\{q_0 \in \mathbb{R}_{++} \mid D_0(q_0, \mathbf{q}_{-0}, m) = 0, \forall(\mathbf{q}_{-0}, m)\}$.[12]

2.3 Taxing Monopolies using Marshallian Total Surplus

Guesnerie and Laffont (1978) show that, under some regularity conditions, a linear excise subsidy on the production of a normal good from a monopolist enables a policy maker to restore first-best Pareto efficiency of a potential second-best equilibrium when lump-sum transfers are available as policy instruments. Hence, their result provides a general equilibrium theoretical support for the conventional wisdom that it is possible to restore first-best Pareto efficiency with appropriate taxation schemes that originated most likely from a partial equilibrium formulation of the problem. However, vindication of "traditional" partial equilibrium claims must originate in its ability to reliably characterize

[12]Of course, it is assumed that $0 < \bar{q}_0 < \infty$. The integral exists if $D_0(\cdot, \mathbf{q}_{-0}, m)$ is continuous and if the region defined by $(q_0, \bar{q}_0)$ is regular (see Widder (1989, p.218)).

general equilibrium results and not the converse. Thus, one needs to verify that "conventional wisdom" claims infered from partial equilibrium formulations of a problem hold in general equilibrium models when a Marshallian total surplus function is the objective function instead of some welfare function.

Still, Guesnerie and Laffont (1978) have shown that even if the policy maker has enough instruments to restore a first-best Pareto optimum, it may not be able to acheive this optimum because of discontinuities in the monopolist's pricing decision.[13] The discontinuity of the optimal pricing correspondence of the monopolist may not permit the decentralization of a feasible allocation into a first-best Pareto optimum. Because such considerations are outside the scope of this essay, consider only cases where the optimal strategies of the monopolist are continuous in the neighborhood of the second-best Pareto optimum.

Assume D_0 is monotonic in q_0 and let $q_0 = Q_0(d_0, \mathbf{q}_{-0}, m)$ be the inverse demand function for good-0. The profit function of the monopolist is:[14]

$$\pi_0(x_0, \mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0) = [Q_0(x_0, \mathbf{q}_{-0}, m) - t_0]x_0 - C(\mathbf{p}_{-0}, x_0)$$

Assume $\overset{*}{x}_0$ is the unique profit maximizing output of the monopolist. $\overset{*}{x}_0$ is a continuous function of the environment $(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0)$ given by:

$$\overset{*}{x}_0 = x_0^{\mathcal{M}}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0)$$

Moreover, they note that for their result to hold the policymaker needs to be able to control locally the pricing decision of the monopolist. Therefore, assume

$$\frac{\partial x_0^{\mathcal{M}}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0)}{\partial t_0} \neq 0 \tag{2.9}$$

This assumption is sufficient to rule out some other types of behavior that would result in inefficient allocations whatever the policy instruments available.[15]

[13]The problem has at its root the failure to obtain a convex-valued, upper semi-continuous pricing correspondence for a monopolist or oligopolist (see Sundaram (1996, Chap. 9)).

[14]Equivalently, one could model the monopolist's problem as a pricing decision (see Guesnerie and Laffont (1978)).

[15]See Guesnerie and Laffont (1978, p.435–36) remarks on this assumption.

A feasible allocation of the economy is given by

$$\Omega = \{\{d_j\}_{j=0}^N, \{y_j\}_{j=1}^N, \{\eta_j\}_{j=1}^N, \{x_0\}\}$$

which consists of consumer demands, competitive firm's supply, and the monopolist's input demand and output associated with $\{\mathbf{q}, \mathbf{p}, m\}$, the consumer's prices, the producers' prices, and the consumer's income such that:[16]

$$y_j(\mathbf{p}_{-0}) - D_j(\mathbf{q}, m) - \eta_j(\mathbf{p}_{-0}, x_0) \geq 0, \quad j = 1, 2, \dots, N; \tag{2.10}$$

$$x_0 - D_0(\mathbf{q}, m) = 0; \tag{2.11}$$

$$x_0 - x_0^{\mathcal{M}}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0) = 0. \tag{2.12}$$

The first two sets of equations ensures that any economic allocation is physically feasible. The last constraint takes into account the fact that the monopolist produces according to its best output strategy. The policy-maker's problem can be described by:[17]

Program 1

$$\max V(\mathbf{q}, m)$$

subject to (2.10), (2.11), *and* (2.12).

The solution to this program results in the characterization of a Pareto optimum that need not coincide with a Marshallian surplus optimum that results when the policymaker maximizes a Marshallian consumer's surplus function allowing for income change. A characterization of the solution to Program 1 is found in Guesnerie and Laffont (1978, Theorem 1).

[16]This essay considers only their "regular" case. The production of the public sector is omitted because it can be shown that it produces efficiently.

[17]Assume that the set of feasible allocations is non-empty, and that solutions to Program 1 exist. There are problems with the characterization of an imperfectly competitive general equilibrium. Adequately dealing with these problems is outside the scope of this article however. See Arrow and Hahn (1971),Gabszewicz and Vial (1972), and Laffont and Larocque (1976) for existence theorems, and Roberts and Sonnenschein (1977) for non-pathological examples of the non-existence of an imperfectly competitive general equilibrium.

Theorem 1 *Assume* $\overset{*}{\mathbf{p}} \gg 0$ *and* $\overset{*}{x}_0 > 0$. *If* $(\overset{*}{\mathbf{p}}, \overset{*}{\mathbf{t}}, \overset{*}{m})$ *is a solution to Program 1, then the economic allocation* $\overset{*}{\Omega}$ *is a first-best Pareto optimum.*

The Marshallian consumer's surplus is an exact measure of a consumer's utility only when the marginal utility of income is constant. Thus, the marginal utility of income must not change following changes in income or prices. As Chipman and Moore (1976) and Blackorby and Donaldson (1999) demonstrate, a normalization must be chosen for the Marshallian consumer's surplus function to be path independent and measure the consumer's utility. Moreover, Blackorby (1998) shows that if no consumer commodity price is normalized, then the Marshallian consumer's surplus function (allowing for income change) could never lead the economy to a Pareto optimum.[18]

For a Marshallian surplus optimum to characterize a Pareto optimum, it must be that the vector of instruments that maximizes the Marshallian consumer surplus function allowing for income change is proportional to $(\overset{*}{\mathbf{p}}, \overset{*}{\mathbf{t}}, \overset{*}{m})$. Indeed, Blackorby (1998) shows that a total surplus optimum can characterize a second-best Pareto optimum if the economic allocation $\overset{*}{\Omega}$ is a first-best Pareto optimum when preferences are quasi-linear.

Program 2

$$\max S_0(\mathbf{q}, m) = \int_{q_0}^{\bar{q}_0} D_0(\chi_0, \mathbf{q}_{-0}, m) d\chi_0 + m$$

subject to $q_N = 1$, (2.10), (2.11), *and* (2.12)

It is important to note that, since the Marshallian surplus problem outlined in program 2 allows for the relative prices of the whole economy to vary, the partial equilibrium problem used in this chapter is slightly more general than a traditional partial equilibrium model where the relative prices for all other commodities are assumed to be constant. Clearly, given the underlying arbitrary nature of determining which commodities should

[18]Note that the *a priori* choice of numéraire has some undesirable ethical consequences (see Blackorby and Donaldson (1996)). The results of this essay are not substantively modified by the choice of numéraire if any other commodity other than good-0 is chosen.

be included in a partial equilibrium model, this supplementary assumption is not likely to be verified.

Theorem 2 *Assume* $\tilde{\mathbf{p}} \gg 0$ *and* $\tilde{x}_0 > 0$. *If* $(\tilde{\mathbf{p}}, \tilde{t}, \tilde{m})$ *is a solution to Program 2 and if the consumer price of good-N is chosen as the numéraire, then the economic allocation* $\tilde{\Omega}$ *is a first-best Pareto optimum if and only if the preferences of the consumer are given by*

$$V(\mathbf{q}, m) = G^N\big(\frac{m - \hat{e}(\mathbf{q})}{q_N}\big).$$

Proof: Suffiency is immediate. For necessity, a surplus optimum is obtained by maximizing:

$$\mathcal{L} = S_0(\mathbf{p}+\mathbf{t}, m) + \sum_{j=1}^{N} \lambda_j \Big(y_j(\mathbf{p}_{-0}) - D_j(\mathbf{p}+\mathbf{t}, m) - \eta_j(\mathbf{p}_{-0}, x_0)\Big)$$
$$+ \lambda_0\Big(x_0 - D_0(\mathbf{p}+\mathbf{t}, m)\Big) + \mu\Big(x_0 - x_0^{\mathcal{M}}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0)\Big) + \rho(1 - p_N + t_N)$$

where the first-order equations are:

$$-\tilde{D}_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial p_0} = 0 \tag{2.13}$$

$$-\tilde{D}_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial t_0} - \tilde{\mu}\frac{\partial x_0^{\mathcal{M}}}{\partial t_0} = 0 \tag{2.14}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} d\chi_0 + \sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} - \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} - \frac{\partial \eta_j(\tilde{\mathbf{p}}_{-0}, \tilde{x}_0)}{\partial p_k}\Big) \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} - \tilde{\mu}\frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial p_k} = 0, \quad k = 1, \dots, N-1;\end{aligned} \tag{2.15}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} d\chi_0 - \sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} - \tilde{\mu}\frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial t_k} = 0, \quad k = 1, \dots, N-1;\end{aligned} \tag{2.16}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial p_N} d\chi_0 + \sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_N} - \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial p_N} - \frac{\partial \eta_j(\tilde{\mathbf{p}}_{-0},\tilde{x}_0)}{\partial p_N} \Big) \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial p_N} - \tilde{\mu} \frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial p_N} - \tilde{\rho} = 0;\end{aligned} \tag{2.17}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial t_N} d\chi_0 - \sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial t_N} \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial t_N} - \tilde{\mu} \frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial t_N} - \tilde{\rho} = 0;\end{aligned} \tag{2.18}$$

$$-\sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial \eta_j(\cdot)}{\partial x_0} + \tilde{\lambda}_0 + \tilde{\mu} = 0; \tag{2.19}$$

$$\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial m} d\chi_0 + 1 - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial m} - \tilde{\mu} \frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial m} = 0 \tag{2.20}$$

First, subtracting (2.14) from (2.13) yields:

$$\tilde{\mu} \frac{\partial x_0^{\mathcal{M}}(\cdot)}{\partial t_0} = 0$$

Given $\tilde{\mu} \geq 0$ and (2.9), this implies

$$\tilde{\mu} = 0. \tag{2.21}$$

Since $\tilde{\mu} = 0$, subtracting (2.16) from (2.15) and (2.18) from (2.17) yields:[19]

$$\sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} - \frac{\partial \eta_j(\tilde{\mathbf{p}}_{-0},\tilde{x}_0)}{\partial p_k} \Big) = 0, \quad k = 1, \dots, N. \tag{2.22}$$

The homogeneity of degree zero of $\eta_j(\cdot)$ and $y_j(\cdot)$ with the symmetry of the Hessian of the monopolist's cost function and of the competitive sector's profit function implies

$$\sum_{j=1}^{N} \tilde{p}_j \frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} = 0, \quad j = 1, \dots, N$$

$$\sum_{j=1}^{N} \tilde{p}_j \frac{\partial \eta_j(\tilde{\mathbf{p}}_{-0},\tilde{x}_0)}{\partial p_k} = 0, \quad j = 1, \dots, N.$$

[19] Note that $\frac{\partial D_l(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial p_k} = \frac{\partial D_l(\tilde{\mathbf{p}}+\tilde{\mathbf{t}},\tilde{m})}{\partial t_k}$.

and with (2.7)

$$\tilde{\lambda}_j = \kappa \tilde{p}_j, \quad j = 1, \dots, N. \tag{2.23}$$

Now, multiply (2.20) by $\tilde{d}_k = D_k(\tilde{\mathbf{q}}, \tilde{m})$ for $k = 0, 1, \dots, N$ which yields

$$\int_{\tilde{q}_0}^{\bar{q}_0} D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 + D_k(\tilde{\mathbf{q}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_j(\tilde{q}_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} = 0, \quad k = 0, 1, \dots, N \tag{2.24}$$

Adding (2.24) to (2.14), (2.16), and (2.18) respectively, yields the following

$$- D_0(\tilde{\mathbf{q}}, \tilde{m}) - \sum \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial q_0} + \int_{\tilde{q}_0}^{\bar{q}_0} D_0(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 + D_0(\tilde{\mathbf{q}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j D_0(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial m} = 0, \tag{2.25}$$

$$\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_k} d\chi_0 - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial q_k} + \int_{\tilde{q}_0}^{\bar{q}_0} D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 + D_k(\tilde{\mathbf{q}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial m} = 0, \quad k = 1, \dots, N-1 \tag{2.26}$$

$$\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_N} d\chi_0 - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial q_N} + \int_{\tilde{q}_0}^{\bar{q}_0} D_N(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 + D_N(\tilde{\mathbf{q}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j D_N(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_j(\tilde{\mathbf{q}}, \tilde{m})}{\partial m} - \tilde{\rho} = 0 \tag{2.27}$$

Using the Slutsky equation, these last $N+1$ equations can be rewritten

$$\tilde{\lambda}^\top \nabla^2_{\mathbf{q}} E(\tilde{\mathbf{q}}, \tilde{u}) = \begin{bmatrix} D_0(\tilde{\mathbf{q}}, \tilde{m}) \int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial^2 D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 \\ \vdots \\ D_k(\tilde{\mathbf{q}}, \tilde{m}) + \int_{\tilde{q}_0}^{\bar{q}_0} \left(\frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_k} + D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} \right) d\chi_0 \\ \vdots \\ D_N(\tilde{\mathbf{q}}, \tilde{m}) + \int_{\tilde{q}_0}^{\bar{q}_0} \left(\frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_N} + D_N(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} \right) d\chi_0 - \tilde{\rho} \end{bmatrix} \tag{2.28}$$

For the surplus optimum to coincide with a Pareto optimum, it must be that the right-hand side of (2.28) is equal to $\mathbf{0}_{N+1}$. In that case, a surplus optimum would generate policy vectors that would be proportional to the one's characterized in Theorem 1. From (2.28), it is clear that a necessary condition for the right-hand side to be zero is

$$\frac{\partial D_0(\mathbf{q}, m)}{\partial m} = 0 \tag{2.29}$$

so that the demand for commodity-0 displays no income effect.

This requirement implies that the preferences of the consumer must be represented by

$$E(\mathbf{q}, u) = e(\mathbf{q}) + \phi(\mathbf{q}_{-0}, u) \tag{2.30}$$

where e is homogeneous of degree one, non-decreasing in $\mathbf{q}$ and ϕ is increasing in u, homogeneous of degree one, and non-decreasing in $\mathbf{q}_{-0}$.

For the rest of the right-hand side of (2.28) to be equal to zero, the integral needs to be equal to $-H_k(\tilde{\mathbf{q}}, \tilde{u})$ for $k = 1, \dots, N-1$. From (2.29), the Slutsky equation, (2.30), and the symmetry of the Hessian of E, the integrals on the right-hand side of (2.28) can be rewritten as:[20]

$$\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial^2 e(\chi_0, \tilde{\mathbf{q}}_{-0})}{\partial \chi_0 \partial q_k} d\chi_0 = \int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial^2 e(\chi_0, \tilde{\mathbf{q}}_{-0})}{\partial q_k \partial \chi_0} d\chi_0 = e_k(\bar{q}_0, \tilde{\mathbf{q}}_{-0}) - e_k(\tilde{\mathbf{q}}) \tag{2.31}$$

for $k = 1, \dots, N-1$, which implies with (2.30)

$$E_k(\tilde{\mathbf{q}}, \tilde{u}) = e_k(\tilde{\mathbf{q}}) + \phi_k(\tilde{\mathbf{q}}_{-0}, \tilde{u})$$

From (2.31), for the surplus optimum to replicate the welfare optima it must be that at the equilibrium

$$-e_k(\tilde{\mathbf{q}}) - \phi_k(\tilde{\mathbf{q}}_{-0}, \tilde{u}) = e_k(\bar{q}_0, \tilde{\mathbf{q}}_{-0}) - e_k(\tilde{\mathbf{q}}), \quad k = 1, \dots, N-1$$

[20] The subscripts here denote the partial derivative with respect to q_k.

or equivalently,

$$\phi_k(\tilde{\mathbf{q}}_{-0}, \tilde{u}) = -e_k(\bar{q}_0, \tilde{\mathbf{q}}_{-0}), \forall \tilde{\mathbf{q}}_{-0}, \forall \tilde{u}; \quad k = 1, \dots, N-1. \tag{2.32}$$

Hence, it must be that

$$-e_k(\bar{q}_0, \mathbf{q}_{-0}) = \phi_k(\mathbf{q}_{-0}, u), \forall \mathbf{q}_{-0}, \forall u \tag{2.33}$$

and $E_k(\mathbf{q}, u) = e_k(\mathbf{q}) - e_k(\bar{q}_0, \mathbf{q}_{-0})$ for $k = 1, \dots, N-1$. This implies that (2.30) can be rewritten as

$$E(\mathbf{q}, u) = \hat{e}(\mathbf{q}) + q_N \hat{\phi}(u) \tag{2.34}$$

where $\hat{e}(\mathbf{q}) = e(\mathbf{q}) - e(\bar{q}_0, \mathbf{q}_{-0})$.

Finally, the using the last line of (2.28) implies

$$D_N(\tilde{\mathbf{q}}, \tilde{m}) - (\hat{e}_N(\tilde{\mathbf{q}}) + \tilde{\rho}) = 0 \tag{2.35}$$

Normalizing $\tilde{\rho} = \hat{\phi}(\tilde{u})$, the surplus optimum replicates the welfare optimum only if

$$u = \hat{\phi}^{-1}\Big(\frac{m - \hat{e}(\mathbf{q})}{q_N}\Big) \tag{2.36}$$

from (2.34).■

This theorem extends the results of Blackorby (1998) to an economy where the second-best distortion has been formally modeled as a monopoly. Given that the policymaker has the necessary instruments to restore the Paretian (first-best) conditions of a second-best Pareto optimum, the Marshallian surplus optimum characterizes a Pareto optimum if the consumer's preferences are quasi-linear. A simple extension to Marshallian "total surplus" is given by the next proposition.

Proposition 1 *Assume the preferences of the representative consumer are quasi-linear. Under the conditions of Theorem 2, consumer surplus allowing for income change at the second-best equilibrium is equal to total Marshallian surplus.*

Proof: Let $\mathcal{S}_0(\mathbf{q}, m) = \int_{q_0}^{\bar{q}_0} D_0(\chi_0, \mathbf{q}_{-0}, m) d\chi_0$ and $(\overset{*}{\mathbf{p}}, \overset{*}{t}, \overset{*}{\boldsymbol{\tau}}{}^f, \overset{*}{m})$ be defined by Theorem 2. By definition,

$$S_0(\overset{*}{\mathbf{q}}, \overset{*}{m}) = \mathcal{S}_0(\overset{*}{\mathbf{q}}, \overset{*}{m}) + \overset{*}{m} \tag{2.37}$$

The government's budget constraint yields:

$$\begin{aligned}
\overset{*}{m} &= (\overset{*}{\mathbf{q}} - \overset{*}{\mathbf{p}})^\top \overset{*}{\mathbf{d}} + \Pi(\overset{*}{\mathbf{p}}) + \overset{*}{\pi}_0 \\
&= (\overset{*}{q}_0 - \overset{*}{p}_0)\overset{*}{d}_0 + \overset{*}{\pi}_0 + (\overset{*}{\mathbf{q}}_{-0} - \overset{*}{\mathbf{p}}_{-0})^\top \overset{*}{\mathbf{d}}_{-0} + \Pi(\overset{*}{\mathbf{p}}) \\
&= \overset{*}{p}_0 \overset{*}{d}_0 - C(\overset{*}{\mathbf{p}}_{-0}, \overset{*}{x}{}_0^{\mathcal{M}}) + \overset{*}{t}_0 \overset{*}{d}_0 \\
&\quad + \Pi(\overset{*}{\mathbf{p}}) + (\overset{*}{\mathbf{q}}_{-0} - \overset{*}{\mathbf{p}}_{-0})^\top \overset{*}{\mathbf{d}}_{-0}
\end{aligned} \tag{2.38}$$

Then, (2.23) with (2.28), and the quasi-linearity of preferences imply

$$\begin{aligned}
\overset{*}{\lambda}_j &= \kappa \overset{*}{p}_j, \quad j = 1, \ldots, N \\
\overset{*}{\lambda}_j &= \kappa' \overset{*}{q}_j, \quad j = 1, \ldots, N
\end{aligned}$$

Normalizing $\overset{*}{\mathbf{q}}$ such that $\overset{*}{p}_j = \overset{*}{q}_j, j = 1, \ldots, N$, such that only commodity-0 is taxed (subsidized for a normal good), the government's budget constraint (2.38) implies

$$\mathcal{S}_0(\overset{*}{\mathbf{q}}, \overset{*}{m}) + \overset{*}{m} = \mathcal{S}_0(\overset{*}{\mathbf{q}}, \overset{*}{m}) + \overset{*}{\Pi}_0 + \Pi(\overset{*}{\mathbf{p}}) + \overset{*}{t}_0 \overset{*}{d}_0$$

■

Walras' law implies that the Marshallian consumer's surplus allowing for income change also includes the government's revenues from the excise tax on good-0 which can be transfered back to the consumer as a lump-sum transfer. Therefore, this partial equilibrium objective function results in a "total surplus" welfare objective function that includes the government in general equilibrium.

2.4 Second-Best Taxing Price Makers

The appeal of the "total surplus" approach often resides in its apparent ability to provide a positive framework for welfare analysis in complex second-best models.[21] However, the reliability of such an approach critically depends on its ability to characterize second-best Pareto optima in general.

Guesnerie and Laffont (1978, p.439) argue that their model of optimal taxation of a price maker could be used in the description of a wide array of oligopolistic competition, and in particular of Cournot competition. Given the policy instruments available to the policy maker in their model, they rightfully argue that the supply of a group of price makers would not be efficient if the price making sector did not consist of identical (or symmetric) firms. Since the policy instruments cannot discriminate among the oligopolists, first-best Pareto optimality cannot be restored in the price making sector. This provides an appropriate set-up to test the validity of the result found in the previous section in real second-best Pareto optimum. This section shows that the addition of firm specific input taxes to the policy maker's instruments does not restore the first-best Pareto optimality of the economy.[22] Firm specific input taxes are not sufficient to restore Paretian conditions in the price making sector.

Following Guesnerie and Laffont (1978), let the firms in sector 0 be price makers and suppose they behave competitively on all other markets (i.e. they are cost-minimizing over their input decisions). Let $C^f(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, x_0^f)$ be firm f's cost function where $\boldsymbol{\tau}^f = (\tau_1^f, \ldots, \tau_N^f)^\top$ is the firm-specific input tax vector. The profit of firms $f = 1, 2, \ldots, F$ is

$$\pi_0^f = \Big[Q_0\Big(\sum_{h=1}^{F} x_0^h, \mathbf{q}_{-0}, m\Big) - t_0\Big] \cdot x_0^f - C^f(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, x_0^f).$$

In the case with a single price maker, an important requirement of the policy maker's

[21]See chapter 3 for an application of this framework.

[22]See Myles (1989) and Myles (1995), for example, for an analysis of optimal taxation (and other types of taxation) in an imperfectly competitive "Diamond-Mirrlees" economy. They find that optimal tax rules are not able to restore first-best Pareto efficiency.

problem lied in his ability to control locally the monopolist's pricing correspondence. While this assumption may be considered a weak one in a monopoly or a symmetric Cournot oligopoly, this requires stronger conditions for it to be satisfied in an asymmetric-cost Cournot oligopoly model.

Asymmetries in costs result in asymmetries in the firm's optimal response to an excise tax that are not necessarily monotonic or continuous. In order to guarantee the differentiability of the optimal production strategy of the firms, assume that the profit function of firm f is strictly concave in x_0^f and let $\overset{*}{x}{}_0^f > 0$ denote the unique Cournot-Nash equilibrium production of firm f in sector-0 for $f = 1, \ldots, F$.

Let $\overset{*}{x}{}_0^f$ and $\overset{*}{x}{}_0^{-f} \equiv \sum_{j \neq f} \overset{*}{x}{}_0^j$ denote the equilibrium values of the Cournot-Nash equilibrium where $\overset{*}{x}{}_0^f$ solves:[23]

$$\mu^f(\overset{*}{x}{}_0^f, \overset{*}{x}{}_0^{-f}, \boldsymbol{\theta}^f) \equiv \frac{\partial Q_0}{\partial d_0} \overset{*}{x}{}_0^f + Q_0\Big(\sum_f \overset{*}{x}{}_0^f, \mathbf{q}, m\Big) - t_0 - \frac{\partial C^f(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, \overset{*}{x}{}_0^f)}{\partial x_0^f} = 0 \qquad (2.39)$$

where $\boldsymbol{\theta}^f \equiv (\mathbf{q}, m, \mathbf{p}_{-0}, \boldsymbol{\tau}^f, t_0)$ for $f = 1, \ldots, F$

Define:

$$a_f \equiv \mu_1^f = 2\frac{\partial Q_0}{\partial d_0} + \overset{*}{x}{}_0^f \frac{\partial Q_0}{\partial d_0} - C_{xx}^f \qquad (2.40)$$

$$b_f \equiv \mu_2^f = \frac{\partial Q_0}{\partial d_0} + \overset{*}{x}{}_0^f \frac{\partial^2 Q_0}{\partial (d_0)^2} \qquad (2.41)$$

using (2.39). Totally differentiating (2.39) with respect to t_0 yields

$$a_f dx^f + b_f \sum_{j \neq f} dx^j = dt_0, \quad f = 1, \ldots, F. \qquad (2.42)$$

Let $dX \equiv dx^f + dx^{-f}$. Assuming the Cournot-Nash equilibrium is stable, rearranging (2.42) and solving for dX yields

$$dX = dt_0 \frac{\sum_f \frac{1}{a_f - b_f}}{1 + \sum_f \frac{b_f}{a_f - b_f}} < 0 \qquad (2.43)$$

[23] See Novshek (1985) for an exposition on the existence of the Cournot-Nash equilibrium and Friedman (1982), for example, for an excellent survey and treatment of the uniqueness of the Cournot-Nash equilibrium.

Define $\Gamma = 1 + \sum_f \frac{b_f}{a_f - b_f}$, $\Delta = \sum_f \frac{1}{a_f - b_f}$, and substitute (2.43) into (2.42) yields

$$dx^f = \frac{dt_0}{(a_f - b_f)\Gamma}\left[\Gamma - b_f\Delta\right] \tag{2.44}$$

It is clear that if $\Gamma - b_f\Delta > 0$ for $f = 1, \ldots, F$, then $\frac{dx^f}{dt_0} < 0$. Lemma 1 provides sufficient conditions for $\frac{dx^f}{dt_0} < 0$.

Lemma 1 *Let* $\alpha^f = x^f/X$ *and define* $\Phi^f \equiv \sum_{j \neq f} \frac{\alpha^j - \alpha^f}{\partial Q_0/\partial d_0 - C^j_{xx}}$. *For* $f = 1, \ldots, F$, *if* $\frac{\partial^2 Q_0}{\partial (d_0)^2}\Phi^f \geq 0$, *then* $\frac{dx^f}{dt_0} < 0$.

Proof: By definition,

$$\Gamma - b_f\Delta = 1 + \frac{\partial^2 Q_0}{\partial (d_0)^2}\left[\sum_f \frac{x^f}{\partial Q_0/\partial d_0 - C^f_{xx}} - x^f \sum_f \frac{1}{\partial Q_0/\partial d_0 - C^f_{xx}}\right].$$

Then, multiplying and dividing the term inside the square brackets by X and rearranging yields

$$\Gamma - b_f\Delta = 1 + \frac{\partial^2 Q_0}{\partial (d_0)^2} X \Phi^f > 0 \Leftrightarrow \frac{\partial^2 Q_0}{\partial (d_0)^2}\Phi^f > -1/X$$

which completes the proof.■

The assumption required to guarantee the local controllability of the equilibrium output strategies is stronger than in Guesnerie and Laffont (1978). The firms need to be not too asymmetric in their costs. For example, if the increase in input or output taxes causes one firm to shut down for some configuration of the price making sector firms' cost, then some firms may increase their output while some others would reduce theirs. This section and the next abstract from such cases. These conditions are satisfied in the neighborhood of common examples of Cournot-Nash equilibrium.[24]

To determine the second-best Pareto optimum of this imperfectly competitive economy, the policy maker maximizes the consumer's utlity function subject to a set of feasibility constraints given the set of institutionally given instruments.

[24]For example, these conditions are satisfied by the symmetric Cournot-Nash equilibrium and the linear demand cases.

Equation (2.39) implies that the Cournot-Nash equilibrium output strategy for firm f is:

$$\overset{*}{x}{}_0^f = x_0^{fC}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0, \boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^F).$$

A feasible allocation in this economy is given by

$$\Xi = \left\{ \{d_j\}_{j=0}^N, \{y_j\}_{j=1}^N, \{\eta_j^f\}_{j=1,f=1}^{N,F}, \{x_0^f\}_{f=1}^F \right\}$$

which consists of consumer demands, competitive firm's supply, and the oligopolists' input demand and output associated with the consumer's and producers' prices, the consumer's income, and the firm specific input taxes $\left\{\mathbf{q}, \mathbf{p}, m, \{\boldsymbol{\tau}^f\}_{f=1}^F\right\}$ such that:

$$y_j(\mathbf{p}_{-0}) - D_j(\mathbf{q}, m) - \sum_f \eta_j^f(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, x_0^f) \geq 0, \quad j = 1, \dots, N; \tag{2.45}$$

$$\sum_f x_0^f - D_0(\mathbf{q}, m) = 0; \tag{2.46}$$

$$x_0^f - x_0^{fC}(\mathbf{p}_{-0}, \mathbf{t}_{-0}, m, t_0, \boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^F) = 0, \quad f = 1, \dots, F. \tag{2.47}$$

The first two sets of equations ensure market-clearing, the last constraint takes into account the fact that each oligopolist, behaving strategically in the good-0 market, produces according to its best strategy.

The policy-maker's problem is given by:

Program 3

$$\max V(\mathbf{q}, m)$$

subject to (2.45), (2.46) *and* (2.47).

The next theorem shows the second-best welfare optimum $\overset{*}{\Xi}$ is not a first-best Pareto optimum even with the planner's expanded set of instruments that includes firm specific input taxes.

Theorem 3 *Assume* $\overset{*}{\mathbf{p}} \gg 0$ *and* $\overset{*}{x}{}_0^f > 0$ *for* $f = 1, \ldots, F$. *If* $(\overset{*}{\mathbf{p}}, \overset{*}{\mathbf{t}}, \{\overset{*}{\tau}{}^f\}_{f=1}^F, \overset{*}{m})$ *is a solution to Program 3, then the economic allocation* $\overset{*}{\Xi}$ *is not a first-best Pareto optimum.*

Proof: The first-order equations of Program 3 are:

$$\frac{\partial V}{\partial p_0} - \sum_{j=1}^{N} \overset{*}{\lambda}_j \frac{\partial D_j}{\partial p_0} - \overset{*}{\lambda}_0 \frac{\partial D_0}{\partial p_0} = 0 \tag{2.48}$$

$$\frac{\partial V}{\partial t_0} - \sum_{j=1}^{N} \overset{*}{\lambda}_j \frac{\partial D_j}{\partial t_0} - \overset{*}{\lambda}_0 \frac{\partial D_0}{\partial t_0} - \sum_f \overset{*}{\mu}_f \frac{\partial x_0^{fC}}{\partial t_0} = 0 \tag{2.49}$$

$$-\sum_j \overset{*}{\lambda}_j \frac{\partial \eta_j^f}{\partial x_0^f} + \overset{*}{\lambda}_0 + \overset{*}{\mu}_f = 0, \quad f = 1, \ldots, F \tag{2.50}$$

$$-\sum_j \overset{*}{\lambda}_j \frac{\partial \eta_j^f}{\partial \tau_k^f} + -\sum_{h=1}^{F} \overset{*}{\mu}_h \frac{\partial x_0^{hC}}{\partial \tau_k^f} = 0, \quad f = 1, \ldots, F,\ k = 1, \ldots, N \tag{2.51}$$

$$\frac{\partial V}{\partial p_k} + \sum_{j=1}^{N} \overset{*}{\lambda}_j \left(\frac{y_j}{\partial p_k} - \frac{\partial d_j}{\partial p_k} - \sum_f \frac{\partial \eta_j^f}{\partial p_k} \right) - \overset{*}{\lambda}_0 \frac{\partial d_0}{\partial p_k} - \sum_f \overset{*}{\mu}_f \frac{\partial x_o^{fC}}{\partial p_k} = 0, \quad k = 1, \ldots, N \tag{2.52}$$

$$\frac{\partial V}{\partial t_k} - \sum_{j=1}^{N} \overset{*}{\lambda}_j \frac{\partial d_j}{\partial t_k} - \overset{*}{\lambda}_0 \frac{\partial t_0}{\partial t_k} - \sum_f \overset{*}{\mu}_f \frac{\partial x_0^{fC}}{\partial t_k} = 0, \quad k = 1, \ldots, N \tag{2.53}$$

$$\frac{\partial V}{\partial m} - \sum_j \overset{*}{\lambda}_j \frac{\partial d_j}{\partial m} - \overset{*}{\lambda}_0 \frac{\partial d_0}{\partial m} - \sum \overset{*}{\mu}_f \frac{\partial x_0^{fC}}{\partial m} = 0 \tag{2.54}$$

The proof is in four steps.

Step 1: Note that $\frac{\partial V}{\partial p_k} = \frac{\partial V}{\partial t_k}$ and $\frac{\partial D_j}{\partial p_k} = \frac{\partial D_j}{\partial t_k}$ for $k, j = 0, 1, \ldots, N$. Taking (2.48) and subtracting from it (2.49) yields

$$-\sum_{f=1}^{F} \overset{*}{\mu}_f \left(\frac{\partial x_0^{fC}}{\partial t_0} \right) = 0, \quad f = 1, \ldots, F.$$

Therefore, $\overset{*}{\mu}_f \geq 0$ with Lemma 1 gives:

$$\overset{*}{\mu}_f = 0, \forall f. \tag{2.55}$$

Step 2: Subtracting (2.53) from (2.54) with (2.51)

$$\sum_{j=1}^{N} \overset{*}{\lambda}_j \frac{\partial \eta_j^f}{\partial \tau_k^f} = 0, \quad k = 1, \ldots, N. \tag{2.56}$$

$$\sum_{j=1}^{N} \overset{*}{\lambda}_j \frac{\partial y_j}{\partial p_k} = 0, \quad k = 1, \ldots, N. \tag{2.57}$$

Since y_j is homogeneous of degree zero in $\mathbf{p}_{-0}$ and η_j^f is homogeneous of degree zero in $\mathbf{p}_{-0} + \boldsymbol{\tau}^f$ then

$$\overset{*}{\lambda}_j = \theta \overset{*}{p}_j, \quad j = 1, \ldots, N. \tag{2.58}$$

$$\overset{*}{\lambda}_j = \theta^f (\overset{*}{p}_j + \overset{*}{\tau}_j^f), \quad f = 1, \ldots, F;\ j = 1, \ldots, N. \tag{2.59}$$

Step 3: Multiplying (2.54) by $\overset{*}{d}_k = D_k(\overset{*}{\mathbf{q}}, \overset{*}{m})$ for $k = 0, 1, \ldots, N$, and adding the k-th equation to (2.49) and (2.53) respectively, gives

$$\sum_{j=0}^{N} \overset{*}{\lambda}_j \Big(\frac{\partial D_j(\overset{*}{\mathbf{q}}, \overset{*}{m})}{\partial q_k} + \overset{*}{d}_k \frac{\partial D_j(\overset{*}{\mathbf{q}}, \overset{*}{m})}{\partial m} \Big) = 0, \quad k = 0, 1, \ldots, N$$

by Roy's theorem and recalling that $\frac{\partial V}{\partial t_k} = \frac{\partial V}{\partial q_k}$ for all k.

From Slutsky's equation and the symmetry of the Hessian of E

$$\sum_{j=0}^{N} \overset{*}{\lambda}_j \frac{\partial^2 E(\overset{*}{\mathbf{q}}, \overset{*}{u})}{\partial q_k \partial q_j} = 0, \quad k = 0, 1, \ldots, N \tag{2.60}$$

Since $\nabla^2_{\mathbf{q}} E(\mathbf{q}, u)$ is of rank N, it follows immediately from (2.60) that

$$\overset{*}{\lambda}_j = \theta' \overset{*}{q}_j, \quad j = 0, 1, \ldots, N. \tag{2.61}$$

Step 4: The previous two steps, equation (2.58), and equation (2.59) implies

$$\frac{\overset{*}{\lambda}_k}{\overset{*}{\lambda}_l} = \frac{\overset{*}{p}_k}{\overset{*}{p}_l} = \frac{\overset{*}{p}_k + \overset{*}{\tau}_k^f}{\overset{*}{p}_l + \overset{*}{\tau}_l^f}, \text{ for } k, l = 1, \ldots, N;\ f = 1, \ldots, F.$$

This and (2.61) imply

$$\frac{\overset{*}{q}_k}{\overset{*}{q}_l} = \frac{\overset{*}{p}_k}{\overset{*}{p}_l} = \frac{\overset{*}{\tau}_k^f}{\overset{*}{\tau}_l^f}, \quad k, l = 1, \ldots, N,\ f = 1, \ldots, F. \tag{2.62}$$

Last, from (2.50),

$$\overset{*}{\lambda}_0 = \theta' \overset{*}{q}_0 = \sum_{j=1}^{N} \theta^f (\overset{*}{p}_j + \overset{*}{\tau}{}^f_j) \frac{\partial \eta^f_j}{\partial x^f_0}, \quad f = 1, \ldots, F.$$

Consequently, by Sheppard's lemma

$$\frac{\theta\prime}{\theta^f} \overset{*}{q}_0 = \frac{\partial C^f(\overset{*}{\mathbf{p}}_{-0} + \overset{*}{\tau}{}^f, \overset{*}{x}{}^f_0)}{\partial x^f_0}, \quad f = 1, \ldots, F. \tag{2.63}$$

Therefore, the production plan for each oligopolists would be competitive with respect to the price vector $\hat{P}^f = (\frac{\theta'}{\theta^f}\overset{*}{q}_0, \overset{*}{p}_1, \ldots, \overset{*}{p}_N)^\top$ or to $\check{P}^f = (\frac{\theta'}{\theta}\overset{*}{q}_0, \frac{\theta^f}{\theta}\overset{*}{p}_1, \ldots, \frac{\theta^f}{\theta}\overset{*}{p}_N)^\top$ by homogeneity of degree one of the cost function for $f = 1, \ldots, F$. Similarly, the consumer faces the price system $\check{Q} = (\overset{*}{q}_0, \frac{\theta}{\theta'}\overset{*}{p}_1, \ldots, \frac{\theta}{\theta'}\overset{*}{p}_N)^\top$. For the economic state $\overset{*}{\Xi}$ and prices $\{\overset{*}{\mathbf{q}}, \overset{*}{\mathbf{p}}\}$ to be an equilibrium and an optimum, it is necessary for the production sector price vector to be proportional to the consumer price vector. Unless $\theta^f = \theta$ for all firms, $\check{P}^f$ is not proportional to $\check{Q}$ (and likewise for $\hat{P}^f$). Therefore, if $\overset{*}{\Xi}$ is an equilibrium, then it cannot be a first-best Pareto optimum (see Debreu (1959, Chap.6)).

Summing both sides of (2.63) over f yields:

$$\begin{aligned} \overset{*}{q}_0 &= \Big(\frac{1}{\theta \sum_f (\theta^f)^{-1}}\Big) \sum_{f=1}^{F} \frac{\partial C^f(\overset{*}{\mathbf{p}}_{-0} + \overset{*}{\tau}{}^f, \overset{*}{x}{}^f_0)}{\partial x^f_0} \\ &= \gamma \sum_{f=1}^{F} \frac{\partial C^f(\overset{*}{\mathbf{p}}_{-0} + \overset{*}{\tau}{}^f, \overset{*}{x}{}^f_0)}{\partial x^f_0} > 0 \end{aligned} \tag{2.64}$$

and appropriately choosing (θ, θ') such that only the commodity-0 is taxed:

$$\overset{*}{q}_k = \overset{*}{p}_k, \quad k = 1, \ldots, N. \tag{2.65}$$

$$\overset{*}{t}_0 = \gamma \sum_{f=1}^{F} \frac{\partial C^f(\overset{*}{\mathbf{p}}_{-0} + \overset{*}{\tau}{}^f, \overset{*}{x}{}^f_0)}{\partial x^f_0} - \overset{*}{p}_0 \tag{2.66}$$

Hence, $\{\overset{*}{\Xi}, \overset{*}{\mathbf{p}}, \overset{*}{\mathbf{t}}, \{\overset{*}{\tau}{}^f\}_{f=1}^F, \overset{*}{m}\}$ is an equilibrium.■

The planner's control of the oligopolists input taxes is not sufficient to restore first-best optimality of feasible allocations. If the choice of instruments was to restore first-best optimality conditions in the imperfectly competitive sector, then the competitive sectors' production prices are not proportional for all firms (i.e. $\check{P}^f$ is not proportional to $\check{P}^h$ for $f, h = 1, \ldots, F$ and $h \neq f$). However, if the competitive sectors' production prices are proportional across all firms, then the oligopolists marginal cost is not equalized. Note that if the firms costs are symmetric, then the optimum described above is a first-best Pareto optimum.

Corollary 1 *Assume* $\overset{*}{\mathbf{p}} \gg 0$, *and* $C^f(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, x_0^f) = C(\mathbf{p}_{-0} + \boldsymbol{\tau}^f, x_0^f)$ *with* $\overset{*}{x}{}_0^f > 0$ *for* $f = 1, \ldots, F$. *If* $(\overset{*}{\mathbf{p}}, \overset{*}{\mathbf{t}}, \{\overset{*}{\boldsymbol{\tau}}{}^f\}_{f=1}^F, \overset{*}{m})$ *is a solution to Program 3, then the economic allocation* $\overset{*}{\Xi}$ *is a first-best Pareto optimum.*

Proof: The proof is immediate from the fact that $\frac{\partial \eta_j^f}{\partial \tau_k^f} = \frac{\partial \eta_j^h}{\partial \tau_k^h}$ for $j, k = 1, \ldots, N$, and $f, h = 1, \ldots, F$.■

2.5 Second-Best Marshallian Surplus Optimum

If a Marshallian surplus optimum characterizes a second-best Pareto optimum, then the Pareto and Marshallian surplus optimal allocations coincide for real second-best economies. In other words, if the shadow prices associated with the constraints (2.45), (2.46) and (2.47) are collinear with their Marshallian surplus optimum counterparts, then the Marshallian consumer's surplus function allowing for income change will correctly characterize a second-best Pareto optimum.

The policymaker's Marshallian surplus maximization problem is:

Program 4

$$\max S_0(\mathbf{q}, m) = \int_{q_0}^{\bar{q}_0} D_0(\chi_0, \mathbf{q}_{-0}, m) d\chi_0 + m$$

subject to $q_N = 1$, (2.45), (2.46), *and* (2.47).

The characterization of Program 4 and its comparison with Program 3 yields the following result:

Theorem 4 *Assume* $\tilde{\mathbf{p}} \gg 0$ *and* $\tilde{x}_0^f > 0$ *for* $f = 1, \dots, F$. *If* $(\tilde{\mathbf{p}}, \tilde{\mathbf{t}}, \tilde{\boldsymbol{\tau}}^1, \dots, \tilde{\boldsymbol{\tau}}^F, \tilde{m})$ *is a solution to Program 4 and if the consumer price of good-N is chosen as the numéraire, then the economic allocation* $\tilde{\Xi}$ *is a second-best Pareto optimum if and only if the preferences of the consumer are given by*

$$V(\mathbf{q}, m) = G^N\Big(\frac{m - \hat{e}(\mathbf{q})}{q_N}\Big).$$

Proof: Sufficiency obtains directly. For necessity, note that the first-order equations of Program 4 are:

$$-\tilde{D}_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_0} = 0 \tag{2.67}$$

$$-\tilde{D}_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_0} - \sum_{f} \tilde{\mu}_f \frac{\partial x_0^{fC}}{\partial t_0} = 0 \tag{2.68}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} d\chi_0 + \sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} - \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} - \sum_{f} \frac{\partial \eta_j^f(\tilde{\mathbf{p}}_{-0}, \tilde{x}_0^f)}{\partial p_k} \Big) \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_k} - \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial p_k} = 0, \quad k = 1, \dots, N-1;\end{aligned} \tag{2.69}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} d\chi_0 - \sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_k} - \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial t_k} = 0, \quad k = 1, \dots, N-1;\end{aligned} \tag{2.70}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_N} d\chi_0 + \sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_N} - \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_N} - \sum_{f} \frac{\partial \eta_j^f(\tilde{\mathbf{p}}_{-0}, \tilde{x}_0^f)}{\partial p_N} \Big) \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial p_N} - \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial p_N} - \tilde{\rho} = 0;\end{aligned} \tag{2.71}$$

$$\begin{aligned}\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_N} d\chi_0 - \sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_N} \\ -\tilde{\lambda}_0 \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial t_N} - \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial t_N} - \tilde{\rho} = 0;\end{aligned} \tag{2.72}$$

$$-\sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial \eta_j^f(\cdot)}{\partial x_0^f} + \tilde{\lambda}_0 + \tilde{\mu}_f = 0, \qquad f = 1, \dots, F; \tag{2.73}$$

$$-\sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial \eta_j^f(\cdot)}{\partial \tau_k^f} - \sum_{h=1}^{F} \overset{*}{\mu}_h \frac{\partial x_0^{hC}(\cdot)}{\partial \tau_k^f} = 0, \quad k = 1, \dots, N, \ \forall f; \tag{2.74}$$

$$\int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial D_0(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial m} d\chi_0 + 1 - \sum_{j=0}^{N} \tilde{\lambda}_j \frac{\partial D_j(\tilde{\mathbf{p}} + \tilde{\mathbf{t}}, \tilde{m})}{\partial m} - \sum_{j=1}^{F} \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial m} = 0 \tag{2.75}$$

The proof follows very closely that of Theorem 2. First, subtracting (2.68) from (2.67) yields:

$$\sum_{f=1}^{F} \tilde{\mu}_f \frac{\partial x_0^{fC}(\cdot)}{\partial t_0} = 0$$

With Lemma 1 and $\tilde{\mu}_f \geq 0$, this implies

$$\tilde{\mu}_f = 0, \quad f = 1, \dots, F. \tag{2.76}$$

Since $\tilde{\mu}_f = 0$, subtracting (2.70) from (2.69) and (2.72) from (2.71) yields:

$$\sum_{j=1}^{N} \tilde{\lambda}_j \Big(\frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} - \sum_{f=1}^{F} \frac{\partial \eta_j^f(\tilde{\mathbf{p}}_{-0} + \tilde{\boldsymbol{\tau}}^f, \tilde{x}_0^f)}{\partial p_k} \Big) = 0, \quad k = 1, \dots, N. \tag{2.77}$$

Noting that $\frac{\partial \eta_j^f}{\partial p_k} = \frac{\partial \eta_j^f}{\partial \tau_k^f}$, (2.74) yields

$$\sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial \eta_j^f(\tilde{\mathbf{p}}_{-0} + \tilde{\boldsymbol{\tau}}^f, \tilde{x}_0^f)}{\partial p_k} = 0, \quad f = 1, \dots, F, \tag{2.78}$$

and the symmetry of the Hessian of the cost function implies

$$\tilde{\lambda}_j = \kappa^f(\tilde{p}_j + \tilde{\tau}_j^f) \text{ for } j = 1, \dots, N \text{ and } f = 1, \dots, F. \tag{2.79}$$

and from (2.78) and (2.77) with the symmetry of the Hessian of the competitive sector's profit function, it follows that

$$\sum_{j=1}^{N} \tilde{\lambda}_j \frac{\partial y_j(\tilde{\mathbf{p}}_{-0})}{\partial p_k} = 0, \quad k = 1, \dots, N.$$

Therefore,

$$\tilde{\lambda}_j = \kappa \tilde{p}_j, \quad j = 1, \dots, N. \tag{2.80}$$

Now, multiply (2.75) by $\tilde{d}_k = D_k(\tilde{\mathbf{q}}, \tilde{m})$ for $k = 0, 1, \dots ; N$ which yields

$$\int_{\tilde{q}_0}^{\bar{q}_0} D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 + D_k(\tilde{\mathbf{q}}, \tilde{m}) - \sum_{j=0}^{N} \tilde{\lambda}_j D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_j(\tilde{q}_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} = 0, \quad k = 0, 1, \dots, N \quad (2.81)$$

Adding (2.81) to (2.68), (2.70), and (2.72) respectively, and rearranging using the Slutsky equations gives

$$\tilde{\lambda}^{\top} \nabla^2_{\mathbf{q}} E(\tilde{\mathbf{q}}, \tilde{u}) = \begin{bmatrix} D_0(\tilde{\mathbf{q}}, \tilde{m}) \int_{\tilde{q}_0}^{\bar{q}_0} \frac{\partial^2 D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} d\chi_0 \\ \vdots \\ D_k(\tilde{\mathbf{q}}, \tilde{m}) + \int_{\tilde{q}_0}^{\bar{q}_0} \left(\frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_k} + D_k(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} \right) d\chi_0 \\ \vdots \\ D_N(\tilde{\mathbf{q}}, \tilde{m}) + \int_{\tilde{q}_0}^{\bar{q}_0} \left(\frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial q_N} + D_N(\tilde{\mathbf{q}}, \tilde{m}) \frac{\partial D_0(\chi_0, \tilde{\mathbf{q}}_{-0}, \tilde{m})}{\partial m} \right) d\chi_0 - \tilde{\rho} \end{bmatrix} \quad (2.82)$$

Following closely the remainder of the proof of Theorem 2 completes the proof.■

While this theorem shows that a Marshallian surplus optimum can characterize a second-best Pareto optimum, the conditions for its application are very restrictive. Not only must the consumer's demand for the commodity-0 display zero income-effect and all distortions (i.e. where Paretian conditions do not hold) must be contained in the commodity-0 sector, all other goods which prices may vary relatively to the numéraire must also have no income effect. Moreover, the requirement that all second-best distortions must be contained in the market under consideration greatly limits the scope of its application in practice.

The requirement that preferences must be quasi-linear is very restrictive: the marginal utility of income must be independent of income and of all other prices than the numéraire which, at best, could be interpreted as a composite commodity. It is important to note that the argument of approximate zero-income effect (e.g. Willig (1976), Vives (1987), Tirole (1988)) for a particular commodity under consideration is not sufficient for the

Marshallian surplus optimum to characterize a second-best optimum. Excluding the numéraire, all other commodities must have zero income-effect and the Paretian conditions must hold for these markets.[25] As shown in Blackorby (1998, Corollary, Theorem 1), if one does not choose a particular commodity as a numéraire then the surplus optimum can never replicate a Pareto optimum.

Corollary 2 *If consumer prices are not normalized, then the surplus optimum will not coincide with the second-best Pareto optimum of Theorem 3.*

Proof: Suppose no prices are normalized. This implies $\mathring{\beta} = 0$. From Theorem 4, then $E(\mathbf{q}, u) = \hat{e}(\mathbf{q})$. This implies that the demand for each commodity is independent of income which contradicts the assumption of well-behaved preferences of Theorem 3.■

Note that an *a priori* choice of a numéraire determines the preferences of representative consumer. This compromises the apparent objectivity of the partial equilibrium Marshallian surplus approach. Still, under the conditions of Theorem 4, a Marshallian total surplus optimum characterizes a second-best Pareto optima in a second-best general equilibrium.

Proposition 2 *Assume the consumer's preferences are quasi-linear. Under the conditions of Theorem 4, the sum of Marshallian consumer's surplus, producer profits, and government revenues is equivalent to consumer surplus allowing for income change in a second-best general equilibrium.*

Proof: Let $(\tilde{\mathbf{p}}, \tilde{t}, \tilde{\tau}^f, \tilde{m})$ be defined by Theorem 4.

Since $\tilde{\Pi}_0 = \sum_f \tilde{\pi}_0^f$, Hotelling's lemma, and the government's budget con-

[25] Clearly, extending Vives (1987) to second-best economies requires a formal investigation.

straint yields:

$$\begin{aligned}
\tilde{m} &= (\tilde{\mathbf{q}} - \tilde{\mathbf{p}})^\top \tilde{\mathbf{d}} + \sum_f \tilde{\boldsymbol{\tau}}^f \tilde{\boldsymbol{\eta}}^f + \Pi(\tilde{\mathbf{p}}) + \tilde{\Pi}_0 \\
&= (\tilde{q}_0 - \tilde{p}_0)\tilde{d}_0 + \sum_f \tilde{\boldsymbol{\tau}}^f \tilde{\boldsymbol{\eta}}^f + \tilde{\Pi}_0 + (\tilde{\mathbf{q}}_{-0} - \tilde{\mathbf{p}}_{-0})^\top \tilde{\mathbf{d}}_{-0} + \Pi(\tilde{\mathbf{p}}) \\
&= \tilde{p}_0 \tilde{d}_0 - \tilde{\mathbf{p}}_{-0}^\top \sum_f \boldsymbol{\eta}^f(\tilde{\mathbf{p}}_{-0} + \tilde{\boldsymbol{\tau}}^f, \tilde{x}_0^{fC}) + \tilde{t}_0 \tilde{d}_0 \\
&\quad + \Pi(\tilde{\mathbf{p}}) + (\tilde{\mathbf{q}}_{-0} - \tilde{\mathbf{p}}_{-0})^\top \tilde{\mathbf{d}}_{-0}
\end{aligned} \tag{2.83}$$

Then, (2.80) with (2.82), and the quasi-linearity of preferences imply

$$\begin{aligned}
\tilde{\lambda}_j &= \kappa \tilde{p}_j, \quad j = 1, \ldots, N \\
\tilde{\lambda}_j &= \kappa' \tilde{q}_j, \quad j = 1, \ldots, N
\end{aligned}$$

Normalizing $\tilde{\mathbf{q}}$ such that $\tilde{p}_j = \tilde{q}_j, j = 1, \ldots, N$ yields

$$\mathcal{S}_0(\tilde{\mathbf{q}}, \tilde{m}) + \tilde{m} = \mathcal{S}_0(\tilde{\mathbf{q}}, \tilde{m}) + \tilde{\Pi}_0 + \Pi(\tilde{\mathbf{p}}) + \tilde{t}_0 \tilde{d}_0 + \sum_f \tilde{\boldsymbol{\tau}}^f \tilde{\boldsymbol{\eta}}^f$$

and the right-hand side of the last equation is equal to total surplus.■

Therefore, the Marshallian total surplus (sum of consumer's surplus, producers' profits, and total government revenues) will be an "appropriate" welfare objective for real second-best economies as long as all the distortions are present in the market under considerations.

Note that when second-best constraints are present in other markets, then the Marshallian total surplus function will not determine a second-best Pareto optimum unless it also satisfies Paretian conditions. The difference between this result and the one in Blackorby (1998) shows the necessity of partial equilibrium formulations to incorporate all markets where prices are indirectly affected by policies and characterize adequately their distortions.

2.6 Summary

This essay investigated the conditions under which a partial equilibrium Marshallian surplus optimum coincides with a Pareto optimum when the production sector of a general equilibrium economy is imperfectly competitive. It is shown that the maximization of the Marshallian consumer surplus function allowing for income change characterizes "true" second-best Pareto optimal allocations if (*i*) the consumer has quasi-linear preferences, and (*ii*) all other markets, except the one under consideration, satisfy Paretian optimality conditions. Therefore, it is shown that under these conditions the Marshallian total surplus function (i.e. sum of consumer's surplus, producers' profit, and total taxes raised) can characterize a "true" second-best Pareto optimum. This essay appears to validate approaches taken by partial equilibrium welfare analysts that make welfare conclusions based on a formulation of "total surplus" that satisfies those two conditions.

While the main result of this essay appears to validate a partial equilibrium formulation of second-best problems, the conditions required for them to hold brings serious doubt on its reliability for real public policymaking. Unless these results can extended to small income effects or could incorporate second-best distortions in other markets, the reliance on the Marshallian total surplus function for policymaking in real economies would seem to originate more from its practical appeal than for its ability to characterize efficient second-best allocations.

Chapter 3

Optimal Discrimination towards Polluters

3.1 Introduction

Environmental regulators often use command-and-control (e.g. performance quotas, design standards, and output control) or incentive-based (e.g. taxes for emissions, subsidies for pollution control technologies, and tradeable permits) or both policies to control the amount of toxic pollution that is discharged in the environment. For example, the Canadian petroleum refining industry's effluents are subject to regulations and guidelines (see Environment Canada (1974)) that limit the amount of toxic substances that a refinery ejects in its waste water per barrel of crude oil treated. Similar regulations apply to the Canadian pulp and paper industry, the Canadian aluminum industry and others as well.[1] In the U.S., similar types of regulation affect the cement manufacturing industry for example. It is generally considered that the objective of environmental regulations is to bridge the gap between the private and social cost of pollution.[2]

[1]For example, see Harrison (1995), Laplante and Rilstone (1996), and Lanoie, Thomas and Fearnley (1998).

[2]For example, see Stiglitz (1988, Chap.8).

There is a substantial literature on how to reconcile the difference between the private and social cost of pollution emissions under perfect competition and perfect information (see for example, Coase (1960), Arrow (1969) and Starrett (1972)). However, these institutional assumptions might not be satisfied when an environmental regulator tries to design and implement an efficient policy. This essay characterizes an optimal pollution emissions regulatory policy under Cournot duopolistic competition and asymmetric information. Following the "new regulatory economics" paradigm (see Baron and Myerson (1982) and Laffont and Tirole (1993)), the essay views the pollution regulatory problem as a welfare maximization problem constrained by informational asymmetries. However, this essay differs from this literature in two ways. First, the polluting industry is not a monopoly, but a duopoly interacting strategically on the output market with uncorrelated private information. Second, the environmental regulator's policy is restricted to pollution emissions control instruments. The first assumption is made because most markets subjected to pollution control are neither monopolized nor perfectly competitive. The second assumption is made because the scope of environmental regulatory policies is often limited to emission taxes or quotas in practice.

This essay shows that if the firms in the industry are better informed about their costs than the regulator and competing in Cournot-fashion in the output market, then the optimal regulatory policy benefits from the competition even though the firms' environment is uncorrelated. Strategic competition is a source of discipline against efficient firms' ability to misreport their types. The firms' output strategies indirectly act as an information correlation externality to reduce the cost of rent-extraction in terms of efficiency for the optimal regulatory policy.

The results presented in this essay provide a theoretical and normative foundation for discrimination between firms in the regulation of pollution; i.e., for environmental regulatory policies that discriminates between firms based on the regulator's prior belief about the firms' cost distribution. If he believes that one type of firm is likely to have higher cost of production for any given level of regulation, then the optimal regulatory policy will discriminate between both firms although they both have the same cost of production *ex post.* For example, if the regulator believes that small and medium-sized firm have a cost disadvantage over larger corporate firms, then the optimal regulatory policy will result in a lower marginal tax on emission for small and medium-sized firms although they could have lower cost of production *ex post.* This occurs because competition in the output market is more efficient in extracting information rents than nonlinear taxes on pollution when firms have identical marginal costs of production.

The main results are that (i) *ex post* strategic competition between the duopolists reduces the informational rents of both firms compared to a monopolist producer even if their cost environment is uncorrelated; (ii) if the regulator's priors are identical for each firm and the firms' cost are *ex post* identical, then the marginal tax rates (pollution emission quota) of each firm are equal but higher (lower) than the symmetric information marginal tax rate; and (iii) if the regulator believes that one firm is always more likely to be efficient than its competitor (in the sense of first-order stochastic dominance) and that both firms are equally efficient *ex post*, then the firm that is more likely to be efficient faces a higher marginal tax (lower quota) than its competitor. Finally, an immediate corollary to this last result provides a theoretical and normative foundation for grandfathering clauses in some industries in which older and *ex ante* inefficient firms face a lower marginal tax (higher quota) on emissions than younger firms even though both are equally efficient *ex post.*

The previous literature on pollution control has taken two approaches. First, the imperfect competition literature, assuming perfect and complete information, has focused on the relative welfare performance of linear taxes (or Pigouvian Taxes) *versus* performance quotas in the context of a monopoly or an oligopoly. Buchanan (1969) argues that when the regulator takes the market structure as given, namely a monopoly, then a pollution tax is inefficient because the regulator attempts to balance the product market inefficiency with the externality inefficiency. The tax is inefficient because the regulator does not have a sufficient number of instruments to restore first-best optimality condition. Besanko (1987) considers pollution control regulation for an oligopolistic market in which all firms have symmetric costs and compete simultaneously. It is shown that performance standards are equivalent to a linear tax on emissions. Copeland (1992) extends Besanko's analysis to four different imperfectly competitive environments.[3] He finds that, when one firm has a strategic advantage over its rivals or when firms can strategically commit to pollution control investments, linear pollution taxes are preferred to performance standards.

The second approach considers the effects of imperfect or incomplete information regulation of pollution in monopolistic or perfectly competitive markets. With imperfect information, this literature establishes the non-equivalence of linear taxes and performance quotas when firms are competitive. Predetermined linear taxes or quotas are no longer satisfactory instruments because they induce too much pollution when costs are unexpectedly low in the case of a quota or when costs are higher than expected in the case of a linear tax. Adar and Griffin (1976) and Fishelson (1976) show that linear excise taxes and pollution standards or quotas are not equivalent in the presence of uncertainty, and that linear taxes are better instruments to control pollution, under some conditions, than standards. Roberts and Spence (1976) extends this result and show that a combination of instruments (namely subsidy, penalties and licenses) are preferable to either effluent fees or licenses separately. Uniform linear taxes result in efficient firms underpolluting and inefficient firms overpolluting. Standards result in efficient firms overpolluting and inefficient firms underpolluting. Under the same condition, Weitzman (1974) shows that if the marginal control cost (i.e. abatement cost) of a single firm producing an externality is not known to the regulator—who has to choose between a tax or a standard, but not both—then standards yields smaller expected deviations from *ex post* efficient

[3]Bruneau (1997) considers a wider range of instruments used by environmental regulators.

outcomes when the marginal social benefits of externality reduction have a steeper slope than marginal costs, and that taxes minimize the expected deviation when the reverse is true. Dasgupta, Hammond and Maskin (1980) generalize Weitzman's result and shows that a nonlinear tax schedule is at least as efficient as standards or taxes separately.

With incomplete information, Baron (1985) considers the optimal regulation of prices and pollution of a monopolist.[4] Laffont (1993) considers the regulation of pollution in an industry; however, because the regulator controls the prices of output and the quantity of pollution emissions, he does not consider the effect of the strategic interaction of the duopolists on the optimal pollution regulatory scheme. In light of the fact that information and competitive distortions may overlap in real economies, this may significantly alter the policies that are derived independently from each other. This essay is concerned with this institutional framework.

The idea that competition in the product market acts as a good incentive device has received some attention in correlated environments.[5] But as Scharfstein (1988) remarks: "[...] *we do not yet understand the precise mechanism through which competition affects incentives*". When firms' costs are uncorrelated Wolinsky (1997) appears to be the only contribution that considers the interaction between imperfect competition and incomplete information in the context of regulation. He analyzes the optimal regulation of an imperfectly differentiated market in which duopolists compete in prices and quality for market-share in the health-care market. The regulator controls prices and market-shares, but cannot observe the quality choices of the firms. He investigates the optimal choice of regulatory regime: whether and under what conditions managed competition (*i.e.*, regulation of prices) or segmentation (*i.e.*, regulation of both prices and market-shares)

[4] See Lewis (1996) for a recent survey.

[5] In the regulation literature, this as been dubbed the *yardstick competition* models (see Laffont and Tirole (1993, p. 84–86) for an overview of this literature and its origins). Auriol (1993) and Auriol and Laffont (1992) consider yardstick competition in a duopoly set-up where output prices are also regulated. Hart (1983) and Scharfstein (1988) investigate the effect of a perfectly competitive product-market on managerial slack when managerial and entrepreneurial firms' costs are positively correlated.

between regulated duopolies achieves better results. Hence, his paper's main contribution is a comparison of the welfare properties of different choices of regulatory instruments.

This essay is organized as follows. Section 2 describes the model. Section 3 models the environmental regulatory process as a two-stage game with incomplete information. Section 4 derives the competitive stage's optimal strategies for the firms taking the regulations as given. To provide a bechmark for the asymmetric information case, section 5 characterizes the optimal pollution emissions regulatory policy when there is symmetric information between the regulator and the firms. Section 6 characterizes the optimal pollution emissions regulatory policy with asymmetric information. Section 7 summarizes the results. Some proofs appear in the appendix.

3.2 The Model

Consider a duopoly in which firm i, $i = 1, 2$, produces q_i units of a homogeneous good. The production of q_i requires firm i to emit e_i units of toxic pollutants into the environment. Let $C(\beta_i, q_i, e_i)$ be the short-run cost function for firm i, where β_i is a productivity parameter which is private information to the firm.[6] The convention adopted is that pollution emissions are inputs to the firms.[7]

For simplicity, the cost function of firm i is assumed to have the following functional form:

$$C(\beta_i, q_i, e_i) = \begin{cases} (\beta_i - e_i)q_i + \frac{1}{2\theta}(e_i)^2, & \text{for } q_i > 0 \\ 0, & \text{otherwise} \end{cases}$$

where $\theta > 0$ is a local regularity condition, and $\beta_i \in \mathbb{B}_i = [\underline{\beta}_i, \bar{\beta}_i] \subset \mathbb{R}_{++}$. Note that $C_{qe} < 0$, $C_{q\beta} > 0$ and $C_{e\beta} = 0$ for all positive levels of q_i and e_i. The first restriction on the cross-partials of C says that if a firm is forced to reduce its use of pollution emissions,

[6]In other words, β_i is an adverse selection parameter.

[7]Considering emissions as outputs or by-products of the output would not change the results.

then its marginal cost of output is increased. This restriction can be interpreted as a *cost-reduction complementarity* of emissions assumption, as in Copeland (1992) and Lewis (1996, p. 835). The second restriction implies that more inefficient firms (higher β_i) have a higher marginal cost of output. The last restriction says that the private information parameter does not affect the marginal cost of pollution emissions. The last two restrictions are commonly known as *single-crossing* conditions in the adverse selection literature.[8]

Assume $e^{*U}(\beta_i, q_i) \equiv \arg\min_x C(\beta_i, q_i, x) = \theta q_i < \infty$ is the unregulated cost-minimizing choice of emissions. The assumed functional form of the cost function implies that $C_{ee} > 0$ for all (β_i, e, q) and $C_e \leq 0$ for $e \leq e^{*U}$. Thus, a firm's marginal cost of reducing its emissions levels below the unregulated level is non-decreasing in e_i.

The firms are assumed to behave as Cournot competitors on the output market. The profit of firm i is given by:

$$\pi_i = P(Q)q_i - (\beta_i - e_i)q_i - \frac{1}{2\theta}(e_i)^2, \quad i = 1, 2$$

where $P(Q)$ denotes the inverse demand function, and $Q = q_1 + q_2$ is the total production of the industry. For simplicity, assume $P(Q) = a - bQ$ if $Q \leq a/b$ and $P(Q) = 0$ otherwise, where $a, b > 0$.[9] Finally, let $E = e_1 + e_2$ denote the aggregate amount of toxic pollution emissions used by the industry.

The regulator does not observe the productivity parameter, β_i, nor does it observe the total short-run cost of either firms. All other information is common knowledge. It is assumed that the environmental regulator's instruments consist of firm specific lump-sum taxes (or subsidies) T_i and pollution emission quotas $\bar{e}_i$ for $i = 1, 2$.[10] The convention

[8]This cost function also implies that there is a pollution shutdown clean-up cost of $\lim_{q_i \to 0^+} C(\beta_i, q_i, e_i) = \frac{1}{2\theta}(e_i)^2$. This feature of the cost function will not affect the results because it is assumed that the parameters of the model are such that all firms operate in equilibrium. Nonetheless, the analysis and the results can be extended to more general cost functions.

[9]It is assumed that a and b are such that in equilibrium, both firms produce. The analysis can be generalized quite easily to more general demand functions provided that an industry equilibrium exists.

[10]An emission quota specifies a maximum permissible level of pollution emission.

used is that $T_i < 0$ is a transfer from firm i to the regulator. It is also assumed that the regulator can redistribute any taxes collected as lump-sum transfers to consumers.

The objective function, W, of the environmental regulator is taken to be a weighted sum of net consumer surplus and producer surplus minus the social cost of toxic pollution emissions.[11] The gross consumer surplus is $S(Q) = \int_0^Q P(t)dt$. The social unit-cost of toxic pollution emission is assumed to be constant and equal to $\nu > 0$. Letting $\alpha \in [0, 1]$ denote the weight of producer surplus in W, the regulator's objective function is:

$$W = S(Q) - P(Q)Q - (T_1 + T_2) + \alpha\left[(\pi_1 + T_1) + (\pi_2 + T_2)\right] - \nu E$$

The weight α is less than one, for example, because the regulator may recognize that all the profits of the firms may not be distributed exclusively to shareholders that reside in its jurisdiction, while all consumers do.[12] A distortionary taxation rationale can also be given to α (See Caillaud, Guesnerie, Rey and Tirole (1988)).

3.3 The Regulatory Process

Following the "new regulatory economics" literature, the regulatory relationship is modeled as a game of incomplete information in which the regulator is a Stackelberg leader and the firms have private information over a productivity parameter in the cost function. This literature deals mainly with the regulation of a monopolist's prices. In contrast, here, firms freely engage in Cournot competition on the output market.

It is important to observe that the organization of regulators is generally separated, and that the objectives and responsibilities of economic regulators (e.g., regulation of prices, entry and exit) are not necessarily the same ones as for social regulators (e.g., health and safety, environment). For example, in the United-States unregulated compe-

[11] See chapter 2 for the conditions under which a partial equilibrium Marshallian surplus function is an appropriate objective function to characterize second-best economic policies.

[12] Bailey (1976) and Bower (1981), both former regulators, argue that regulators do not put as much weight on industries' profit as on consumers' welfare.

tition issues are generally handled by the Federal Trade Commission and the Department of Justice while the environmental regulation is the responsibility of the Environmental Protection Agency. In Canada, a similar separation of regulatory oversight is observed between the Competition Bureau for competition matters, and Environment Canada and Natural Resources Canada for environmental regulations. This chapter takes the separation of powers as given because environmental regulators generally have legal jusrisdiction only on pollution issues and not competition issues.[13]

Let $\hat{\mathcal{M}} = \{(T_i(\hat{\beta}_1, \hat{\beta}_2), \bar{e}_i(\hat{\beta}_1, \hat{\beta}_2))\}_{i=1}^2$ be the regulator's direct-revelation environmental policy. $\hat{\mathcal{M}}$ specifies a tax/subsidy transfer $T_i : \mathbb{B}_1 \times \mathbb{B}_2 \mapsto \mathbb{R}$ and a pollution emissions standard $\bar{e}_i : \mathbb{B}_1 \times \mathbb{B}_2 \mapsto \mathbb{R}_+$ as a function of the reports from the firms of their productivity parameters. The timing and the information structure of the regulatory process is the following:

Stage 1: Nature **independently** draws each firm's productivity parameter, $(\beta_1, \beta_2) \in \mathbb{B}_1 \times \mathbb{B}_2$, from their respective cumulative distribution functions, F_1 and F_2. It is assumed that the cumulative distribution functions are continuously differentiable on their respective supports and that, with the probability distribution functions f_i, $i = 1, 2$, they satisfy the monotone hazard rate property (F_i/f_i is increasing). The latter assumption rules out trivial cases of bunching. The value of firm i's productivity parameter β_i is private information.[14]

Stage 2: The regulator commits to the environmental policy, $\hat{\mathcal{M}}$.

Stage 3: Both firms simultaneously send reports $\hat{\beta}_i \in \mathbb{B}_i$, $i = 1, 2$, to the regulator. These reports determine the relevant pollution emission standard and tax/subsidy for each firm according to the schedules announced in Stage 2.

[13] Martimort (1996), Laffont and Martimort (1997b) formally address this problem.

[14] For simplicity, assume that firm j and the regulator share the same beliefs about firm i's type, as summarized by the CDF F_i.

Stage 4: If a firm rejects the environmental policy, then the firm shuts down and receives its reservation profit, which is normalized to be zero. If the firms accept the environmental policy, then they proceed to the competitive stage (Stage 5).

Stage 5: Both firm acquire the information of their rival's productivity parameter and engage in Cournot competition on the final product market, taking the environmental policy as given.

The structure of the regulatory process makes three important assumptions in order to conform with the stylized facts and institutional characteristics of environmental regulation.

First, as Vickers and Yarrow (1988, p. 99) point out:"In reality [...] managers are much better informed about the industry conditions than are the firm's owners and regulators[...]." In other words, firms often know the opponent's type when they are making their strategic decisions at the competitive stage. To capture this observation in a heuristic way, an assumption of symmetric and complete information at the competitive stage (Stage 5) is made. This assumption permits the analysis of the competitive stage's strategic interaction in pure strategies. Nonetheless, the assumption of complete and perfect information at the competitive stage is not crucial for the results of this chapter as long as the firms' best-response in output are strategic substitutes.[15] Another motivation for this assumption is also provided by Wolinsky (1997): since most environmental regulatory decisions are made for a relatively long period during which firms learn each others' costs relatively quickly, the firm's competitive interaction would occur mostly under complete information. Indeed, this is likely to characterize the case for some environmental regulations. For example, the *Petroleum Refinery Effluent Regulations and Guidelines* that were enacted on November 1, 1973 still regulates this Canadian industry today.

Second, it is assumed that the regulator does not share the information the firms'

[15]Note that a Bayesian equilibrium for the Cournot output game with incomplete information, for example, exhibits this crucial feature of the model.

possess about their productivity parameter at Stage 1 and, more importantly, the firms also do not observe the rival firm's productivity parameter at Stage 1. It has been recognized in both the applied and theoretical literature that for environmental regulation, compliance with standards involves a fair amount of investment in new and uncertain technologies that require some learning-by-doing by the appropriate staff in order to efficiently implement the new abatement or control technology. In addition, this investment often takes places over a long period and sometimes prior to the enactment of regulatory statutes or laws (see Gruenspecht and Lave (1989)). Consequently, even if the managers of firms in a particular industry might have had symmetric information about the industry's cost structure at some point in the past, at the revelation stage they might not have the information on how a particular investment has affected (or will affect) the cost structure of the rival firm in the industry.

Finally, following Wolinsky (1997), it is assumed that the regulator commits to $\hat{\mathcal{M}}$ and only uses the firms' reports of their types in Stage 3. It is possible to design other types of mechanisms which directly exploit the firms' superior information in the competitive stage by having them report each other's type.[16] For such mechanisms, which rely on sufficiently harsh punishments when firms cheat, the complete information solution can be implemented. However, in contrast to many other types of economic regulation, these mechanisms may not be interesting or viable in this case, because environmental regulations are rarely revised, modified or updated.[17] For example, the *Petroleum Re-*

[16]Consider the following example of such a mechanism: Each firm reports its private information parameter and the complete information regulatory policy is implemented. Then, after having observed each other's type, the firms have to send another report to the regulator in which they each report both firms' types simultaneously. If these report do not match, they are severely punished. If the reports indicate that only firm i lied, then firm i is punished, but not as harshly as when both firms lie. If the punishments are chosen appropriately, this mechanism will implement truth-telling as an equilibrium (see Moore and Repullo (1988), and Ma (1988) in the context of a moral hazard principal-multiple agents model).

[17]Two of the most common forms of economic regulation are rate-of-return regulation and price-cap regulation. Rate-of-return regulations are revised following the request of either the firm or the regulator. Rate revisions often occur within a period of two to three years. Price-cap regulations are theoretically revised at a predetermined frequency (generally five years). Recent observations, however, have shown that price-cap revisions are often made before the pre-determined date.

finery Effluent Regulations and Guidelines was enacted on November 1, 1973 and still regulates this industry in Canada. In the U.S., the regulation of effluent emissions of cement manufacturing plants were mostly adopted on Febuary 20, 1974 as part of the Federal Water Pollution Act and eventually some sections were amended in 1995.[18] While some rationales might be given to explain why environmental regulators commit to their regulatory policies, this chapter takes this commitment as given.[19]

Another important feature of the regulatory process is that it is assumed that the regulator is satisfied with mechanisms that induce truth-telling as a Bayes-Nash equilibrium (that is, it is optimal to tell the truth when the other firm also tells the truth, and so on). The model uses this equilibrium concept because this chapter's concern is with the structure and welfare properties of an optimal pollution regulatory scheme. However, there are potential problems associated with this approach.

First, for a given incentive scheme there may exist multiple Nash equilibrium reporting strategies. If one of these equilibria yields higher profits, then the regulatory policy may fail to implement the regulator's preferred allocation.[20] Second, if the agents happen to play a cooperative rather than a noncooperative game, they may end up adopting other reporting strategies than the ones that the regulator wishes to implement.[21] Because the choice of an appropriate equilibrium concept for implementing reporting strategies that possess "better" properties have been adequately dealt with in the incentive literature, this chapter puts aside such considerations because they are outside the main scope of

[18]39 FR 6591, Part 411.

[19]For example, environmental regulators may not be able to impose retroactive punishments based on non-verifiable information. This situation is very likely to pertain to this case. In order to impose punishments on the firms, the regulator would have to take a firm to court and base its case on a non-verifiable report from that firm's competitor. It seems very unlikely that a court of law would rule in favor of the environmental regulator in such circumstances.

[20]For example, in a correlated-type environment Demski and Sappington (1984, Proposition 3) show that when a mechanism constrains agents to reveal their private information as a Nash equilibrium, the incentive scheme that maximizes the principal's expected utility will induce the agents to adopt strategies other than truth-telling.

[21]See Laffont and Martimort (1997a) for an analysis of the collusion problem among agents in a principal-multiple agents model.

the question that is addressed.[22]

The model also implicitly assumes that firms learn each other's type from an independent source (e.g. Nature) in stage 5. This assumption ensures that at the competitive stage, the optimal output strategies are derived under complete information for all possible equilibria. Because the model concentrates on Bayes-Nash implementation, it does not matter how the firms acquire this information, provided both firms send truthful reports of their types at stage 3.[23]

Finally, the model also assumes that the regulator takes the market structure as given. Therefore, the optimal regulatory policy does not consider the possibility of endogenously choosing the market structure (in this case, a monopoly or a duopoly) by shutting down one of the firms. The next section computes the firms' optimal output strategies given the regulatory policy.

3.4 The Competitive Outcome

The regulator commits to an environmental regulatory policy that specifies a lump-sum transfer, T_i, and a pollution emission quota, $\bar{e}_i$, to each firm leaving the quantities of final product output to be determined by the firms in the competitive stage.

Taking the regulatory policy as given, the firms will choose their output and emission quantities to maximize their profits. Firm i's profit maximizing strategy is to

$$\max_{q_i, e_i} P(q_i + q_j) \cdot q_i - C(\beta_i, q_i, e_i) + T_i$$

subject to $e_i \leq \bar{e}_i$ for $i = 1, 2$ and $j \neq i$.

The following conditions characterize the firm's best-response function when it is

[22]See Mookherjee (1984, Section 3) for a discussion and examples of these problems in a moral hazard context and Ma (1988) for an exposition on how to modify Mookherjee's game to uniquely implement the desired equilibrium. See Ma, Moore and Turnbull (1988) for a similar treatment in adverse selection problems. Palfrey (1992) surveys this problem.

[23]In this case, the regulator could publicly post (e.g. on the internet) the allocated tax and pollution quotas for each firm.

optimal for the firm to produce a positive output:

$$P'(q_i^* + q_j) \cdot q_i^* + P(q_i^* + q_j) - C_q(\beta_i, q_i^*, e_i^*) = 0 \tag{3.1}$$

$$P''(q_i^* + q_j) \cdot q_i^* + 2P'(q_i^* + q_j) - C_{qq}(\beta_i, q_i^*, e_i^*) < 0 \tag{3.2}$$

$$\text{for } \bar{e}_i \leq e_i^{*U}(\beta_i, q_i^*), \ -C_e(\beta_i, q_i^*, e_i^*) \geq 0 \tag{3.3}$$

Let $q_i^* = R_i(q_j; \beta_i, \bar{e}_i)$ denote firm i's best-response function. For arbitrary values of $\bar{e}_i$, firm i's emission constraint may not bind if q_i^* is sufficiently low because $e_i^{*U}(\beta_i, q_i^*)$ is increasing in q_i^*. Given $\bar{e}_i$ is fixed, if $e_i^{*U}(\beta_i, q_i^*) \leq \bar{e}_i$, then the emission quota is not binding, and

$$q_i^* = \tilde{R}_i(q_j; \beta_i, \bar{e}_i) = \frac{a - \beta_i}{2b - \theta} - \frac{b}{2b - \theta} q_j$$

with

$$\theta q_i^* \leq \bar{e}_i.$$

If $e_i^{*U}(\beta_i, q_i^*) > \bar{e}_i$, then the emission quota is binding, and

$$q_i^* = \hat{R}_i(q_j; \beta_i, \bar{e}_i) = \frac{a - \beta_i + \bar{e}_i}{2b} - \frac{1}{2} q_j$$

with

$$\theta q_i^* > \bar{e}_i.$$

For any $\bar{e}_i$, firm i is constrained by the emission quota if it is producing more than $\bar{e}_i/\theta$.

Consider only the case where $\bar{e}_i/\theta < \frac{a-\beta_i+\bar{e}_i}{2b}$ since the pollution emission quotas would never be binding if the contrary was true. Because $\bar{e}_i/\theta < \frac{a-\beta_i+\bar{e}_i}{2b}$ implies $\bar{e}_i/\theta < \frac{a-\beta_i}{2b-\theta}$, the intercept of $\hat{R}_i$ is smaller than the intercept of $\tilde{R}_i$. Since $\theta > 0$, the slope of $\tilde{R}_i$ is steeper than the slope of $\hat{R}_i$. Therefore, firm i's best-response function is kinked at $q_i^* = \bar{e}_i/\theta$, and is given by:

$$q_i^* = R_i(q_j; \beta_i, \bar{e}_i) = \begin{cases} \frac{a-\beta_i+\bar{e}_i}{2b} - \frac{1}{2} q_j, & \text{for } q_i^* > \bar{e}_i/\theta \\ \frac{a-\beta_i}{2b-\theta} - \frac{b}{2b-\theta} q_j, & \text{for } 0 < q_i^* \leq \bar{e}_i/\theta \end{cases}$$

Each firm's reaction function (or best-response function) are illustrated in Figure C.1. They show the substitute nature of their strategic output decision: an increase in firm j's output reduces firm i's output decision. The Cournot-Nash equilibrium is found at the intersection of both firms' best-response function $R_i(q_j; \beta_i, \bar{e}_i)$ for $i = 1, 2$ and $j \neq i$. If $b/\theta \neq 2/3$, then (q_1^{*c}, q_2^{*c}) is a unique equilibrium of the competitive stage game for any (β_1, β_2), and any pollution emission standards $(\bar{e}_1, \bar{e}_2)$.

Assuming that at the equilibrium the quotas are strictly binding (and verifying it at the optimal policy), let $q_i^{*c} = q_i^c(\bar{e}_1, \bar{e}_2, \beta_1, \beta_2)$ denote the Cournot-Nash equilibrium output of the competitive stage where:

$$q_i^{*c} = \frac{a - 2(\beta_i - \bar{e}_i) + (\beta_j - \bar{e}_j)}{3b} \quad i = 1, 2;\ j \neq i. \tag{3.4}$$

Equation (3.4) illustrates the strategic effects of the pollution emission quota in the competitive stage resulting from the Cournot competition. Note that the control of the pollution emission quotas influences the reaction functions of the firms. An increase in firm i's pollution emission quota, decreases firm i's marginal cost of output $(\beta_i - \bar{e}_i)$, which decreases firm j's output decision, and then increases firm i's output and share of total output. This is illustrated as an outward shift in firm 1's reaction function in Figure C.1. The decrease in firm 1's marginal cost of output causes the solid reaction function of firm 1 to shift outward to the dotted reaction function. Figure C.1 shows the new equilibrium outcome at point a where firm 1's share of total output has increased. Similarly, the dashed reaction function of firm 1 is a result of an increase in firm 1's marginal cost of output.[24]

When pollution emissions are unregulated, each firm chooses the profit-maximizing level of pollution (e_i^{*U}). However, if the social cost of pollution emissions is positive, then firms pollute too much. The implementation of an optimal pollution emission regulation would increase a firm's marginal cost of output from its unregulated level. Because

[24]Note also that an increase in firm i's marginal cost reduces firm i's output proportionally more than it increases firm j's output. This observation does not depend on the specific functional form chosen.

there exists a *cost-reduction complementarity* between pollution emissions and output, pollution emission quotas move the output reaction functions inward. Consequently, when the firms emission quotas are binding, they shift both firms' reaction function inward, and the equilibrium total output of the industry is reduced.

3.5 Complete Information Regulation

As a benchmark, this section derives the optimal environmental regulatory policy that results when the regulator has complete information about the firms' cost parameters; that is, the environmental regulator observes the firms' private information and designs a regulatory policy that takes the the imperfect competition on the output market as given.

The complete information regulatory policy is a pair of lump-sum tax and pollution emission quota for each firm $\{(T_1, e_1), (T_2, e_2)\}$.[25] Substituting (q_1^{*c}, q_2^{*c}) into the inverse demand function and each firm's cost function, the reduced-form profit functions are $\Pi_i^c = \pi_i^c(e_1, e_2, \beta_1, \beta_2) + T_i$ for $i = 1, 2$. The objective function of the regulator can be rewritten as

$$W = S(q_1^{*c} + q_2^{*c}, e_1 + e_2) - C(\beta_1, q_1^{*c}, e_1) - C(\beta_2, q_2^{*c}, e_2) - (1-\alpha)(\Pi_1^{*c} + \Pi_2^{*c}) - \nu E$$

and the regulator's problem is to

$$\max_{\{(T_1,e_1),(T_2,e_2)\}} W \text{ subject to } \Pi_i^{*c} \geq 0, \text{ for } i = 1, 2$$

The following proposition characterizes the optimal regulatory policy under complete incormation:

Proposition 3 *Let $Q^{*c} = q_1^{*c} + q_2^{*c}$ and $\varepsilon(Q^{*c}) = -P'(Q^{*c}) \cdot Q^{*c}/P(Q^{*c})$. The optimal*

[25]To simplify the notation, e_i will denote the pollution emission quotas $\bar{e}_i$.

regulatory policy $\hat{M} = \{(\hat{T}_i, \hat{e}_i)\}_{i=1}^2$ *is characterized by:*

$$\begin{aligned} \hat{T}_i &= -\pi_i^c(\hat{e}_1, \hat{e}_2, \beta_1, \beta_2) \\ -C_e(\beta_i, q_i^{*c}, \hat{e}_i) &= \nu - \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_i^{*c}}{Q^{*c}}\frac{dq_i^c}{de_i} + \frac{q_j^{*c}}{Q^{*c}}\frac{dq_j^c}{de_i}\right] \end{aligned}$$

for $i = 1, 2$ *and* $j \neq i$.

Proof: Observing that W is strictly decreasing in T_i yields the first equation. Straightforward maximization of W with respect to e_i, the competitive stage's first-order equation (3.1), and some algebra gives the second equations.■

The first equation simply means that the complete information optimal lump-sum tax is the amount of profit the firms make. The second equation determines the optimal level of pollution emission quotas for both firms. The optimal quota levels are not first-best efficient because the regulator must trade-off two market imperfections with a single instrument: the quotas. The quota levels trade-off a reduction in pollution emission with an increase in prices resulting from an increase in the output's cost. An efficient level of quota would equate for each firm the private marginal benefit of pollution emissions $-C_e(\beta_i, q_i^{*c}, \hat{e}_i)$ to the social cost of emission ν.[26] However, since the regulator cannot control the firms' level of production, it distorts both firms' quota levels to minimize an increase in the price of output for the consumers. This is Buchanan (1969)'s result for a Cournot duopoly.

From the functional forms of the demand and cost functions, the optimal complete information pollution emission quotas $(\hat{e}_1, \hat{e}_2)$ solve:

$$q_1^c(\hat{e}_1, \hat{e}_2, \beta_1, \beta_2) - \hat{e}_1/\theta = \nu - \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_1^{*c}}{Q^{*c}}\frac{2}{3b} + \frac{q_2^{*c}}{Q^{*c}}(-\frac{1}{3b})\right] \tag{3.5}$$

$$q_2^c(\hat{e}_1, \hat{e}_2, \beta_1, \beta_2) - \hat{e}_2/\theta = \nu - \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_1^{*c}}{Q^{*c}}(-\frac{1}{3b}) + \frac{q_2^{*c}}{Q^{*c}}\frac{2}{3b}\right] \tag{3.6}$$

[26] Since C_e is the private marginal *cost* of pollution emissions, $-C_e$ is the private marginal *benefit* of pollution emissions.

If the right-hand side of these two equations is positive, then both firms' quota of pollution emissions would be less than the unregulated levels of pollution emissions.[27] This corollary states these features of Proposition 3:

Corollary 3 *Assume* $\nu > \frac{(a+\max\{\bar{\beta}_1,\bar{\beta}_2\})^2}{3(2a-\max\{\bar{\beta}_1,\bar{\beta}_2\})}\frac{2}{3b}$.

1. *If* $(\beta_1, \beta_2) \in \mathbb{B}_1 \times \mathbb{B}_2$, *then* $\hat{e}_i \leq e_i^{*U}$ *and* $\hat{q}_i < q_i^{*U}$ *for* $i = 1, 2$;

2. *If* $\beta_i \geq \beta_j$, *then* $\hat{e}_i \leq \hat{e}_j$ *and* $\hat{q}_i \leq \hat{q}_j$ *for* $i = 1, 2$.

Proof: See Appendix A.1.■

The first part of Corollary 3 confirms that if pollution is sufficiently more costly than the imperfect competition in the output market, then both firms' pollution emission quotas will be less than the unregulated levels of pollution emissions. Another interpretation can be given to Proposition 3 and its corollary in terms of the familiar Pigouvian taxes on pollution. Letting $\tau_i = \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[(1-\frac{q_i^{*c}}{Q^{*c}})(\frac{-1}{3b}) + \frac{q_i^{*c}}{Q^{*c}}\frac{2}{3b}\right]$, note that the equations of Proposition 3 can be rewritten as follows: $-C_e^i = \nu - \tau_i$. The right-hand side is the complete information marginal tax level levied on firm i equivalent to the imposition of a quota $\hat{e}_i$. Figure C.2 illustrates this characteristics of the complete information regulatory policy, $\hat{M}$, where $\hat{e}_i = a$ for firm i . The curve represents the marginal private benefit of an increase in emissions for one firm. This figure shows that this optimal regulatory policy is equivalent to a firm specific non-linear tax $T_i(e_i, e_j)$ for $i = 1, 2$ and $j \neq i$ where $T_i'(\hat{e}_i, \hat{e}_j) = \nu - \tau_i$. Therefore, under complete information, the most efficient firm faces a lower marginal tax on pollution emissions than the inefficient firm. In other words, a firm that produces more, pollutes more and faces a lower marginal tax on pollution emissions.

[27] This assumption reflects the fact that the pollution externality is sufficiently more costly than the market's imperfect competition inefficiency. This may justify the environmental regulator desire to control pollution emissions in this market while the *competition* regulators do not intervene.

The second part of this corollary shows that the optimal regulatory policy takes into account the asymmetry of the firms' cost functions. A standard result of the asymmetric-cost Cournot duopoly model is that, when the industry is composed of two firms with asymmetric types ($\beta_1 \neq \beta_2$), the market share of the most efficient firm (lower β_i) is too small compared to the efficient level. Equations (3.5) and (3.6) show that under complete information, the optimal regulatory scheme corrects for this feature of the market structure by allowing the more efficient firm to use more emissions than the inefficient firm. Or equivalently, in terms of Pigouvian taxes, the more efficient firm has a lower tax on emission than the less efficient firm. As $C_{qe} < 0$, this reduces the marginal cost of output for the efficient firm and increases the one of the inefficient firm. In the competitive stage, that results in an outward shift of the reaction function of the efficient firm compared with the unregulated levels and an inward shift of the inefficient firm. This increases the market share of the efficient firm and reduces the market share of the inefficient firm. This result is very intuitive. For any amount of produced good and pollution, it is always more efficient to have the output and the pollution produced by a less costly firm. The next section investigates if this intuition is still verified when the firms have more information than the environmental regulator.

3.6 Regulation under Incomplete Information

The environmental regulatory policy derived under the assumption of complete information exhibits Buchanan (1969)'s claim that when a regulator tries to resolve two sources of distortions with only one instrument that the optimal policy is inefficient. In this chapter, the sources of distortion are the externality of pollution emissions and the duopolistic structure of the industry. The previous section showed that efficient firms were allowed to pollute more than inefficient firms in order to mitigate the effect on output price of an increase in the marginal cost of output. However, as it was argued, the assumption of symmetric information between the regulator and the firms is realistically not satisfied for environmental regulations. The relaxation of this assumption may well modify the qualitative and quantitative nature of an optimal policy. This section characterizes the optimal regulatory policy with incomplete information.

3.6.1 The Regulator's Problem

From the Revelation Principle, any regulation mechanism is equivalent to a revelation mechanism which specifies for each announcement $(\hat{\beta}_1, \hat{\beta}_2)$ a pair of pollution emission quotas and lump-sum transfer to the firms $\hat{\mathcal{M}} = \{(T_i(\hat{\beta}_1, \hat{\beta}_2), e_i(\hat{\beta}_1, \hat{\beta}_2))\}_{i=1}^2$. The regulator restricts its attention to feasible incentive compatible (or Bayes-Nash implementable) regulatory policies.[28] That is, the incentive constraints and the participation constraints ensure that it is a Bayes-Nash equilibrium for each firm to accept the regulatory policy of the regulator and pollute in the amount of the quota the firm was given.

The regulator's objective is stated by the following program:

Program 5 $\max_{\{(T_i,e_i)\}_{i=1,2}} E_{\beta_1,\beta_2}[W]$ *subject to*

$$\begin{aligned}
E_{\beta_j}[\pi_i^c(e_1(\beta_1,\beta_2), e_2(\beta_1,\beta_2), \beta_1, \beta_2) + T_i(\beta_1,\beta_2)] &\geq 0 && (3.7)\\
E_{\beta_2}[\pi_1^c(e_1(\beta_1,\beta_2), e_2(\beta_1,\beta_2), \beta_1, \beta_2) + T_1(\beta_1,\beta_2)] &\geq \\
E_{\beta_2}[\pi_1^c(e_1(\hat{\beta}_1,\beta_2), e_2(\hat{\beta}_1,\beta_2), \beta_1, \beta_2) &+ T_1(\hat{\beta}_1,\beta_2)] && (3.8)\\
E_{\beta_1}[\pi_2^c(e_1(\beta_1,\beta_2), e_2(\beta_1,\beta_2), \beta_1, \beta_2) + T_2(\beta_1,\beta_2)] &\geq \\
E_{\beta_1}[\pi_2^c(e_1(\beta_1,\hat{\beta}_2), e_2(\beta_1,\hat{\beta}_2), \beta_1, \beta_2) &+ T_2(\beta_1,\hat{\beta}_2)] && (3.9)
\end{aligned}$$

$\forall(\hat{\beta}_i, \beta_i) \in \mathbb{B}_i \times \mathbb{B}_i$ *and* $i = 1, 2$ *with* $j \neq i$.

Equation (3.7) is the *interim* participation constraint for both firms that ensures that the firms will accept the regulatory policy. Equations (3.8) and (3.9) are the *interim*

[28]See Section 3.3 for a discussion of the issues associated with this restriction.

incentive compatibility constraints for firm 1 and 2 respectively. Both constraints ensure that a firm's best-response to truth-telling by its rival is also telling the truth at the Bayes-Nash equilibrium.

To solve this problem, let $\phi(\hat{\beta}_i, \beta_i)$ be the *expected* profit of firm i when it reports type $\hat{\beta}_i \in \mathbb{B}_i$ when its true type is $\beta_i \in \mathbb{B}_i$:

$$\begin{aligned}
\phi(\hat{\beta}_1, \beta_1) &= E_{\beta_2}[\pi_1^c(e_1(\hat{\beta}_1, \beta_2), e_2(\hat{\beta}_1, \beta_2), \beta_1, \beta_2) + T_1(\hat{\beta}_1, \beta_2)] \\
\phi(\hat{\beta}_2, \beta_2) &= E_{\beta_1}[\pi_2^c(e_1(\beta_1, \hat{\beta}_2), e_2(\beta_1, \hat{\beta}_2), \beta_1, \beta_2) + T_1(\beta_1, \hat{\beta}_2)]
\end{aligned}$$

and define $\Phi(\beta_i) \equiv \phi(\beta_i, \beta_i)$, the maximum value function of the firm's revelation strategy.

Such policies are described in the following lemma:

Lemma 2 *A regulatory policy $\mathcal{M}$ is implementable if and only if*

$$\begin{aligned}
\dot{\Phi}(\beta_1) &= E_{\beta_2}[-b \cdot q_1^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2) \cdot \frac{dq_2^{*c}}{d\beta_1} \\
&\quad -q_1^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2)] \qquad (3.10)\\
\dot{\Phi}(\beta_2) &= E_{\beta_1}[-b \cdot q_2^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2) \cdot \frac{dq_1^{*c}}{d\beta_2} \\
&\quad -q_2^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2)] \qquad (3.11)
\end{aligned}$$

$$\begin{aligned}
E_{\beta_2}[T_1(\beta_1, \beta_2)] &= \Phi(\bar{\beta}_1) - E_{\beta_2}[\pi_1^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2)] \\
&\quad +E_{\beta_2}[\int_{\beta_1}^{\bar{\beta}_1} [b \cdot q_1^c(e_1(\tilde{\beta}_1, \beta_2), e_2(\tilde{\beta}_1, \beta_2), \tilde{\beta}_1, \beta_2) \cdot \frac{dq_2^{*c}}{d\beta_1} \\
&\quad +q_1^c(e_1(\tilde{\beta}_1, \beta_2), e_2(\tilde{\beta}_1, \beta_2), \tilde{\beta}_1, \beta_2)]d\tilde{\beta}_1] \qquad (3.12)\\
E_{\beta_1}[T_2(\beta_1, \beta_2)] &= \Phi(\bar{\beta}_2) - E_{\beta_1}[\pi_2^c(e_1(\beta_1, \beta_2), e_2(\beta_1, \beta_2), \beta_1, \beta_2)] \\
&\quad +E_{\beta_1}[\int_{\beta_2}^{\bar{\beta}_2} [b \cdot q_2^c(e_1(\beta_1, \tilde{\beta}_2), e_2(\beta_1, \tilde{\beta}_2), \beta_1, \tilde{\beta}_2) \cdot \frac{dq_2^{*c}}{d\beta_1} \\
&\quad +q_2^c(e_1(\beta_1, \tilde{\beta}_2), e_2(\beta_1, \tilde{\beta}_2), \beta_1, \tilde{\beta}_2)]d\tilde{\beta}_2] \qquad (3.13)
\end{aligned}$$

$$\frac{de_1}{d\beta_1} \leq 0 \quad and \quad \frac{de_1}{d\beta_2} \geq 0 \qquad (3.14)$$

$$\frac{de_2}{d\beta_1} \geq 0 \quad and \quad \frac{de_2}{d\beta_2} \leq 0 \qquad (3.15)$$

$$\Phi(\beta_i) \geq 0 \tag{3.16}$$

$\forall(\beta_1, \beta_2) \in \mathbb{B}_1 \times \mathbb{B}_2$ *and for* $i = 1, 2$ *with* $j \neq i$.

Proof: See Appendix A.2 ■

The set of equations above describes the properties of an optimal pollution emissions regulation scheme necessary for it to induce truth-telling by both firms as a Bayes-Nash equilibrium. Equations (3.10) and (3.11) describe how fast the rents of firms must decrease in order to let efficient firms (that have informational rents to be gained by misreporting their types) be indifferent between truth-telling and misreporting.

Unlike most regulatory models, these equations are composed of two terms whose role is to extract rent from the firms. The last term, which is common to the economic regulation of a monopoly literature, is the *efficiency* rent-extracting factor (ERF). The lower the efficiency (higher β_i), the more rent must be given to a more efficient firm ($\tilde{\beta}_i < \beta_i$) in order for it to have as much rent it would have by imitating a firm of type β_i. By distorting the efficiency of less efficient firms, the amount of rent given to more efficient firms is reduced. This is the well-known "efficiency rent-extraction" trade-off mentioned in the principal/single-agent models. However, what makes this chapter different from the literature, is the impact of unregulated duopolistic competition in the output market. Its effect on the optimal regulatory policy is captured by the first-term.

Lacking an established terminology, let $P'(Q^{*c}) \cdot q_i^{*c} \cdot dq_j^{*c}/d\beta_i$ be labeled the *competitive* rent-extracting factor (CRF). As this term is negative, competition adds rent-extracting power to optimal regulatory policy. Therefore, Cournot competition on the output market reduces the informational rent of the firms. The CRF shows the negative impact on rents of duopolistic competition by reducing the profit margin firms get on the *infra*-marginal units produced by misreporting their type. To see this, remark that from the firms' first-order equation (3.1), $P'(Q^{*c}) \cdot q_i^{*c}$ is the duopoly mark-up $(P(Q^{*c}) - C_q(\beta_i, q_i^{*c}, e_i))$ that firm i gets on its infra-marginal units q_i^{*c}. If firm i would over-report its type, it would reduce the profitability of its infra-marginal units as firm j would increase its production ($\frac{dq_j^{*c}}{d\beta_i} > 0$) in the competitive stage. Therefore, adding to the well documented ERF is a CRF that comes from the presence of *ex post* competition on the product market. However, unlike Hart (1983) and Scharfstein (1988) where informational rents are extracted through prices indirectly as costs are positively correlated, strategic competition is a direct source of discipline for the firms even though costs are independently drawn.

In most principal/multi-agents models, the regulator uses the correlation of the firms' type to extract rents. This part of the regulation literature has been "coined" yardstick competition as the information of one firm gives a better measure of the other firm's type. However, equations (3.10) and (3.11) exhibit some of the features that are present in models with correlated types because firm j's equilibrium output strategy appears in the rent function of firm i. Therefore, strategic interaction between the firms in the output market acts as a correlation externality for the firms' private information parameter.[29]

Some interesting intuition can be obtained from the CRF. When both firms have symmetric *ex post* costs, the CRF is equal for both firms and is similar to a lump-sum tax on rents. But, if firms have asymmetric *ex post* costs then an interesting pattern emerges. Let $\beta_2 > \beta_1$, for example. As q_2^{*c} falls proportionally more than q_1^{*c} increases as β_2 becomes larger than β_1—resulting from the $C_{q\beta} > 0$ and the strategic substitutability assumptions)—observe that firm 2's CRF decreases proportionally less than firm 1's CRF increases.[30] Therefore, as the efficiency of firm 2 gets lower the regulator gains more rent-extracting power from the more efficient firm 1.

Equations (3.12) and (3.13) determine the transfers that are required in order to implement truth-telling by both firms. Equations (3.14) and (3.15) guarantee that the local incentive compatibility constraints are also global. And finally, equation (3.16) are

[29]This feature of the incentive compatible regulatory policy would still be present if the firms were to compete under incomplete information at the competitive stage.

[30]More precisely, $\mid CRF_1 \mid > \mid CRF_2 \mid$.

the individual rationality constraints for the firms.

Using the previous lemma, Program 5 can be simplified using the fact that equations (3.10), (3.11) and $\Phi(\bar{\beta}_i) = 0$ imply $\Phi(\beta_i) \geq 0$, $\forall \beta_i \in [\underline{\beta}_i, \bar{\beta}_i)$. This reduces the continuum of individual rationality constraints to $\Phi(\bar{\beta}_i) = 0$ which is analytically more convenient. Ignoring the second-order conditions (3.14)–(3.15), but checking that they are met at the equilibrium regulatory policy, Program 1 is rewritten as:

Program 6

$$\begin{aligned}\max_{e_1,e_2} \iint\limits_{\mathbb{B}_1 \times \mathbb{B}_2} \Big(& S(q_1^c(e_1,e_2,\beta_1,\beta_2) + q_2^c(e_1,e_2,\beta_1,\beta_2)) - \nu(e_1+e_2) \\ & - \big(C(\beta_1, q_1^c(e_1,e_2,\beta_1,\beta_2), e_1) + C(\beta_2, q_2^c(e_1,e_2,\beta_1,\beta_2), e_2)\big) \\ & - (1-\alpha)\{\frac{F_1(\beta_1)}{f_1(\beta_1)}(\mathcal{X}_1 - C_\beta(\beta_1, q_1^{*c}, e_1)) \\ & + \frac{F_2(\beta_2)}{f_2(\beta_2)}(\mathcal{X}_2 - C_\beta(\beta_2, q_2^{*c}, e_2))\}\Big)\, dF_1(\beta_1)\, dF_2(\beta_2)\end{aligned}$$

where $\mathcal{X}_i = -bq_i^c(e_1,e_2,\beta_1,\beta_2)\frac{dq_j^c(e_1,e_2,\beta_1,\beta_2)}{d\beta_i}$, *for* $i = 1, 2$ *and* $j \neq i$.

Straightforward maximization yields the following first-order conditions:

$$\begin{aligned} q_1^c(\tilde{e}_1,\tilde{e}_2,\beta_1,\beta_2) - \tilde{e}_1/\theta = \nu \quad & - \quad \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_1^{*c}}{Q^{*c}}\frac{2}{3b} + \frac{q_2^{*c}}{Q^c}(-\frac{1}{3b})\right] \\ & - \quad (1-\alpha)\left[\frac{F_1(\beta_1)}{f_1(\beta_1)}(-\frac{2}{9b} - \frac{2}{3b})\right. \\ & \qquad \left. + \frac{F_2(\beta_2)}{f_2(\beta_2)}(\frac{1}{9b} - \frac{-1}{3b})\right] \end{aligned} \tag{3.17}$$

$$\begin{aligned} q_2^c(\tilde{e}_1,\tilde{e}_2,\beta_1,\beta_2) - \tilde{e}_2/\theta = \nu \quad & - \quad \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_1^{*c}}{Q^c}(-\frac{1}{3b}) + \frac{q_2^{*c}}{Q^c}\frac{2}{3b}\right] \\ & - \quad (1-\alpha)\left[\frac{F_1(\beta_1)}{f_1(\beta_1)}(\frac{1}{9b} - \frac{-1}{3b})\right. \\ & \qquad \left. + \frac{F_2(\beta_2)}{f_2(\beta_2)}(-\frac{2}{9b} - \frac{2}{3b})\right] \end{aligned} \tag{3.18}$$

These equations implicitly define the optimal regulatory policy's pollution emissions quotas $(\tilde{e}_1, \tilde{e}_2)$ under asymmetric information with the transfers (3.12) and (3.13). For this regulatory policy to be optimal, equations (3.14) and (3.15) also have to be satisfied.

It is easy to verify that they are met at the optimum.[31] Since it was shown in the previous section that these optimal levels of pollution emission quotas are equivalent to firm-specific marginal taxes, equations (3.17) and (3.18) can be written as:

$$q_i^{*c} - \tilde{e}_i/\theta = \nu - \tilde{\tau}_i - \tilde{\kappa}_i, \qquad \text{for } i = 1,2$$

where

$$\begin{aligned} \tilde{\kappa}_i &= (1-\alpha)\left[\frac{F_i(\beta_i)}{f_i(\beta_i)}(\frac{-8}{9b}) + \frac{F_j(\beta_j)}{f_j(\beta_j)}(\frac{4}{9b})\right]; \\ \tilde{\tau}_i &= \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_i^{*c}}{Q^{*c}}\frac{2}{3b} + (1 - \frac{q_i^{*c}}{Q^{*c}})(-\frac{1}{3b})\right]. \end{aligned}$$

for $i = 1,2$ and $j \neq i$.

Proposition 3 implies that $\nu - \tilde{\tau}_i$ is the marginal tax for firm i under symmetric information. $\tilde{\kappa}_i$ is the distortion brought upon $\nu - \tilde{\tau}_i$ due to the impossibility of the regulator observing the firms' private information. Following Corollary 1, it can be shown that $\tilde{\tau}_i > 0$, $\frac{d\tilde{\tau}_i}{d\beta_i} < 0$ and that $\frac{d\tilde{\tau}_i}{d\beta_j} > 0$. It can also be shown that, at the equilibrium, $\frac{d\tilde{\kappa}_i}{d\beta_i} < 0$ and $\frac{d\tilde{\kappa}_i}{d\beta_j} > 0$ as well. However, $\tilde{\kappa}_i$ can be either positive or negative depending on the *ex post* cost configuration of the industry. Therefore, in the presence of asymmetric information between the regulator and the firms, the effective marginal tax rate of the firms might be higher($\tilde{\kappa}_i < 0$) or lower($\tilde{\kappa}_i > 0$) than in the symmetric information case.

3.6.2 Ex Post Cost Asymmetry

To simplify the analysis of the optimal regulatory policy with asymmetric information, consider the case where the regulator's priors are identical for both firms (i.e. $\mathbb{B}_1 = \mathbb{B}_2 = \mathbb{B}$ and $F_1 = F_2 = F$) and that the firms have symmetric *ex post* costs ($\beta_1 = \beta_2$).

Proposition 4 *Assume* $\mathbb{B}_1 = \mathbb{B}_2 = \mathbb{B}$ *and* $F_1 = F_2 = F$. *If* $\beta_1 = \beta_2 = \beta$ *then* $\tilde{e}_i \leq \hat{e}_i$ *and* $\tilde{q}_i \leq \hat{q}_i$ *for* $i = 1,2$.

[31] The sufficient conditions are that F_i/f_i is non-decreasing for $i = 1,2$.

Proof: First, if $\beta_1 = \beta_2 = \underline{\beta}$ then $F(\underline{\beta}) = 0$ and $\tilde{e}_i = \hat{e}_i$ for $i = 1, 2$ and from $C_{qe} < 0$ and the competitive stage equilibrium quantities $\tilde{q}_i = \hat{q}_i$ for $i = 1, 2$. Now, let $\beta_1 = \beta_2 > \underline{\beta}$. Then $\tilde{\tau}_1 = \tilde{\tau}_2 = \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}(\frac{1}{6b}) > 0$ and $\tilde{\kappa}_1 = \tilde{\kappa}_2 = (1-\alpha)F(\beta)/f(\beta)\frac{-4}{9b} < 0$. Therefore, $\tilde{e}_i < \hat{e}_i$ for $i = 1, 2$ with $\tilde{e}_1 = \tilde{e}_2$ as $q_i^{*c} - \tilde{e}_i$ is strictly decreasing in e_i. From the cost-reduction complementarity assumption $(C_{qe} < 0)$, $\tilde{e}_i < \hat{e}_i$ implies $\tilde{q}_i \leq \hat{q}_i$ which completes the proof. ■

In other words, the marginal tax rate on emissions is higher under asymmetric information than under symmetric information when the firms are *ex post* identical and the regulator's priors are also identical. This feature of the optimal regulatory policy can be seen on Figure C.2. The quota levels for both firms would be lower than in the symmetric information situation ($\bar{e}_i = a$) because $\tilde{\kappa}_i < 0$. And this implies $-C_e^i(.)$ would equate the marginal tax above $\nu - \tilde{\tau}_i$ and therefore implies a higher marginal tax of emissions. However, more interesting insights can be gained from the optimal regulatory policy when the firms have *ex post* asymmetric costs.

Proposition 5 *Assume* $\mathbb{B}_1 = \mathbb{B}_2 = \mathbb{B}$ *and* $F_1 = F_2 = F$. *If* $\beta_1 \leq \beta_2$ *then* $\tilde{e}_1 \geq \tilde{e}_2$ *and* $\tilde{q}_1 \geq \tilde{q}_2$.

Proof: Starting at a point of symmetry between the *ex post* types of the firms, we have from the previous proposition that $\tilde{e}_1 = \tilde{e}_2$. Since $\tilde{\tau}_1 + \tilde{\kappa}_1$ is increasing in β_2 and $\tilde{\tau}_2 + \tilde{\kappa}_2$ is decreasing in β_2, then$\tilde{e}_1 \geq \tilde{e}_2$ and $\tilde{q}_1 \geq \tilde{q}_2$. ■

Therefore, the more efficient firm always pollutes more than the inefficient firm under asymmetric information and this result follows our intuition from the symmetric information case. However, the pollution emission quotas can be either higher or lower than their symmetric information levels because $\tilde{\kappa}_i$ is either positive or negative. The next proposition compares the symmetric information optimal regulatory policy with the asymmetric information regulation policy when the distribution functions are restricted to be uniform.[32]

Proposition 6 *Assume* $\mathbb{B}_1 = \mathbb{B}_2 = \mathbb{B}$ *and* $F_1 = F_2 = U[\underline{\beta}, \bar{\beta}]$. *If* $\underline{\beta} < \beta_1 \leq \beta_2$ *then*

1. *there exists an industry's configuration of ex post efficiency types* (β_1, β_2) *close to the ex post symmetric configuration where* $\tilde{e}_i \leq \hat{e}_i$ *and* $\tilde{q}_i \leq \hat{q}_i$ *for* $i = 1, 2$;

2. *there exists an industry's configuration of ex post efficiency types* (β_1, β_2) *where firm 1's efficiency is sufficiently lower than firm's 2 where* $\tilde{e}_1 > \hat{e}_1$, $\tilde{q}_1 > \hat{q}_1$ *and* $\tilde{e}_2 < \hat{e}_2$, $\tilde{q}_2 < \hat{q}_2$.

Proof: At a point (β_1, β_2) where $\beta_1 = \beta_2$, $\tilde{\kappa}_1 = \tilde{\kappa}_2 < 0$. Since $\tilde{\kappa}_1$ is decreasing in β_1 and $\tilde{\kappa}_2$ is increasing in β_1, a decrease in β_1 increases $\tilde{\kappa}_1$ and decreases $\tilde{\kappa}_2$. Therefore, $\tilde{\kappa}_2 < 0$ where $\beta_1 \leq \beta_2$. From the previous propositions, the statement for firm 2 is proved. Since

$$\tilde{\kappa}_1 \gtreqless 0 \Leftrightarrow \frac{\frac{F(\beta_2)}{f(\beta_2)}}{\frac{F(\beta_1)}{f(\beta 1)}} \gtreqless 2,$$

characterizing the set of (β_1, β_2) such that $\tilde{\kappa}_1 = 0$ and expressing the relationship between β_2 and β_1 as $\beta_2 = K_1(\beta_1)$, some algebra shows that K_1 is convex (linear from the origin $(\underline{\beta}_1, \underline{\beta}_1)$. Therefore, for all (β_1, β_2) such that $\beta_2 > K_1(\beta_1)$ then $\tilde{\kappa}_1 > 0$ and this results in $\tilde{e}_1 > \hat{e}_1$. For all (β_1, β_2) such that $\beta_2 < K_1(\beta_1)$ then $\tilde{\kappa}_1 < 0$ and therefore $\tilde{e}_1 < \hat{e}_1$. Then, following the arguments from the previous proofs, we derive the remaining statements with respect to the output of firm 1. ■

Figure C.3 illustrates the previous propositions in the (β_1, β_2) type-space. In Region 1 (the 45° line) and Region 2, both firm have lower pollution emission quotas than

[32] The result can be generalized to other cumulative distribution functions that satisfy our assumptions. The uniform distribution was chosen for its simple analytical properties.

with the complete information regulatory policy. However, in Region 3 firm 1's quota is higher than its complete information level. Therefore, firm 1's quota emissions are distorted from their complete information levels even though it is the most efficient firm of the two. This suggests that Cournot competition in the output market modifies our intuition from the single firm regulatory policies as even the most efficient firm 1 ($\underline{\beta}_1$) is distorted from its complete information levels of pollution emission quota. That is, there *is* distortion "at the top". A numerical representation of the first part of Proposition 6 is given by Figure C.6. The dashed lines represent the complete information quota levels for firm 1 and 2 when $\beta_2 = 10$. The full lines represent the incomplete information level of quotas for each firm when β_1 is more efficient than firm 2. The distortion "at the top" occurs when the incomplete information emissions quota of firm 1 crosses the complete information emission quota. However, the reason for this feature of the incomplete information regulatory policy is more obvious from Figure C.5. Here, the incomplete regulatory policy is numerically represented by an equivalent marginal tax schedules.

In Figure C.5, the dashed lines represent the complete information tax schedules $(\nu - \hat{\tau}_i)$ for both firms when $\beta_2 = 10$. Remark that as firm 1 gets more efficient than firm 2, firm 1's complete information marginal tax schedule does not decrease a lot while firm 2's marginal tax increases relatively more. This reflects the desire of the regulator to have an efficient market-share allocation with complete information. However, the incomplete information marginal tax schedules $(\nu - \tilde{\tau}_i - \tilde{\kappa}_i)$ differ significantly from their complete information levels. Here, as firm 1 gets more efficient than firm 2, the regulator distorts the complete information marginal tax of firm 1 relatively more than firm 2 because it does not want to leave rents to firm 1. Since product market competition is a very effective rent-extraction device, the regulation policy puts the firms on a more "even" ground in order to extract the most rent. In this case, firm level cost efficiency does not extract as much rents. In other words, the CRF is a better rent-extraction device than the ERF when the industry's *ex post* cost configuration is more asymmetric.

Making a parallel between Figure C.3 and Figure C.5, in Region 1 and 2 the industry's *ex post* cost configuration is not too asymmetric. In that case, the regulatory policy taxes **more** than the complete information policy because it affects the firm-level cost efficiency and reduces the amount of rents the regulator needs to give to the firms. But in Region 3, the regulator is able to extract more rents from the firms if it lets them compete on a more even basis. Here, allowing firm 2 to be more competitive (through the cost-reduction complementarity between pollution emissions and ouput) extracts more rents from firm 1.

Proposition 6 characterized the optimal regulatory policy when firms have *ex post* asymmetrical costs. However, the regulator may possess other relevant information on each firm that makes its prior on each firm different(e.g. vintage of the firm's technology, the location of the firms). This reflects a situation where the firms' cost are *ex ante* asymmetric.

3.6.3 Ex Ante Cost Asymmetry

Consider the following. Assume there exists an observable characteristic ω_i for each firm i. This characteristic induces the regulator to believe that firm 2 is more likely to be efficient than firm 1 or *vice versa* (e.g. $F(\beta \mid \omega_1) \leq F(\beta \mid \omega_2)$ and $\omega_1 \neq \omega_2$ for all β). This subsection characterizes the effect of this *ex ante* asymmetry between the firms' cost structure.

For simplicity, suppose the regulator believes that firm 2 is more likely to be efficient than firm 1 and that the regulator's priors are uniform distributions (i.e. $F(\beta \mid \omega_1) \leq F(\beta \mid \omega_2)$).[33]

Proposition 7 *Let F_1 and F_2 be uniform with supports $\mathbb{B}_1 = [\underline{\beta}_1, \bar{\beta}_1]$ and $\mathbb{B}_2 = [\underline{\beta}_2, \bar{\beta}_2]$ where $\underline{\beta}_1 > \underline{\beta}_2$ and $\bar{\beta}_1 - \underline{\beta}_1 = \bar{\beta}_2 - \underline{\beta}_2$ so that $F_1(\beta) \leq F_2(\beta)$ for all β.*

[33]Let $F_i(\beta_i) \equiv F(\beta_i \mid \omega_i)$ for $i = 1, 2$. More general distributions would not change the result substantially.

1. *If* $\beta_1 = \beta_2 = \beta > \underline{\beta}_1$*, then firm 1's pollution emission quota is higher than firm 2's quota;*

2. *Moreover, there exists a region of ex post type configuration* (β_1, β_2) *with* $\beta_1 > \beta_2$ *such that the pollution emission quota of firm 1 is higher than firm 2.*

Proof: The proof is best understood by viewing Figure C.4 and in terms of equivalent marginal taxes. Under our assumptions, the marginal tax rates (or pollution emission quotas) are independent of translation of the lower bound of the support of the distributions. Therefore, the analysis of Figure C.3 applies to Figure with an appropriate translation of the axes. The first statement of the Proposition is proved where the types are *ex post* symmetric $\beta_1 = \beta_2$ on the heavy 45 degree line. Along that 45 degree line, firm 2's marginal tax rate is higher than firm 1 as $\nu - \tilde{\tau}_1 - \tilde{\kappa}_1 < \nu - \tilde{\tau}_2 - \tilde{\kappa}_2$ (recall Proposition 6). Therefore, firm 1's optimal pollution emissions quota is higher than firm 2's quota. This proves the first statement of the proposition. From Proposition 6, between the heavy 45 degree line and the dotted 45 degree line, firm 1's pollution emissions quota are higher than firm 2's quota. In this region of *ex post* type configuration, $\beta_1 > \beta_2$.■

This counter-intuitive Proposition results from the fact that the regulator's rent-extracting power is higher when firm 1 is able to compete more evenly *ex ante* with firm 2. In this case, higher quotas to more likely inefficient firms result in a more competitive industry and the CRF extracts more rents than the ERF.

Figure C.7 is a numerical representation of the marginal tax rates that are imposed on both firms in the β_1-space when $\beta_2 = 10$. As it was pointed out in Figure C.4, this example shows clearly that, even though firm 1 is as efficient as firm 2 ($\beta_1 = \beta_2 = 10$), the marginal tax rate on firm 1 is lower than on firm 2. Furthermore, for $11.5 > \beta_1 > \beta_2 = 10$, the marginal tax of firm 1 is still lower than that of firm 2 even though firm 2 is more efficient than firm 1. This is a stark difference from the optimal pollution emissions regulation policy under complete information where the marginal tax of the more efficient firm is always lower than the marginal tax of the less efficient firm (dashed marginal tax schedules). By decreasing the marginal tax rate of firm 1, the regulator increases the amount of rent that this firm would gain and reduces the amount of rent that firm 2 could get. However, since $F_1(\beta) \leq F_2(\beta)$ the expected rent given to firm 1 is lower than that of firm 2 and *ex post* competition on the market is increased such that the resulting inefficiency is compensated by a substantial reduction in rents given to both firms. The regulator stops favoring firm 1 over firm 2 when the efficiency cost becomes bigger than the benefits of rent-extraction. Figure C.8 gives a numerical representation of the optimal quotas in this case.

The following section applies the previous result to the case of a product market where a leading firm accomodates an entrant and argues that Grandfather clauses can be optimal.

3.7 Stackelberg Competition and Grandfather Clauses

It is often argued that one benefit of competition is that new firms' entry in a market raise competition and leads to a more efficient outcome. This argument is intuitively appealing when new firms have more efficient technologies because of technological improvements in the production process.[34] In that case, how would an optimal environmental regulatory policy deal with this situation? This section briefly analyzes the optimal environmental policy that would result if entry was given in this model.

For example, assume that the entrant's technology is always more efficient than the incumbent's technology. Two cases can be considered. First, if the output market struc-

[34]For example, in an industry where production depends heavily on vintage capital and that newer vintages are more efficient (without any depreciation), new lower-cost firms could enter the industry and earn non-negative profits. This argument obviously assumes that the technology involves no learning-by-doing by the firms such that new firms are always more efficient than older firms.

ture does not give a first-mover advantage to the incumbent firm, then the incumbent and the entrant would compete in Cournot-fashion on the output market and the optimal regulatory policy derived in the previous sections are in order. If the regulator has complete information on the firms' type, then the *ex post* most efficient firms always has a higher pollution quota (see Corollary 1, part 2). However, the optimal regulatory policy with incomplete information has quite different implications.

Following Proposition 7, with the incumbent's cost being more likely to be above the entrant, then there exists an *ex post* type configuration such that the incumbent is less efficient than the entrant but the pollution emissions quota for the incumbant is higher than that of the entrant. This optimal policy is interestingly reminiscent of **grandfather clauses** in some environmental regulations(See below and Appendix B).

Second, the output market structure can give the incumbent a first-mover advantage. Let the incumbent firm be firm 1 and firm 2 be the entrant. Firm 1 is then a Stackelberg leader at the competitive stage. As in the simultaneous-move case, firms choose their profit maximizing strategies taking as given the environmental regulatory policy. Letting $q_i^{*s} = q_i^s(e_1, e_2, \beta_1, \beta_2)$ denote the Stackelberg-Nash equilibrium quantities arising in the competitive stage, the equilibrium output strategies are:

$$\begin{aligned} q_1^{*s} = q_1^s(e_1, e_2, \beta_1, \beta_2) &= \frac{a - 2(\beta_1 - e_1) + (\beta_2 - e_2)}{2b} \\ q_2^{*s} = q_2^s(e_1, e_2, \beta_1, \beta_2) &= \frac{a - 3(\beta_2 - e_2) + 2(\beta_1 - e_1)}{4b} \end{aligned}$$

As in the simultaneous-move case, an increase in firm i's marginal cost results in an increase in firm j's output. The difference here is the asymmetry between firm 1 and 2 optimal response to an increase in the opponent's marginal cost. An increase in firm 1's marginal cost results in a higher reduction of total output than an increase in firm 2's marginal cost. We now turn to the regulator's problem.

As one can observe, the analysis of the previous sections can be applied to this case because the important features (strategic substitutes' character of the firms reaction function, and the cost-reduction complementarity of pollution emissions and output) that are necessary are present in this case. However, the "magnitude" of their interaction has changed given that firm 1 has a first-mover advantage. As Figure C.9 illustrates however, the inefficiency of the output market leads the regulator to give higher pollution emissions quota to the incumbent for the type range considered in both the complete and incomplete information set-up. Notice also that the incomplete information policy does not differ a lot from the complete information policy. That is because the role of competition with a first-mover advantage is not as strong. The regulator's instruments can not overcome the lack of competitiveness in the output market. In this case, as one would suspect, the output market competition is not as effective as a rent-extraction device. The CRF is very small and has only a small effect. Nonetheless, the optimal regulatory policy still has a flavour of **grandfather clauses**.

Therefore, it is interesting to note that this section's results provide a normative foundation for observed *grandfathering clauses* in pollution emissions policies. Such policies can be *ex ante* optimal from the point of view of the regulator.[35] This is a departure from the existing theories of grandfather clauses that rely on political constraints as motivation for such policies. For example, the table in Appendix B represents the toxic effluent emissions restrictions in the Canadian petroleum refining industry. Effluent limitations are presented in two groups. Regulations apply to all refineries that did not started to operate January 1, 1974. Guidelines apply to all refineries that operated in Canada on or before January 1, 1974. Notice that existing refineries are allowed to pollute twice as much as new refineries in all categories except for pH and the fish mortality toxicity tests.

[35]This reasoning holds obviously only for industries that fit the structure of the model.

3.8 Summary

This essay considered the optimal regulation of point-source pollution emissions with duopolistic competition in the output market and asymmetric information between the firms and the regulator. Under symmetric information, it is shown that the marginal tax rate on pollution emissions (or Pigouvian Taxes) follows Buchanan (1969)'s claim that the tax level is lower than the efficient level in order to trade-off pollution emissions reduction with an increase in output. Moreover, if one firm is more efficient than the other one, the efficient firm faces a lower marginal tax than its competitor or equivalently, it is given a bigger pollution emission quota. Then, using the "new regulatory economics" framework which emphasizes the asymmetry of information between the regulator and the firms, it is shown that the optimal regulatory policy benefits from product market competition even though the firms' environment is uncorrelated.

It is shown that the strategic interaction on the output market acts as a correlation externality for the firm's private information. The equilibrium output competition is a source of discipline as efficient firms' ability to misreport their types is reduced. The firms' interaction on the output market reduces the mark-up a firm would get on infra-marginal units produced if it would over-report its type (costs). Since competition is an efficient way to extract information rents from the firms, the optimal environmental policy influences the level of *ex post* competition in the output market by an appropriate choice of pollution emission quotas. An interesting result found is that if the regulator believes that firm A is always more likely to be efficient than firm B (in the sense of first-order stochastic dominance) and that both firms are equally efficient (productivity parameter is equal) *ex post*, then firm B is given a higher pollution emission quota. Furthermore, it is shown that if firm B is somewhat less efficient than firm A, firm B is still allocated a higher level of pollution emissions quota than firm A. Finally, it is argued that this model provides a normative foundation for grandfather clauses in pollution emissions regulation when entry is accommodated by the incumbent firm in some industries.

Chapter 4

Conclusion

Colander (2000) writes: "[I]n the modern study of the history of economic thought we often use 2000 as the end of the neoclassical era and the beginning of the New Millenium Era.[...] New Millenium economics does not base policy on the neoclassical welfare theorems, which are part of its broader "right price" view of policy. That view of policy has been replaced by our current "right institutions" view of policy." However, economic policymaking or policy evaluation is probably one of the most difficult task being performed by the modern economist. Even Pareto improving economic policies may fail to be implemented in "real" second-best economies (see Stiglitz (1998)). The task appears so difficult that it has led many to consider it impossible. Arguably, this perception could be attributed to the following general negative remarks that apply to second-best economic policymaking:

- If a distortion exists in one sector, then it is generally no longer desirable to apply first-best policies in other sectors (e.g. Lipsey and Lancaster (1956));

- If $n \geq 2$ distortions exist, an economist cannot claim that a policy that results in a competitive equilibrium with $n-1$ distortions is preferable to a competitive equilibrium with n distortions (e.g. Green and Sheshinski (1975));

- The problems of equity and efficiency can no longer be separated unless personalized lump-sum transfers are feasible (e.g. Guesnerie and Laffont (1978)); and,

- The results obtained in second-best analysis may contradict the economist's intuition developed in a first-best analysis (e.g. Blackorby (1990)).

Yet, one still encounters plenty of examples where distinguished economists provide normative and positive first-best policy analysis to government policymakers while acknowledging that economies are factually of second-best nature. By showing that one can derive second-best optimal policies in a partial equilibrium setting, the first essay of this dissertation provides limited relief to economists given the restrictive conditions necessary for the result to hold. Then, by deriving optimal discriminatory environmental regulation in the second essay, this dissertation illustrates the benefits of modelling explicitly the second-best environment of policymakers: a better understanding of existing industrial policies and potentially, better policy prescriptions that reflect the real trade-offs that policymakers must effect to formulate their industrial policies.

Thus, the issue is: which commoditities (or, sectors) allow for a second-best partial equilibrium analysis? Truly, this is the relevant empirical question that is often left unanswered. Obviously, the approach would appear to be doomed for most commodities given the conditions that must be verified. Nonetheless, this dissertation's results combined with those of Blackorby (1998) suggests that it may be possible to determine an empirical procedure to endogenize the selection of the commodities that need to be incorporated into a partial equilibrium analysis in order for it to correctly characterize second-best Pareto optimal policies.

Appendix A

Proofs

A.1 Proof of Corollary 3

The proof of Corollary 1 requires the following lemma:

Lemma 1 *If* $\nu > \frac{(a+\max\{\bar{\beta}_1,\bar{\beta}_2\})^2}{3(2a-\max\{\bar{\beta}_1,\bar{\beta}_2\})}\frac{2}{3b}$, *then the right-hand side of equation* (3.5) *and equation* (3.6) *is positive.*

Proof: First, it is easy to show that $\forall \beta_1 \leq \bar{\beta}_1$

$$\frac{(a+\bar{\beta}_1)^2}{3(2a-\bar{\beta}_1)} \geq \frac{(a+(\beta_1-e_1))^2}{3(2a-(\beta_1-e_1))} \quad ,e_1 \geq 0$$

Moreover, as $q_1^{*c}/Q^{*c} \leq 1$

$$\frac{2}{3b} \geq \left[(1-\frac{q_1^{*c}}{Q^{*c}})(\frac{-1}{3b}) + \frac{q_1^{*c}}{Q^{*c}}\frac{2}{3b}\right]$$

Combining the previous two equations with equation (3.5) yields:

$$\frac{(a+\bar{\beta}_1)^2}{3(2a-\bar{\beta}_1)} \geq \frac{P(Q^{*c})}{\varepsilon(Q^{*c})}\left[\frac{q_1^{*c}}{Q^{*c}}\frac{dq_1^c}{de_1} + \frac{q_2^{*c}}{Q^{*c}}\frac{dq_2^c}{de_1}\right]$$

Repeating the previous steps for $\beta_2 \leq \bar{\beta}_2$, and combining it the previous equation completes the proof.■

Proof: In an unregulated industry, the left-hand side of equation (3.5) and equation (3.6) is equal to zero. From the convexity assumption, the marginal cost of pollution reduction $-C_e^i$ is decreasing in e_i and is equal to the marginal benefit of pollution reduction ν minus a term (τ_i) that is positive by the previous lemma. As $C_{qe} < 0$ then $\hat{q}_i < q_i^{*U}$. This completes the proof for the first statement. Now, without loss of generality, assume $\beta_i \geq \beta_j$. The competitive stage's reaction function and $C_{q\beta} > 0$ implies

$$0 < \frac{q_i^c}{Q^c}\frac{dq_i^c}{de_i} + \frac{q_j^c}{Q^c}\frac{dq_j^c}{de_i} < \frac{q_i^c}{Q^c}\frac{dq_i^c}{de_j} + \frac{q_j^c}{Q^c}\frac{dq_j^c}{de_j}$$

for $j \neq i$ and from $C_{ee}^i > 0$ we have $\hat{e}_i \leq \hat{e}_j$ and $C_{qe} < 0$ implies $\hat{q}_i \leq \hat{q}_j$.

A.2 Proof of Lemma 2

Note that $\phi(\hat{\beta}_i, \beta_i)$ can be rewritten as:

$$\phi(\hat{\beta}_i, \beta_i) = \mathcal{A}(\hat{\beta}_i, \beta_i) - \mathcal{B}(\hat{\beta}_i, \beta_i) - E_{\beta_j}[T_i(\hat{\beta}_i, \beta_j)], \ i = 1, 2 \wedge i \neq j \tag{A.1}$$

where

$$\begin{aligned} \mathcal{A}(\hat{\beta}_i, \beta_i) &= E_{\beta_j}[P'(q_i^c(\vec{\eta}) + q_j^c(\vec{\eta})) \cdot q_i^c(\vec{\eta})] \\ \mathcal{B}(\hat{\beta}_i, \beta_i) &= E_{\beta_j}[C(\beta_i, q_i^c(\vec{\eta}), e_i(\hat{\beta}_i, \beta_j))] \end{aligned}$$

and $\vec{\eta} = (e_i(\hat{\beta}_i, \beta_j), e_j(\hat{\beta}_i, \beta_j), \beta_i, \beta_j)$.

Adding and substracting $\mathcal{A}(\hat{\beta}_i, \hat{\beta}_i) - \mathcal{B}(\hat{\beta}_i, \hat{\beta}_i)$ to equation (A.1) yields:

$$\phi(\hat{\beta}_i, \beta_i) = \phi(\hat{\beta}_i, \hat{\beta}_i) + [\mathcal{A}(\hat{\beta}_i, \beta_i) - \mathcal{A}(\hat{\beta}_i, \hat{\beta}_i)] - [\mathcal{B}(\hat{\beta}_i, \beta_i) - \mathcal{B}(\hat{\beta}_i, \hat{\beta}_i)]$$

For type $\beta_i \in \mathbb{B}_i$ the incentive compatible constraint (3.8) and (3.9) requires :

$$\begin{aligned} \phi(\beta_i, \beta_i) &\geq \phi(\hat{\beta}_i, \beta_i) \\ &\geq \phi(\hat{\beta}_i, \hat{\beta}_i) + [\mathcal{A}(\hat{\beta}_i, \beta_i) - \mathcal{A}(\hat{\beta}_i, \hat{\beta}_i)] - [\mathcal{B}(\hat{\beta}_i, \beta_i) - \mathcal{B}(\hat{\beta}_i, \hat{\beta}_i)] \end{aligned}$$

for all $\hat{\beta}_i \in \mathbb{B}_i$. Then by definition,

$$\Phi(\hat{\beta}_i) - \Phi(\beta_i) \leq [\mathcal{A}(\hat{\beta}_i, \hat{\beta}_i) - \mathcal{A}(\hat{\beta}_i, \beta_i)] - [\mathcal{B}(\hat{\beta}_i, \hat{\beta}_i) - \mathcal{B}(\hat{\beta}_i, \beta_i)] \tag{A.2}$$

Using the same approach for type $\hat{\beta}_i \in \mathbb{B}_i$,

$$\phi(\beta_i, \hat{\beta}_i) = \phi(\beta_i, \beta_i) + [\mathcal{A}(\beta_i, \hat{\beta}_i) - \mathcal{A}(\beta_i, \beta_i)] - [\mathcal{B}(\beta_i, \hat{\beta}_i) - \mathcal{B}(\beta_i, \beta_i)]$$

and the incentive compatibility constraint for type $\hat{\beta}_i$ implies

$$\Phi(\hat{\beta}_i) - \Phi(\beta_i) \geq [\mathcal{A}(\beta_i, \hat{\beta}_i) - \mathcal{A}(\beta_i, \beta_i)] - [\mathcal{B}(\beta_i, \hat{\beta}_i) - \mathcal{B}(\beta_i, \beta_i)], \forall \beta_i \in \mathbb{B}_i \tag{A.3}$$

Combining both inequalities (equations (A.2) and (A.3)) with $\hat{\beta}_i > \beta_i$ and taking the limit as $\hat{\beta}_i \to \beta_i$ yields the following local incentive compatibility constraint:

$$\begin{aligned} \dot{\Phi}(\beta_i) &= \mathcal{A}_2(\beta_i,\beta_i) - \mathcal{B}_2(\beta_i,\beta_i), \text{ a.e.} && \text{(A.4)} \\ &= E_{\beta_j}[P'(q_i^c(\vec{\eta}) + q_j^c(\vec{\eta})) \cdot q_i^c(\vec{\eta}) \cdot \frac{dq_j^c(\vec{\eta})}{d\beta_i} && \text{(A.5)} \\ &\quad -C_\beta(\beta_i, q_i^c(\vec{\eta}), e_i(\beta_i,\beta_j))], \text{ a.e.} \end{aligned}$$

Now we can find the transfer $T_i(\beta_i,\beta_j)$ that will implement the truth-telling on the part of the firms. Integrating by parts and using the definition of $\Phi(\beta_i)$, we find that:

$$\begin{aligned} E_{\beta_j}[T_i(\beta_i,\beta_j)] &= \Phi(\bar{\beta}_i) \\ &\quad -E_{\beta_j}[P(q_i^c(\vec{\eta}) + q_j^c(\vec{\eta})) \cdot q_i^c(\tilde{\eta}) - C(\beta_i, q_i^c(\vec{\eta}), e_i(\beta_i,\beta_j))] \\ &\quad -E_{\beta_j}[\int_{\beta_i}^{\bar{\beta}_i} P'(q_i^c(\tilde{\eta}) + q_j^c(\tilde{\eta})) \cdot q_i^c(\tilde{\eta}) \cdot \frac{dq_j^c(\tilde{\eta})}{d\beta_i} \\ &\quad -C_\beta(\beta_i, q_i^c(\tilde{\eta}), e_i(\tilde{\beta}_i,\beta_j))d\tilde{\beta}_i] \end{aligned}$$

where $\tilde{\eta} = (e_i(\tilde{\beta}_i,\beta_j), e_j(\tilde{\beta}_i,\beta_j), \tilde{\beta}_i, \beta_j)$

These conditions are only necessary for the regulatory policy to be optimal. Without assuming the differentiability of the policy, finding sufficient conditions is an hazardous task without assuming specific functional forms. So in order to obtain relatively general conditions, we will assume for the remainder that the policies are differentiable.

It is relatively easy to show that if the policies are differentiable then the necessary and sufficient conditions for truth-telling are:

$$\begin{aligned} \phi_1(\hat{\beta}_i^*,\beta_i) \mid_{\hat{\beta}_i^*=\beta_i} &= 0 \\ \phi_{11}(\hat{\beta}_i^*,\beta_i) \mid_{\hat{\beta}_i^*=\beta_i} &\leq 0 \end{aligned}$$

From the envelope theorem,

$$\phi_{11}(\hat{\beta}_i^*,\beta_i) \mid_{\hat{\beta}_i^*=\beta_i} \leq 0 \quad \Leftrightarrow \quad \phi_{12}(\hat{\beta}_i^*,\beta_i) \mid_{\hat{\beta}_i^*=\beta_i} \geq 0$$

and the monotonicity constraints are:

$$\phi_{12}(\beta_i,\beta_i) = E_{\beta_j}[\frac{\partial^2\pi_i}{\partial e_i\partial\beta_i}\cdot\frac{de_i}{d\beta_i}+\frac{\partial^2\pi_i}{\partial e_j\partial\beta_i}\cdot\frac{de_j}{d\beta_i}]\geq 0,\ i=1,2\wedge i\neq j\wedge\forall\beta_i\in\mathbb{B}_i$$

and using the definitions:

$$\begin{aligned}\frac{\partial^2\pi_i}{\partial e_i\partial\beta_i} &= P''(Q^c(\vec{\eta}))\cdot q_i^c(\vec{\eta})\cdot\frac{dq_j^c(\vec{\eta})}{de_i}\frac{dQ^c(\vec{\eta})}{d\beta_i}\\ &+P'(Q^c(\vec{\eta}))\cdot\frac{dq_j^c(\vec{\eta})}{de_i}\cdot\frac{dq_i^c(\vec{\eta})}{d\beta_i}\\ &+P'(q_i^c(\vec{\eta})+q_j^c(\vec{\eta}))\cdot q_i^c(\vec{\eta})\cdot\frac{d^2q_j^c(\vec{\eta})}{de_id\beta_i}\\ &-C_{e\beta}(\beta_i,q_i^c(\vec{\eta}),e_i(\beta_i,\beta_j))\\ &-C_{qe}(\beta_i,q_i^c(\vec{\eta}),e_i(\beta_i,\beta_j))\cdot\frac{dq_i^c(\vec{\eta})}{d\beta_i}\end{aligned}$$

and

$$\begin{aligned}\frac{\partial^2\pi_i}{\partial e_j\partial\beta_i} &= P''(q_i^c(\vec{\eta})+q_j^c(\vec{\eta}))\cdot q_i^c(\vec{\eta})\cdot\frac{dq_j^c(\vec{\eta})}{de_j}\frac{dQ^c(\vec{\eta})}{d\beta_i}\\ &+P'(q_i^c(\vec{\eta})+q_j^c(\vec{\eta}))\cdot q_i^c(\vec{\eta})\cdot\frac{d^2q_j^c(\vec{\eta})}{de_jd\beta_i}\\ &+P'(q_i^c(\vec{\eta})+q_j^c(\vec{\eta}))\cdot\frac{dq_i^c(\vec{\eta})}{d\beta_i}\cdot\frac{dq_j^c(\vec{\eta})}{de_j}\end{aligned}$$

These monotonicity constraint will determine how the optimal policies $e_i(\beta_i,\beta_j)$ varie with (β_i,β_j). Substituting our model specification into these equations, the necessary and sufficient conditions are:

$$\dot{\Phi}(\beta_1) = E_{\beta_2}[P'(Q^{*c})\cdot q_1^{*c}\cdot\frac{dq_2^{*c}}{d\beta_1}-C_\beta(\beta_1,q_1^{*c},e_1(\beta_1,\beta_2))] \tag{A.6}$$

$$\dot{\Phi}(\beta_2) = E_{\beta_1}[P'(Q^{*c})\cdot q_2^{*c}\cdot\frac{dq_1^{*c}}{d\beta_2}-C_\beta(\beta_2,q_2^{*c},e_2(\beta_1,\beta_2))] \tag{A.7}$$

and

$$\frac{de_1}{d\beta_1}\leq 0\quad\text{and}\quad\frac{de_1}{d\beta_2}\geq 0 \tag{A.8}$$

$$\frac{de_2}{d\beta_1}\geq 0\quad\text{and}\quad\frac{de_2}{d\beta_2}\leq 0 \tag{A.9}$$

A.3 Incentive Correction Terms

Since

$$\begin{aligned}\dot{\Phi}_1(\beta_1) &= E_{\beta_2}\left[-\frac{4}{3}q_1^c(e_1,e_2,\beta_1,\beta_2)\right]\\ \dot{\Phi}_2(\beta_2) &= E_{\beta_1}\left[-\frac{4}{3}q_2^c(e_1,e_2,\beta_1,\beta_2)\right]\end{aligned}$$

then in equations (17) and (18):

$$\begin{aligned}\frac{d(\mathcal{X}_1 - C_\beta^1)}{de_1} &= \frac{-8}{9b}\\ \frac{d(\mathcal{X}_1 - C_\beta^1)}{de_2} &= \frac{4}{9b}\\ \frac{d(\mathcal{X}_2 - C_\beta^2)}{de_1} &= \frac{4}{9b}\\ \frac{d(\mathcal{X}_2 - C_\beta^2)}{de_2} &= \frac{-8}{9b}\end{aligned}$$

Appendix B

Tables

Canadian Petroleum Refining Industry Effluent Limitations						
	Monthly Amount		One-day Amount		Max. Daily Amount	
Substance	Guidelines	Regulations	Guidelines	Regulations	Guidelines	Regulations
Oil & Grease	17.1	8.6	31.4	15.7	42.8	21.4
Phenols	1.7	0.9	3.1	1.6	4.3	2.1
Sulphides	0.6	0.3	1.7	0.9	2.9	1.4
Amonia Nitrogen	14.3	10.3	22.8	16.3	28.5	20.5
Suspended Matter	41.1	20.6	68.5	34.2	85.6	42.8
pH (units)					6.0–9.5	6.0–9.5
Fish Mortality Toxicity	$\leq$ 50%					

Amounts are in $kg/(10^3 \times m^3)$

Source: Canada. Petroleum Refinery Effluent Regulations and Guidelines: Regulations, Codes and Protocols. Report EPS 1-WP-74.1. January 1974.

Table B.1: Canadian Petroleum Refining Industry Effluent Regulations and Guidelines

Appendix C

Figures

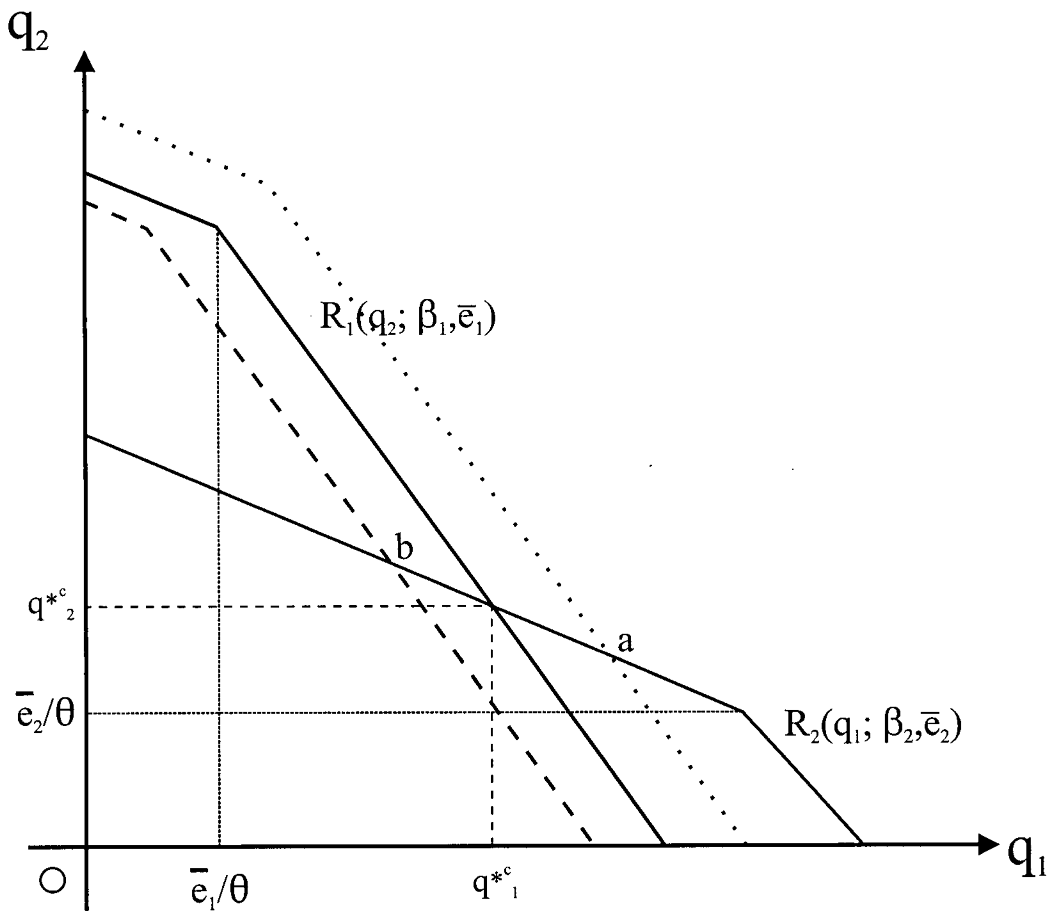

Figure C.1: Firms' Output Reaction Function

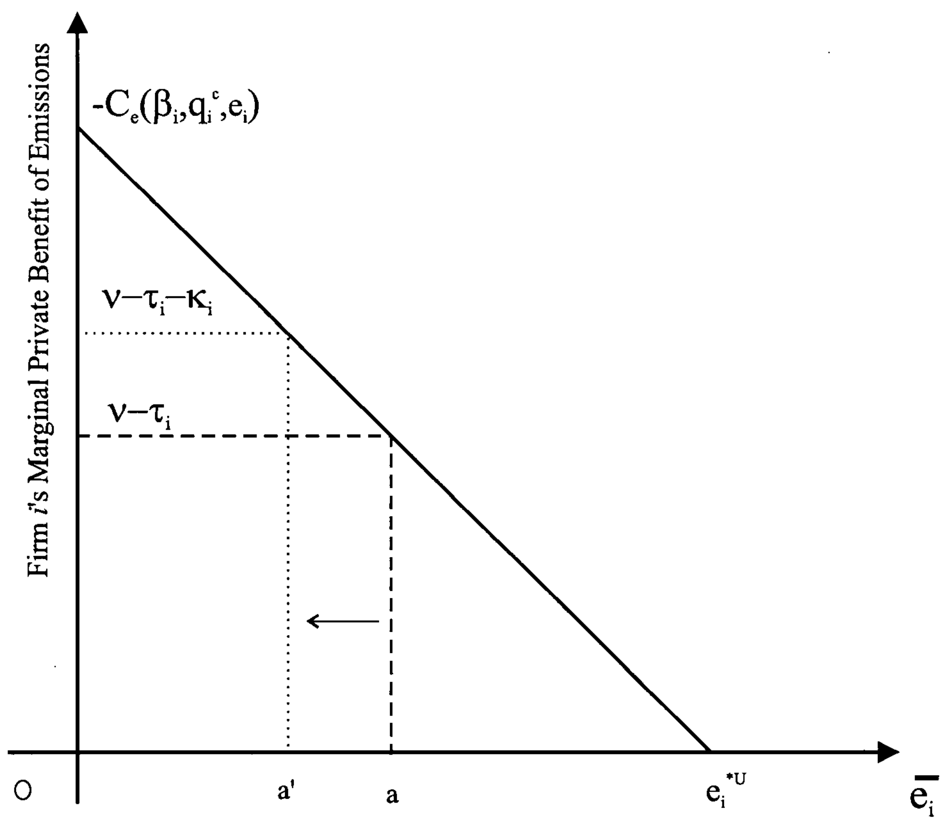

Figure C.2: Firm i's Quota and Marginal Tax

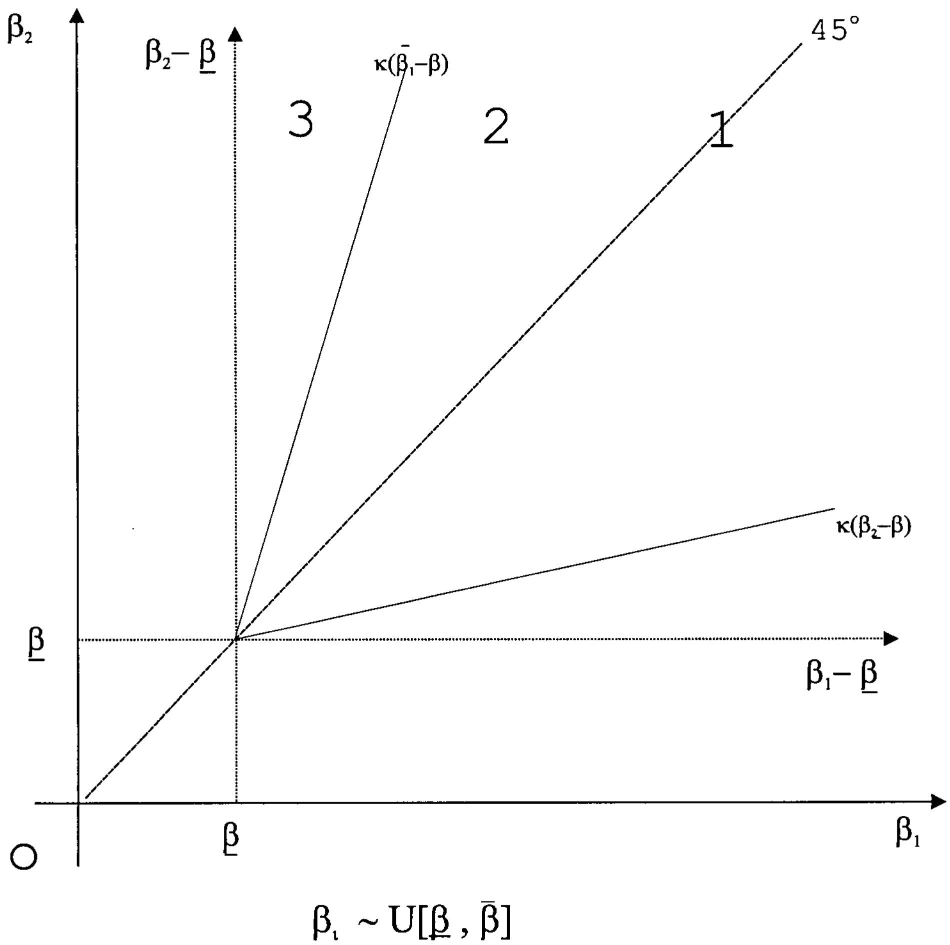

Figure C.3: Identical Uniform Priors

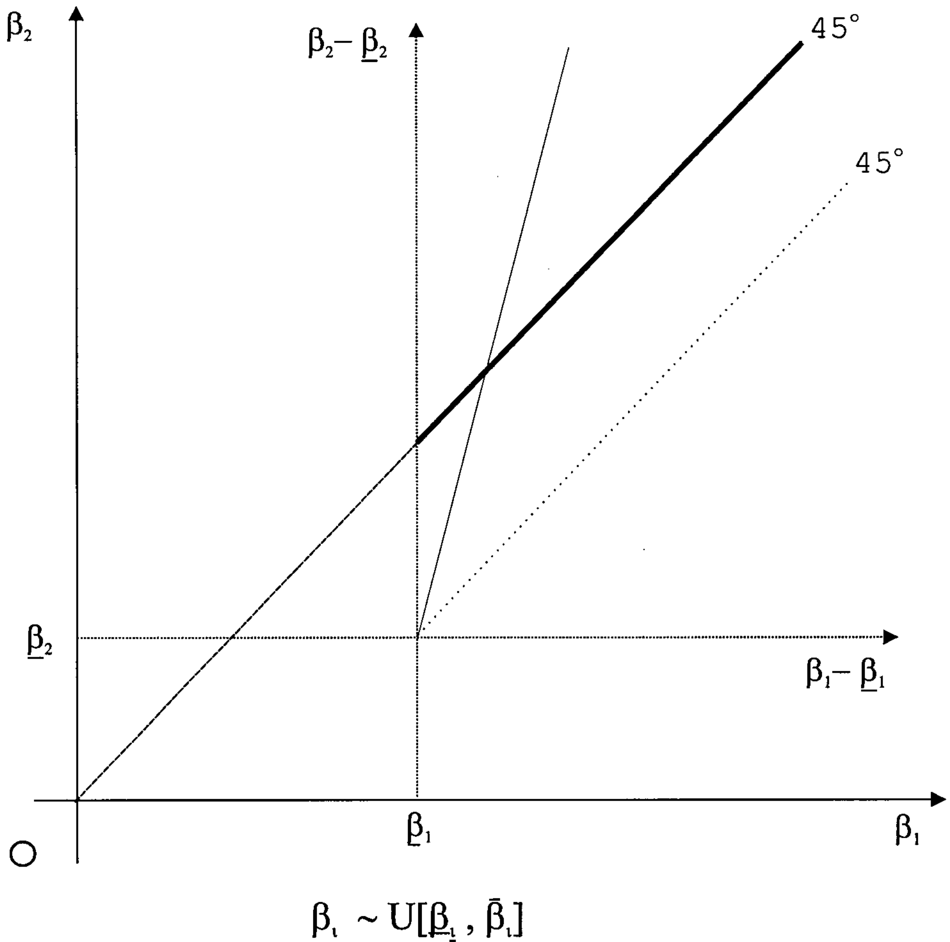

Figure C.4: $F_2(\beta)$ FOSD $F_1(\beta)$

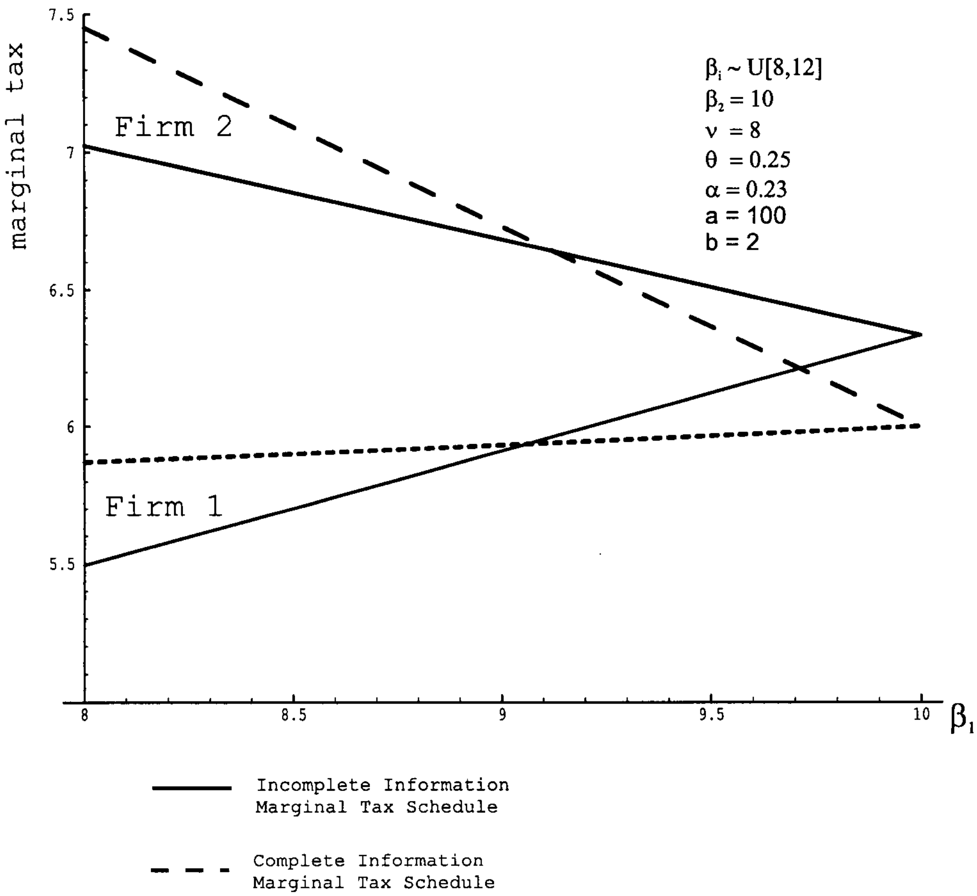

Figure C.5: Identical Distributions

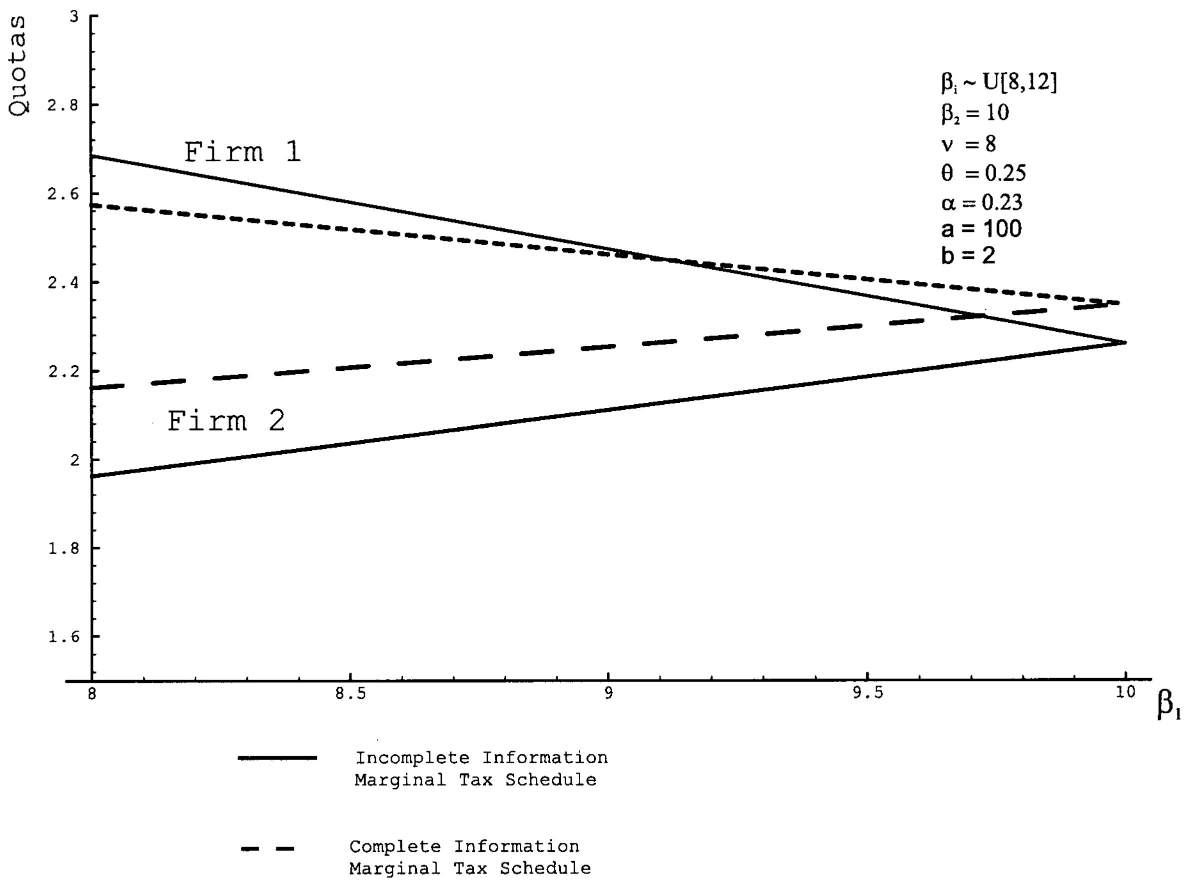

Figure C.6: Identical Distributions

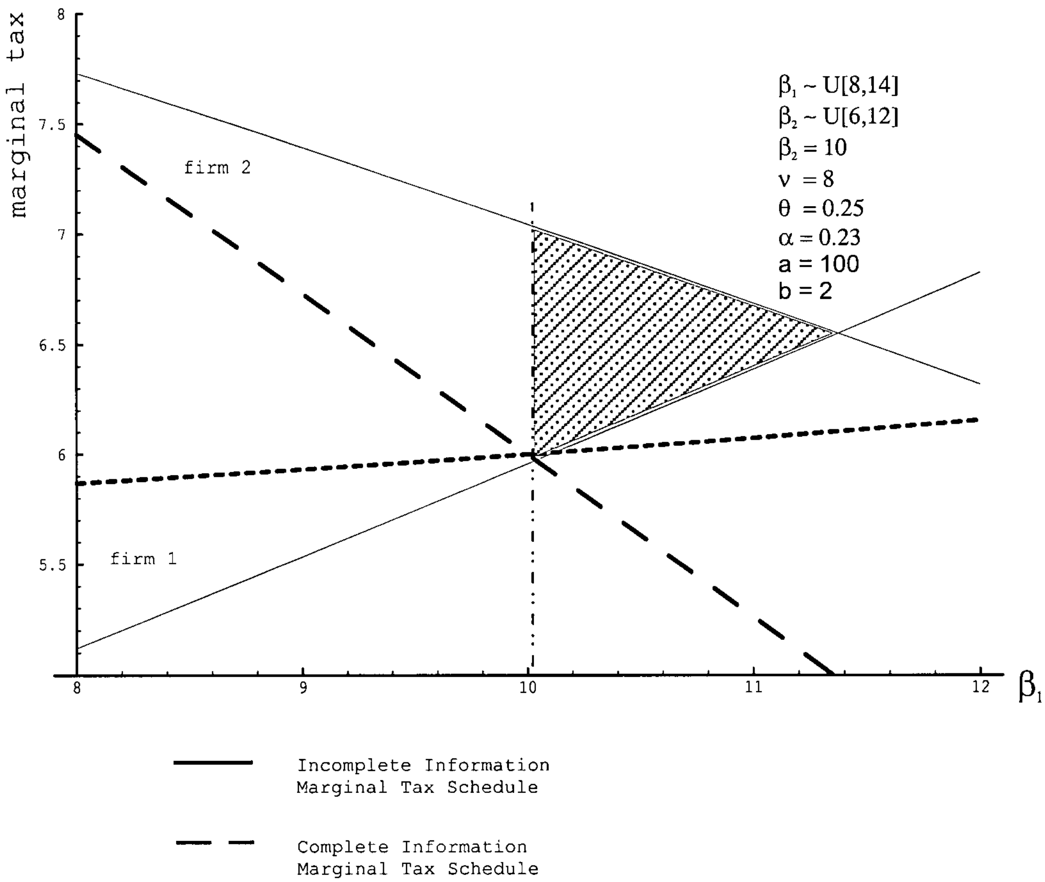

Figure C.7: $F_2(\beta)$ FOSD $F_1(\beta)$

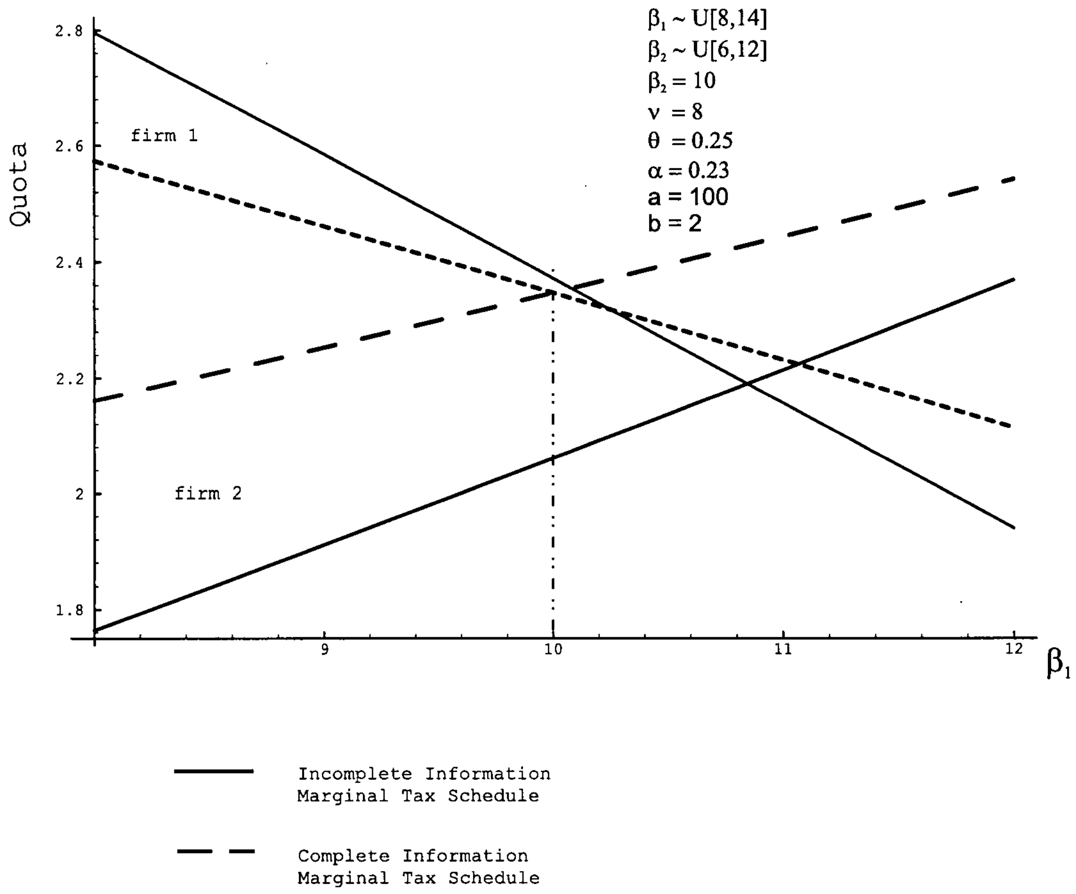

Figure C.8: $F_2(\beta)$ FOSD $F_1(\beta)$

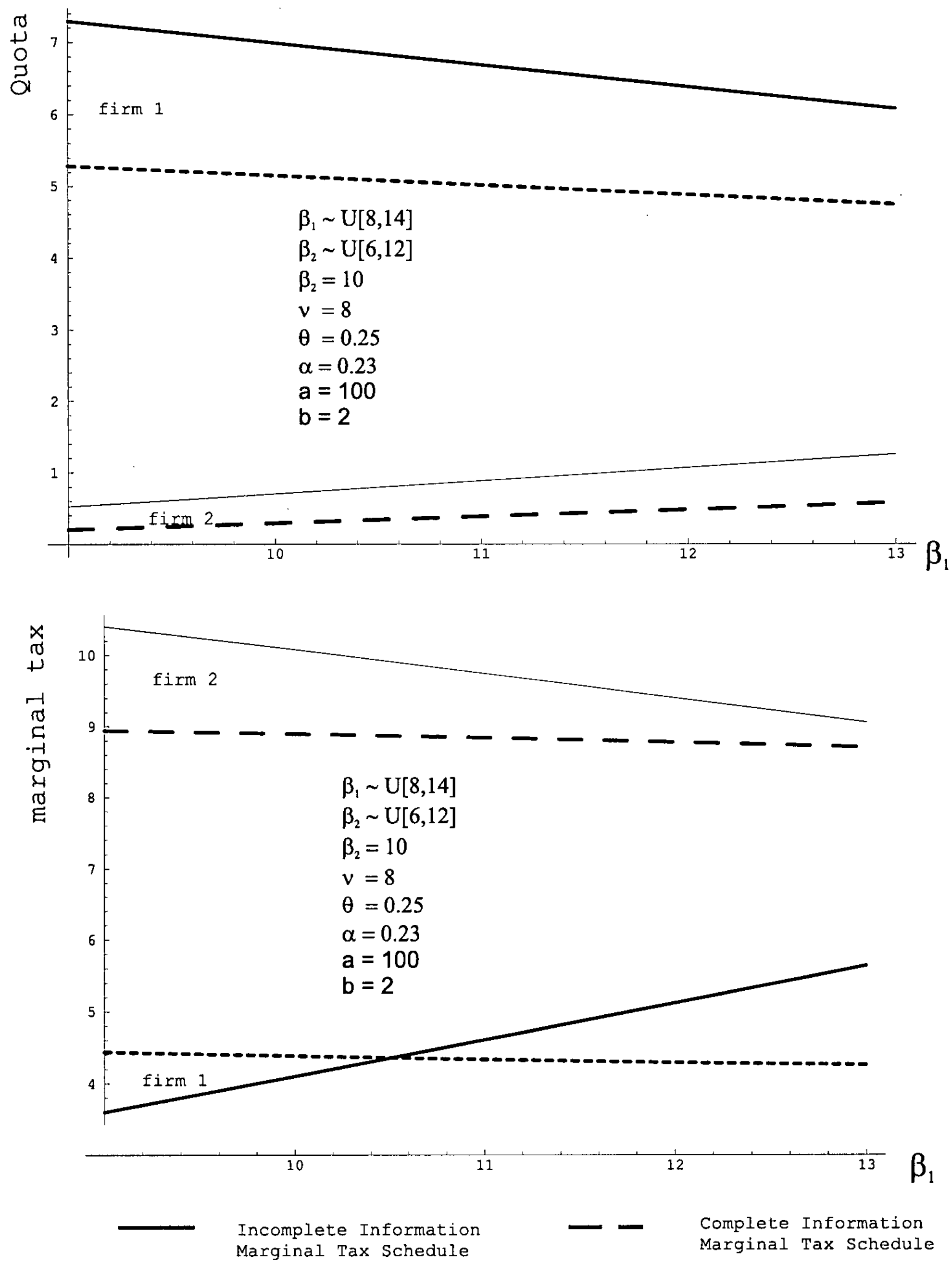

Figure C.9: Stackelberg Competition

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