

The Strategic Use of Innovation to Influence
Regulatory Standards: Theory and Evidence

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Abstract

Regulation often attempts to force an industry to develop cleaner technology. I investigate whether firms in an oligopoly setting use innovation strategically to affect the amount of regulation they face. I develop a simple model to capture strategic incentives both to suppress and heighten innovation. This paper dissects the various incentives and disincentives for pollution-abatement innovation in response to technology-forcing regulation. I find that the equilibrium level of R&D will be determined by the net of five effects: (1) Compliance Cost Reduction, (2) Raising Rivals' Cost, (3) Ratcheting, (4) Spillovers, and (5) R&D Costs. A simple numerical example demonstrates that firms may face higher or lower incentives to innovate relative to the case of exogenous regulation ("regulation-taking"). Empirical analysis finds evidence of endogeneity between the innovation of chemical manufacturers and regulation under the 1990 Clean Air Act Amendments. These results suggest that regulation should not necessarily be treated as exogenous in either empirical or theoretical models.

1 Introduction

Many innovations in environmentally cleaner products and processes are a result of pressure by government regulation. For example, the California Air Resources Board has required large automobile manufacturers to develop zero emission vehicles. Other examples of “technology-forcing” include the Corporate Average Fuel Economy (CAFE) standards for vehicle emissions, EPA technology-based standards for air toxic emissions from manufacturing facilities, and Department of Energy standards for energy efficiency of household and commercial appliances. A common feature of these regulations is that cost-effective technology is not available at the time of the mandate so that the regulator must rely upon the industry to develop the technology. The regulation may be welfare-improving only after the industry has engaged in sufficient innovation to reduce the cost of producing the “cleaner” product. Consequently, if for some reason the industry did not innovate, the regulator would have an incentive to back down on the regulation so as not to impose socially expensive policy on society. If the regulation is not seen as set in stone, then the industry may behave strategically with the regulator in ways which have important welfare implications. This work analyzes incentives to innovate when firms are not “regulation-takers”.

The motivation for this work is the conjecture that oligopolists faced with technology-forcing regulation do not take regulation as given but rather behave strategically with regulators. Anecdotal evidence supports this claim. For example, advocates of electric vehicle regulation in California have contended that auto manufacturers have suppressed fuel cell technology in order to discourage regulation. In the case of energy efficiency regulation of household appliances, Whirlpool Corporation invested heavily in designing more efficient refrigerators and then lobbied for stronger regulation to gain a competitive advantage over less innovating rivals. To quote a competitor, “They (Whirlpool) believe government regulations can be used to their competitive advantage”.¹ In international regulation to reduce stratospheric ozone depleters, DuPont was a leader in CFC alternatives and announced a plan to phase-out CFC production ahead of schedule in what some analysts claim was

¹ Doug Horstmann, Maytag Corporation vice president [11].

the hope of accelerating regulation and hurting rivals who did not possess viable CFC alternatives.² Also, analysts have claimed that auto emission standards were held up for several years in the 1970s due to footdragging in innovation by automanufacturers. Even regulation less in the public spotlight such as power tool regulation boasts stories of some firms in the industry innovating and encouraging regulation, while other firms do not innovate and press regulators for less stringent standards.³

Although this type of strategic behavior would seem to be fairly prevalent, I am not aware of any work in either the theoretical or empirical economics literature which accounts for the endogeneity of regulation and innovation in oligopoly settings. The economics literature has focused on the incentives of a regulated monopolist to innovate. The literature on monopoly regulation has emphasized the disincentive to innovate due to the “ratchet effect” of regulation. The theory states that there are lower incentives to innovate since a regulator without a commitment mechanism will have an ex post incentive to ‘ratchet’ up regulation and appropriate gains from cost-reducing innovation. In anticipation of appropriation, the monopolist has dampened incentives to innovate. An understanding of this ratchet effect has provided insight on the optimal dynamic regulation of natural monopolies.

However, it is also important to understand innovation incentives for regulated firms outside of monopoly settings. Environmental, energy, health, safety, and product quality regulation affects the behavior of firms in virtually every industry in the United States, so it would seem important to extend the theory developed for natural monopolies to regulation in more competitive settings. Unfortunately, the theory of the effect of regulation on innovation which has been developed for natural monopoly does not readily extend to the regulation of oligopolistic and competitive industries. To see this, consider an oligopolistic firm choosing to innovate in pollution-control technology. As with the monopoly case, the firm will have a disincentive to innovate since innovation will cause the regulator to ratchet up the standard. However, the firm may wish to innovate and encourage regulation since the standard may operationalize a cost advantage which the firm has over competitors in complying with the regulation.

²Murphy[9]

³Wall Street Journal [8].

Most papers in the theoretical IO literature which examine the relationship between regulation and innovation have assumed regulation to be exogenous to firm behavior. Implicitly these studies are assuming that firms are “regulation-takers”. For some regulatory situations, this regulation-taking assumption seems valid. For example, an individual laundromat in a highly competitive industry probably has little control over the regulatory process. However, many regulations apply to concentrated industries where the individual firms are key players in the regulatory process. For example, large manufacturers such as GE and Whirlpool are visible players in the process of setting energy efficiency standards for household appliances. Also, the production technology of the Big Three auto manufacturers plays a pivotal role in any mandated sales of zero emission vehicles. Generally, in more concentrated industries, there appears to be a clear endogeneity between innovation and regulation.

Despite the absence of a theory of regulation for oligopolies, some empirical studies have attempted to estimate the effects of regulation on the innovative effort of firms.⁴ None of these studies contain an explicit model of the regulatory process. Rather, these studies have assumed the regulatory outcome to be exogenous to firm behavior.⁵ The absence of a theoretical model where regulation is endogenous to firm behavior makes estimation of the effects of regulation problematic. Because of the endogeneity between regulation and firm behavior, single equation regressions of innovation on regulation will yield, in general, biased and inconsistent parameter estimates if regulation is indeed endogenously determined. However, in the absence of a good general theory of regulation, it is not possible to jointly estimate regulation and innovation.⁶

This paper addresses the endogeneity of regulation and innovation in the following manner. First, I develop a general model of technology-forcing regulation based upon a stage game between the regulator and the firms in the industry. The model identifies the major incentives and disincentives

⁴Jaffe and Palmer [5], Scott [14, 15], Jaffe et al. [2], and Newell, Jaffe, and Stavins [10].

⁵More precisely, these researchers have assumed that regulation is randomly assigned conditional on observables to identify the Average Treatment Effect of regulation on innovation.

⁶Stigler, Peltzman, and Becker have developed models of the demand side of regulation, but the supply side needs to be further developed. See Keohane, Revesz, and Stavins [6] for a framework to develop an equilibrium model of positive political economy for environmental regulation.

to innovate in oligopoly settings where regulation is endogenous to regulation. The model suggests that firms may face higher or lower incentives to innovate relative to the case of exogenous regulation (“regulation-taking”). Second, I analyze a particular example of technology-forcing regulation to test empirically whether firms behave as if regulation is exogenous or endogenous to their innovative choices. I analyze regulation of the chemical manufacturing industry under the 1990 Clean Air Act Amendments and find at least some evidence that firms treat regulation as endogenous and suppress innovation when faced with technology-forcing regulation.

2 Model of Innovation Incentives under Endogenous Regulation

2.1 Technology-Forcing as a Stage Game

I model the incentives to innovate in regulatory compliance technology by firms faced with potentially endogenous regulation. The process of innovation and regulation is a stage game of complete and perfect information between a welfare maximizing regulator and profit maximizing firms. In period 1, the regulator chooses an initial performance-based standard and a penalty for non-compliance. The standard is a mandated improvement in the firm’s product or production process to which consumers are indifferent, but which reduces external costs. At the time of the initial regulation, the standard is too costly to be socially beneficial, so in period 2 the industry is expected to invest in research and development to reduce the cost of compliance.⁷ I assume that the innovation only serves to reduce the cost of complying with the regulation. Also, I assume innovative output to be a deterministic function of R&D expenditures. In period 2, firms in the industry choose a level of independent innovation to reduce the cost of complying with the standard.⁸ In period 3, the

⁷I assume that innovation is only conducted by the firms which produce the final goods. Therefore, innovation by suppliers of inputs is ruled out. This may or may not be reasonable. In the electric vehicle case, a small fuel cell manufacturer unconnected to the auto industry played the role of independent innovator which sold its product to Daimler-Benz and was the basis of the NECar [Wall Street Journal, March 15, 1999]. In the appliance standard case this assumption is perhaps more reasonable.

⁸Future work could explore the possibility of firms innovating both independently and jointly through a research joint venture. Collaborative research in regulatory compliance technology is not uncommon. For example, in the case of reformulated gasoline to reduce ozone precursors, ARCO participated in both the AQIRP consortium while continuing independent research on alternative fuels [13].

regulator reviews the success of innovation, evaluates the cost of the regulation, and has the option to modify the standard.⁹ The regulator will have an incentive to modify the original standard if available technology is so costly that the original standard does not maximize social welfare. In period 4, firms observe the final regulation and their resulting costs, and compete in the output market.

2.2 Notation

I represent the general model with reduced-form profit and welfare functions in order to illustrate the various incentives most clearly. Assume the industry consists of N (not necessarily identical) firms which have marginal cost which is constant in output. The reduced-form profit to firm i (π_i) from competing in a particular market is a function of its marginal cost c_i and the marginal cost c_{-i} of the $(N - 1)$ other firms in the industry: $\pi_i(c_i, c_{-i})$. A firm's marginal cost is a function of the regulatory standard (x)¹⁰, its own independent innovation to reduce the cost of compliance (I_i), and the innovation which spills over to firm i from other firms ($\sigma_i(\mathbf{I}_{-i})$). This suggests the following form: $c_i(T_i, x)$ where $T_i = T_i(I_i, \sigma_i(\mathbf{I}_{-i}))$ is the pollution abatement technology possessed by firm i . I assume that marginal cost is strictly increasing in regulation because regulation will increase the cost of producing every unit of the good. Marginal cost is weakly decreasing in abatement technology because the technology will strictly reduce marginal cost so long as compliance costs are positive, but pollution abatement technology cannot reduce marginal cost below the unregulated level. Spillovers $\sigma_i(\cdot)$ are weakly increasing in the innovation by the other firms in the industry. Finally, technology is assumed to be strictly increasing in own innovation and weakly increasing in spillovers from other firms. Total profit Π_i is the reduced form profit π_i net of the research and development cost of innovation ($R_i(I_i)$). I assume that the cost of research and development $R_i(\cdot)$

⁹This updating can also be seen as a failure to be able to commit to the period one standard. I argue that in most examples of regulation, the regulator does not have a commitment mechanism since regulators often do not have the ability to restrict their future behavior or that of future regulators.

¹⁰I assume that a firm can meet any regulatory standard at sufficiently high marginal cost. For example, a refrigerator manufacturer may be able to switch to very costly refrigerants to temporarily satisfy energy efficiency standards until more cost effective refrigerants are phased in. Alternatively, regulations such as the CAFE standards in the Energy Policy and Conservation Act of 1975 often contain a penalty for non-compliance which is a function of the number of units sold.

is weakly increasing in innovative output.¹¹ Total profit is represented as: $\Pi_i = \pi_i(c_i, \mathbf{c}_{-i}) - R(\cdot)$.

In order to determine the behavior of the regulator, I need to specify the other components of welfare: consumer surplus and externality costs. Consumer surplus is a function of the exogenous demand function and output. Since output is a function of the vector of marginal costs and the type of competition, I will represent reduced-form consumer surplus as $CS(\mathbf{c}(\mathbf{T}, x), \theta)$, where θ is the competition parameter. Externality costs are a function of output and the regulatory standard imposed on those goods produced and are represented as $EC(\mathbf{c}(\mathbf{T}, x), \theta, x)$. Therefore, welfare is a function of the firms marginal costs and the regulation: $W(\mathbf{c}(\mathbf{T}, x), \theta, x)$. Later, I make assumptions about this welfare function to guarantee that regulation is weakly increasing in industry innovation.

2.3 Choice of Regulatory Standard

The equilibrium concept is subgame-perfect equilibrium for this dynamic policy game so we can solve backwards. Output in period 4 will depend on the nature of competition and marginal costs, but that will be captured by the reduced-form profit function $\pi_i(c_i, \mathbf{c}_{-i})$.¹² In period 3, the regulator will choose regulation to maximize welfare as a function of the technological capability of the N firms.

If all N firms are identical and have equal compliance capability, we expect regulation and innovation to be strategic complements. Intuitively, if firms innovate to reduce the (social) marginal cost of regulation, the regulator will have an incentive to raise the standard to reduce externality costs and maximize welfare. In the appendix, I show sufficient conditions of the welfare function to ensure that $x^*(T_i(\cdot), \mathbf{T}_{-i}(\cdot))$ is weakly increasing in the technological capability of the N firms.

Regulation and innovation are not necessarily strategic complements under non-symmetric equilibria. On one hand, the regulator may find it optimal to ratchet up the standard in response to increased innovation because the marginal cost of compliance by the innovating firm has decreased.

¹¹ I assume innovative output is a deterministic function of R&D expenditures known to both the firms and the regulator. This will make my result even more stark: even without uncertainty and asymmetric information which often lead to socially inefficient outcomes, the lack of commitment to the T=1 standard can lead to dire welfare consequences.

¹² In this paper we hold the nature of competition constant, so θ is suppressed.

On the other hand, if the increased regulation sufficiently increases the marginal cost of other firms in the industry, the regulator may not increase the standard in order to avoid competition concerns. In the extreme, increasing regulation may drive lesser-innovating firms out of the industry and increase market power. For example in the case of energy efficiency standards set in April of 1998 for the superefficient refrigerator, the Department of Energy was concerned that if it required energy efficiency levels of the more efficient firm, antitrust concerns may have arisen.¹³ I have yet to derive sufficient conditions for innovation and regulation being strategic complements under non-symmetric equilibria. In the following section I will simply assume that when firms choose different levels of innovation, an increase in innovation by any firm will increase the regulatory standard which all firms face. Later I provide a numerical example in which this condition is satisfied.

2.4 Industry Innovation

In period 2, firms in the industry will choose levels of innovation to reduce the cost of compliance with any eventual regulation. Assume sufficient smoothness in the marginal cost, profit, innovation cost, technology, spillover, consumer surplus, and externality cost functions. The firm's profit maximizing level of independent innovation (assuming an interior solution) will satisfy the F.O.C. $\frac{d\Pi_i(c_i, c_{-i})}{dI_i} = 0$.

We obtain the following F.O.C. for the firm:

$$\frac{d\Pi_i}{dI_i} = \frac{\partial \pi_i}{\partial c_i} \cdot \left[\frac{\partial c_i}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i} + \frac{\partial c_i}{\partial x^*} \cdot \frac{dx^*}{dI_i} \right] + \sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \left[\frac{\partial c_j}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i} + \frac{\partial c_j}{\partial x^*} \cdot \frac{dx^*}{dI_i} \right] - \frac{\partial R_i(\cdot)}{\partial I_i} \Bigg|_{x^*(I_i^*, I_{-i}^*)} = 0 \quad (1)$$

where the ratcheting of regulation due to increased innovation is given by:

$$\frac{dx^*}{dI_i} = \frac{\partial x^*}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i} + \sum_{j \neq i} \frac{\partial x^*}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i} \quad (2)$$

Eqn. (1) says that firms will choose independent innovation so that the marginal effect on profits through own and rival costs is zero. Innovation will affect all firms' marginal costs through the effects on the level of regulation and the technological capability of the firm. Of particular interest in eqn. (1) is the differentiation parameter $\frac{\partial \pi_i}{\partial c_j}$ which measures the effect on profits of other firms' marginal

¹³Personal Communication, James McMahon, Lawrence Berkeley Laboratory, 2/3/1998.

cost. Profits are weakly increasing in competitors' marginal costs. In particular, this can capture the type of (behavioral) competition in the output market, the amount of product differentiation, and the amount of competition from imports. Eqn. (2) simply says that innovation by firm i affects the level of regulation by increasing the technological capability of all firms. If innovation and regulation are strategic complements, regulation is increasing in innovation.

We can separate this equation into the terms that determine the major incentives and disincentives to innovate. In the following equation which holds at the equilibrium outcome, the left side are the “marginal benefits of innovation” and the right side are the “marginal costs of innovation”:

$$\underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial T_i} \cdot \frac{\partial T_i}{\partial I_i}}_{\text{Cost Reduction Effect}} + \underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial x^*} \cdot \frac{dx^*}{dI_i}}_{\text{Raise Rivals Cost Effect}} = - \left[\underbrace{\frac{\partial \pi_i}{\partial c_i} \cdot \frac{\partial c_i}{\partial x^*} \cdot \frac{dx^*}{dI_i}}_{\text{Ratchet Effect}} + \underbrace{\sum_{j \neq i} \frac{\partial \pi_i}{\partial c_j} \cdot \frac{\partial c_j}{\partial T_j} \cdot \frac{\partial T_j}{\partial \sigma_j} \cdot \frac{\partial \sigma_j}{\partial I_i}}_{\text{Spillover Effect}} - \underbrace{\frac{\partial R_i(\cdot)}{\partial I_i}}_{\text{R\&D Cost}} \right] \quad (3)$$

Each of the marginal benefits and marginal costs of innovation can be classified into one of five effects. Firms will benefit from additional innovation due to two factors: (1) reducing their own marginal costs and (2) raising their rivals' marginal costs by encouraging more regulation.¹⁴ At the same time, an increase in innovation will also hurt the firm: (1) innovation will encourage the regulator to ratchet up regulation, (2) some innovation will spillover and reduce the marginal costs of competing firms, and (3) additional innovation will raise R&D costs.

Several special cases commonly seen in the literature can be seen from this formulation. First, when there is only one firm in the industry so that there is no raise the rivals cost or spillover effects, this formulation reduces to the standard incentives of a regulated monopolist to innovate. Second and more interesting, we can compare the innovation incentives of firms facing exogenous (fixed) regulation to firms faced with regulation which is endogenous to innovation. The classification of incentives to innovate in (3) reduces to the typical incentives for the exogenously regulated firm

¹⁴The concept of raising rivals' costs is developed in Salop and Scheffman [12] for the case of an industry consisting of a dominant firm and a competitive fringe. As an example of raising rivals' costs, Salop and Scheffman suggest that firms may engage in rent-seeking behavior such as encouraging government regulation to raise rivals' relative compliance costs.

when the ratchet and raise the rivals cost effects are zeroed out ($\frac{dx^*}{dt_i} = 0$). Therefore, the added element of this model is that the incentives to innovate under endogenous regulation relative to the exogenously regulated case will depend upon the net effect of the ratchet and raise the rivals cost effects.

This model formalizes the notion that firms should not be modeled as “regulation-takers” when faced with technology-forcing regulation. When innovation by the regulated firms affects the social net benefits of the regulatory standard, the firms will have incentives to behave strategically with the regulator and among themselves in choosing innovation. However, the equilibrium level of innovation in such a strategic game can be lower or higher than the level of innovation if regulation were exogenous.¹⁵ Firms may have heightened incentives to innovate if the increased profits due to raising the marginal costs of rivals counteracts the reduction in profits due to raising own costs. On the other hand, firms would have dampened innovation incentives relative to exogenous regulation if the ratchet effect outweighs the raise the rivals cost effect. The net of the raise the rivals cost and ratchet effects will determine the extent to which firms “markup” or “markdown” innovation from the “regulation-taking” level of innovation.

2.5 A Numerical Example

A simple numerical example demonstrates that firms faced with endogenous regulation may markup or markdown innovation relative to levels if regulation were exogenously determined. I assume some specific functional forms and calculate the equilibrium outcomes numerically. Consider Cournot duopolists who face a market demand of $P(Q) = 1 - Q$. Assume that before any regulation and innovation, the firms has constant marginal cost $\tilde{c} = 0$. Regulation and pollution abatement technology can shift marginal cost up or down. For example, if refrigerator manufacturers are required to adopt a higher efficiency standard, a single refrigerator will cost more to produce. However, the cost to produce the refrigerator under the standard will fall if the firm has innovated to produce

¹⁵In this model, exogenous regulation would correspond to the regulator committing to the period 1 standard and not re-optimizing in period 3.

more effective (less costly) refrigerants. Let spillovers be a constant fraction of the other firm's innovation ($\sigma_i = \sigma I_j$) and assume that spillovers contribute additively to the firm's own innovation ($T_i = I_i + \sigma I_j$). Finally, assume that the effect of regulation and abatement technology on marginal cost can be well approximated by a second-order polynomial:

$$c_i(x, I_i, I_j) = \tilde{c} + \alpha_i \cdot x + \lambda \cdot x^2 - \beta \cdot (I_i + \sigma I_j) - \eta \cdot (I_i + \sigma I_j)^2 - \phi \cdot x \cdot (I_i + \sigma I_j) \quad (4)$$

where $\sigma \in [0, 1]$

All parameters are assumed to be non-negative. This formulation would suggest that regulation will increase marginal cost and do so at an increasing rate. Innovation, on the other hand, will shift marginal cost down where the shift is larger for higher levels of innovation. The positive coefficient on the interaction term ϕ suggests that for higher levels of innovation, regulation will shift up marginal cost by less than at lower levels of innovation.

I assume that the externality costs are linear in both quantity and regulation: $EC(x, q) = \gamma \cdot (1 - x) \cdot q$. For example, in the electric vehicle case, the amount of externalities from air pollution (EC) will be falling in the percent of new vehicles required to be electric (x), but rising in the total number of vehicles sold (q). Assume that innovation exhibits rising average costs: $R(I) = \frac{1}{2} \cdot \delta \cdot I^2$. Finally, it is important to recognize that the regulator will face competition concerns in the output market when choosing the level of regulation. If one firm innovates very little and another very much, then imposing a significant amount of regulation could raise the low innovator's marginal cost to a sufficiently high level that the regulator effectively creates a monopoly. Therefore, welfare is given by:

$$W(x) = \begin{cases} \text{Duop Welfare} & \text{for } p_i^M(c_i(x)) \geq c_j(x) \\ \text{Monop Welfare} & \text{for } p_i^M(c_i(x)) < c_j(x) \end{cases}$$

The endogenous regulation equilibrium corresponds to the outcome of the game described in section 2.1. The exogenous regulation game in which the regulator can commit to an initial standard is simply the game described in section 2.1 in which period 3 is removed. I choose what I believe are

reasonable parameter values and numerically calculate the equilibrium outcomes under “regulator as first-mover” and “firms as first-movers”. The results are shown in Table 1.

The first example shows that firms may innovate more under endogenous than under exogenous regulation. In choosing parameters, I make α vary by firm so that Firm 1 has lower marginal compliance costs than Firm 2. When regulation is exogenously chosen, the regulator will calculate the two firms’ best responses to given levels of regulation and choose the regulatory standard which maximizes welfare. The equilibrium level of regulation is $x^* = 0.10$ to which the firms’ equilibrium responses are $I_1 = 0.10$ and $I_2 = 0.14$. The firm best response functions are depicted in Figure 1. However under endogenous regulation, we observe more innovation in equilibrium. Each firm anticipates the regulator’s welfare-optimizing response to each possible level of industry innovation and finds the profit-maximizing level of innovation for each innovation choice of the competitor. The best-response functions and resulting equilibrium are depicted in Figure 2. In equilibrium, both firms will innovate more and the regulatory standard will be higher than under exogenous regulation. However, both firm profits and welfare will be lower.

In our second example (the fourth and fifth columns of Table 1), I allow modest spillovers ($\sigma = 0.20$) and the firms are made symmetric ($\alpha_1 = \alpha_2 = 0.35$). Solving numerically, I find an equilibrium in which the regulator chooses a standard $x^* = 0.44$ and the equilibrium best response of the two firms is innovation $I_1 = I_2 = 0.22$. The best response functions are shown in Figure 3. In the case where the regulator cannot commit to an initial standard so that the firms are not “regulation-takers”, the equilibrium outcome levels of innovation are lower $I_1 = I_2 = 0.16$ as seen in Figure 4. In addition, the regulatory standard and total welfare are lower under endogenous regulation.¹⁶

¹⁶It is noteworthy that welfare need not be higher under exogenous regulation, suggesting that first-mover status does not necessarily afford the regulator an advantage. In other simulations, welfare was higher under endogenous regulation. We have the intuition that an agent will be better off if he is the first-mover because he is not constrained to play on his best-response function but rather chooses where on the other agent’s best-response function he would prefer to lie. For example, in standard quantity competition, the Stackelberg leader will achieve higher profits than under the simultaneous move (Cournot) outcome. This intuition would carry over to the regulatory game I describe if the industry consisted on only one firm. However, I do not believe the intuition carries over to an oligopolistic industry. The nature of the game changes when the regulator rather than the firms are the first-movers. When the regulator is the first-mover, the firms play against each other in the following periods. However, when the firms

These two numerical examples demonstrate that it is not unambiguous whether firms “markup” or “markdown” innovation from “regulation-taking” levels. Depending upon the particulars of the industry and regulatory setting, either the raise the rivals cost effect or the ratchet effect can dominate when regulation is endogenous. This analysis suggests that if regulation is indeed endogenous to innovation, it will be an empirical question of whether innovation, regulation, and welfare are higher relative to exogenous regulation.

2.6 Relationship between Model and Existing Theoretical Literature

In the previous section I classify the major incentives and disincentives an oligopoly firm will have to innovate when faced with technology-forcing regulation. Many of these incentives are captured by other papers in the literature, however no paper of which I am aware focuses on generally identifying all of the various incentives.

Yao [17] models technology-forcing regulation where the regulator cannot commit to a standard *ex ante*. He shows that industry will have incentives to underinvest due to asymmetric information regarding the industry’s innovative potential, yet he models the industry as a single decisionmaker. Kleit [7] demonstrates how administrative procedures which restrict the choices of enforcement agencies may allow time-inconsistent regulation to be implemented. Hackett [4] endogeneizes regulation with a political influence game to identify incentives for pollution-control innovation in oligopolistic industries. Wilson [16] analyzes the effects of technology-forcing regulation on market structure, but does not include a regulator’s objective function to allow firms to anticipate regulatory responses and behave strategically. Gersbach [3] does allow for strategic behavior between the firms and regulator and proposes a scheme to avoid this problem. However, Gersbach does not include all incentives to innovate – he allows for dampened incentives to innovate due to the ratchet effect yet he does not incorporate heightened incentives to innovate and gain a compliance cost advantage over choose innovation before regulation is set, the firms are playing a game not only between each other but also with the regulator. To put it slightly differently, in the Stackelberg leader example, both best-response functions are the same under Cournot and Stackelberg; the order of play determines the equilibrium outcome. However, in the game I describe, the firms’ best-response functions depend upon the order of the game, as we see in the figures.

competitors.

3 Empirical Evidence of Endogenous Regulation

The motivation for this work is the conjecture that regulation may not be exogenous to decision variables of the firm such as innovation. This conjecture suggests that firms have incentives to behave strategically with regulators in ways which may have important welfare consequences. Although we have anecdotal evidence of strategic behavior, I am not aware of any empirical evidence of strategic interaction or other endogeneities between firm-level innovation and regulation. Therefore, my first step in the empirical section of this paper is to investigate whether there is evidence of endogeneity or whether it is reasonable to assume regulation to be exogenous, as other empirical research has done.

3.1 Title III Clean Air Act Amendment Regulation

I shall use a particular example of regulation with data available on innovation and regulatory stringency at the firm level. Title III of the Clean Air Act Amendments of 1990 (CAAA) identified 189 chemicals and chemical groups which were previously unregulated hazardous air pollutants. The Act instructs the EPA to develop categories and subcategories of major sources of the hazardous air pollutants and promulgate standards based upon a schedule ranging from 2 to 10 years. In the first phase, these standards were technology-based standards based upon maximum achievable control technology (MACT).

Scott's [14, 15] survey and empirical analysis of firms which emit Title III chemicals provides us with some anecdotal insights into the response to the CAAA.¹⁷ First, the response could be characterized as both innovation into new processes and routine engineering, which suggests that the expenditures in response to Title III could show up as capital costs as well as R&D.¹⁸ I will focus

¹⁷Scott surveyed firms to collect information on R&D in general and also R&D specifically targeted to reduce Title III hazardous air pollutants.

¹⁸Scott did not see a systematic pattern to firms claiming engineering rather than innovation expenditures; occasional respondents suggested that their compliance costs were largely engineering [John Scott, personal communication, March 7, 1999].

on R&D because the firm is most likely to be able to holdup the regulator at the innovation stage since innovation (or lack thereof) acts as a commitment mechanism for the firm. Second, Scott's survey suggests that firms' response to regulation occurred before the standards were promulgated. His questionnaire responses suggests that firms innovated prior to the actual standard-setting in a forward-looking manner. Questionnaire responses included "The research is in anticipation of regulation" and "We are trying to get out front and avoid future problems".¹⁹ Scott has data on the fraction of total R&D expenditures devoted to developing processes to lessen Title III emissions and finds that firms associated with Title III emitting industries devote a larger share of R&D to emission reduction research.

I will focus on the standard-setting for the first set of rules promulgated under Title III – called the HON standards. The CAAA required the EPA to establish MACT standards within 2 years for at least 40 source categories. The EPA's first goal was to develop technology-based standards for the chemical manufacturing industry.²⁰ It is during the time from the passage of the CAAA in November of 1990 to the promulgation of the specific 2 year MACT standards, that strategic interaction between chemical manufacturers and the EPA would occur.

The EPA clearly had discretion in choosing which processes within the chemical manufacturing industry to regulate and how severe that regulation would be. In order to obtain the information necessary to develop these standards, the EPA developed a comprehensive information gathering program which assembled data from sources within each category of emissions on the types and costs of control technology. According to the EPA, the goal of the information gathering program was to help the EPA identify "the controls and practices used by the better and best performing sources" and was to "form the basis for determining the MACT floor levels."²¹ EPA was to set a final standard which entailed requiring the use of "maximum" or "generally achievable control

¹⁹Scott [14], page 6.

²⁰This industry (SIC 28) contains the largest incidence of Title III pollutants. [Scott [14], Figure 1] Due to a 1987 D.C. Circuit Court decision and a promise by the EPA administrator, the EPA was effectively committed to set standards first for the chemical industry. [Personal communication, Jan Meyer, U.S. EPA, April 21, 1998]

²¹In order to establish the standards, EPA used a formal negotiation process involving industry associations (such as the Chemical Manufacturers Association and the American Petroleum Institute) as well as regulatory agencies and environmental groups.

technology”.²²

Given this process of standard-setting, manufacturers would face several strategic incentives. On one hand, firms may wish to suppress pollution control technology in order to make regulatory costs higher and presumably reduce the EPA standards. On the other hand, an individual firm may use innovation in control technology to encourage regulation and gain a compliance cost advantage over competitors. The EPA approach to standard-setting, I believe, allows for these forms of strategic interaction. When the standards were ultimately set, the technology-based regulation targeted the synthetic organic chemical manufacturing industry and several other processes. The rules applied to approximately half of the chemical substances produced by synthetic organic chemical manufacturing industries as commercial products. EPA estimated that 355 facilities in 35 states were affected.

I will test whether this choice of regulatory outcome was endogenous to firms’ innovative behavior. In particular, EPA potentially could have regulated numerous facilities that operated in the chemical manufacturing industry (SIC 28). However, by some means, it chose to regulate the processes of the 355 facilities identified in the impact analysis.²³ I will estimate whether this choice was affected by firm innovation.

3.2 Testing for Endogeneity Using a Binary Treatment Measure

The natural experiment the econometrician would like to observe is the behavior of otherwise identical firms after some are “treated” with exogenous regulation while others are “treated” with endogenous regulation. Simply put we would like to observe “exogenous variation in endogeneity”. Specifically, we would like to observe one set of firms subjected to the standards of a regulator who can commit to first period standards, and another set of firms subject a regulator lacking a commitment mechanism.

Finding such an example is difficult for a variety of reasons. In most examples of regulation, the regulator does not have a commitment mechanism since regulators often do not have the ability to

²²Unified Air Toxics Website <http://www.epa.gov/ttn/uatw/happlan.html>

²³Actually, the list from the impact analysis is known to be inaccurate and I address the issue of measurement error below.

restrict their future behavior or that of future regulators.²⁴ Even if one could observe two different examples of regulation with differing levels of commitment, comparing firms subjected to entirely different types of regulation is problematic.

Therefore, one plausible solution to this dilemma is for the econometrician to “create” the desired experiment with instrumental variables estimation. A simple regression of innovation on regulation will identify the effect of potentially endogenous regulation on innovation (i.e. identify the selected average treatment effect). If regulation is instrumented with exogenous determinants of regulation (i.e. we have selection on unobservables), we can identify the average treatment effect of exogenous regulation. If our estimated selected average treatment effect differs substantially from our estimated average treatment effect, we have evidence of endogeneity. This is the approach we will follow to empirically test for endogeneity. However, since we are entirely relying upon valid instruments for this test, we want to be careful to choose as instruments variables which are determinants of regulation but are not unobserved determinants of innovation. To some extent we can test this assumption.

To estimate whether regulation is endogenous, we first specify a model of innovation. A firm will choose to innovate in order to reduce the cost of complying with any eventual regulation. However, a firm will recognize the possible effect of its innovation on the optimal choice of the regulator. As a result, the choice to innovate by the firm is forward-looking. A firm will choose innovation in period t (I_{it}) based upon the expectation of future regulation (x_{it+1}^*) (which may be a function of innovation) conditional on firm innovation and exogenous determinants of innovation such as the type of industry and size of the firm (W_{it}):

$$I_{it} = f_1(E_t[x_{it+1}^*|I_{it}], W_{it}) \tag{5}$$

In order to estimate this model, we need to specify firms’ expectations of future regulation. Firms are uncertain as to the regulator’s best response to any given level of innovation, however all firms

²⁴ However, Kleit [7] suggests that the degree of commitment may vary depending upon the administrative procedures of the agency delegated to oversee the regulation.

have a common prior belief $f_2(\cdot)$. The actual regulation x_{it+1}^* will differ from firms' expectations by a mean zero conditional forecast error term. Accordingly, observed regulation (x_{it+1}^*) is modeled:²⁵

$$x_{it+1}^* = f_2([I_{it} + \sum_{j \neq i} I_{jt}], Z_{it}) + \epsilon_{it+1} \quad (6)$$

where Z_{it} are exogenous determinants of firm-level regulation such as number or toxicity of the firm's pollutants.²⁶

Assume that firms can predict $I_{jt} \quad \forall j \neq i$ by forecasting how other firms play the regulatory game. From (5) and (6) and these assumptions we obtain the following innovation equation for the econometrician to estimate:

$$I_{it} = f_1[f_2(I_{it} + \sum_{j \neq i} I_{jt}, Z_{it}), W_{it}] + u_{it} \quad (7)$$

This specification allows for both exogenous and endogenous regulation. If regulation is exogenous to the firm's choice of innovation, then only the exogenous determinants of regulation Z_{it} rather than firm level innovation I_{it} will affect optimal regulation. However, this formulation also makes clear the possibility of endogenous regulation. A firm's choice of innovation will affect the level of regulation which in turn affects the optimal level of innovation. Current innovation will depend on the expected future response of the regulator to that innovation. If innovation and regulation are strategic complements, the firm will expect the regulator to respond to more innovation with more regulation.

Our investigation into the possible endogeneity of regulation asks the following question: if regulators respond to firm innovation in setting regulation, do firms take this endogeneity into account when choosing innovation levels? If regulation is endogenous, equation (7) tells us that a regression of innovation on regulation will yield in general inconsistent estimates of the effect of regulation on innovation. To test for endogenous regulation, we will first estimate (7) assuming exogeneity as other empirical work has done. Then we will instrument for regulation with Z_{it} and

²⁵ We allow regulatory stringency to vary by firm since a given standard will have differential impact depending on the firm's production processes.

²⁶ Note that this specification explicitly separates uncertainty from endogeneity.

test whether we obtain statistically different parameter estimates.

Estimating (7) with the observed data is complicated by the fact that we observe actual regulation x_{it+1}^* rather than the firm's predicted regulatory response $f_2(\cdot)$, which differs from actual regulation by the forecast error term ϵ_{it+1} . If we were to regress innovation on observed rather than predicted regulation, we would build in a measurement error which would bias our estimates toward zero. If we then were to estimate (7) with instrumental variables (which is consistent under both measurement error and endogeneity), we would not know if statistically different parameter estimates were due to the endogeneity for which we are testing or simply the measurement error we have built into the model.

We deal with this complication by using two different estimators. One estimator is consistent under measurement error but not under endogeneity. The other estimator is consistent under both measurement error and endogeneity. Statistically different parameter estimates for these two estimators will be interpreted as evidence of endogenous regulation.

3.2.1 Data

I compile a unique dataset to allow me to use the Clean Air Act Amendments to test for endogenous regulation. The dataset contains data on the pollution by and regulation of facilities in the chemical manufacturing industry. The firms which faced regulation are those parent firms which own manufacturing facilities which were affected by the promulgated standards, according to EPA impact analysis estimates. In order to obtain appropriate instruments, I require data on the pollutants emitted by these facilities. Under the Emergency Planning and Community Right-to-Know Act, firms meeting certain criteria are required to report on toxic chemicals which are manufactured, processed, or otherwise used at their facilities.²⁷ These data are gathered in the Toxics Release Inventory (TRI). I match the facilities in the TRI dataset to the facilities estimated by the EPA to

²⁷Facilities must report if they are in the manufacturing sector (SICs 20-39) with ten or more full-time employees and either manufacture or process more than 25,000 pounds of the chemical or otherwise use more than 10,000 pounds of the chemical in the calendar year. Although the TRI does not contain data on all of the 189 Title III chemicals, facilities were required to report on 168 of the 189 Title III chemicals in 1991.

be impacted by the HON standards. I use TRI data from the 50 states and the District of Columbia for 1991.

Data on innovation expenditures and other firm level variables is from COMPUSTAT. Since many facilities are owned or operated by a parent firm which may conduct the research and development for all the facilities, I aggregate the TRI data to the parent firm level and merge this data to COMPUSTAT data on research and development expenditures and other parent firm characteristics.²⁸ This measure of innovation includes all forms of innovation – not only pollution-control innovation. One potential problem with this measure of innovation is that in vertically related industries, R&D to reduce emissions by one firm may be performed by another firm. Scott’s survey work suggests that at least some pollution reduction R&D is done by suppliers of the polluting input.²⁹

As instruments I seek variables which are determinants of EPA regulation of the chemical manufacturing industry but are not unobserved determinants of firm level innovation. One candidate is some measure of the toxicity of the chemicals which the firm’s facilities emit. For example, if one firm owns facilities which emit a very toxic chemical, we would expect it to be more likely to be regulated by the EPA. I have two measures of the toxicity of emitted chemicals. For many of the Title III chemicals, EPA developed an index of both the carcinogenicity and chronic toxicity. By summing these measures across all chemicals of a facility and all facilities owned by the parent firm, I obtain parent firm level variation in both the toxicity and carcinogenic potency of the firm’s production process. We would expect these measures to be positively related to the eventual level of regulation. Other plausible instruments for which we have data are the number of facilities owned which emit Title III pollutants, the number of Title III pollutants at a facility summed across all facilities owned by the firm, and the total number of air releases of any TRI pollutant emitted by the firm’s facilities.

²⁸ We use the Industrial Primary-Supplementary-Tertiary, Full Coverage, and Research files for 1991. COMPUSTAT identifies firms by the CUSIP number while TRI identifies firms by the DUNS classification. Therefore, I use the Compact Disclosure database of 10-K reports to create a match between CUSIP and DUNS. If a firm contains missing data on R&D, then I assume the firm did not innovate. However, missing data for variables such as cash and capital result in the firm being excluded from the analysis.

²⁹ See Scott [14], page 6.

When I merge the TRI and COMPUSTAT data and exclude observations with missing data, we obtain an analysis dataset of 140 parent firms. Descriptive statistics of the data are included in Table 2. Of the firms in our dataset, 24 percent own at least one facility regulated by the standards. On average, each firm owns 0.77 HON regulated facilities. The distribution of the number of SIC=28 regulated facilities is depicted in Figure 5. Of the 140 parent firms in our sample, 122 firms conducted some R&D in the past five years and 120 firms conducted R&D in the year of the sample. I do not explore the possibility of censoring, but that will be a priority for future research. At the very least, I am estimating if regulation is endogenous to firm behavior for the firms in my sample. I can use equation (7) taking $t=1991$ and $t+1=1992$ to test for the endogeneity of (future) regulation to firms' (current) innovation.

3.2.2 Results

One of the major problems we have in estimating the model is that the data on regulation is not really the desired measure of regulatory stringency. Ideally, we would like a measure of the level of pollution abatement which each parent firms' facilities were required to meet; we would like to know the height of the regulatory hurdle. Our measure of regulation is not a measure of stringency but rather a measure of how the firm was impacted by the standard; it is a measure of how many facilities were believed not to clear the regulatory hurdle. However, depending upon how this measure was determined, we may still be able to estimate the model.

According to the EPA, the impact analysis which estimated the facilities impacted by the standards was not based upon information on facility technology in 1992. Rather the EPA used pre-1992 state and federal regulatory databases to identify those facilities which would not meet the proposed standard. Therefore, our measure of regulation is the number of facilities (pre-innovation) which were estimated to be impacted by the ultimate standard. Since the ultimate standard may have been endogenous to innovation, our measure of regulatory stringency is endogenous to innovation. A regression of innovation on this measure of regulation will estimate the effect on innovation of being

treated with one more pre-innovation facility which will fail to meet an *endogenously* determined regulatory standard. We use instrumental variables to estimate the effect on innovation of being treated with one more pre-innovation facility which will fail to meet an *exogenous* standard.

This description of how EPA estimated the impact of regulation begs the question: if EPA did not have information on 1992 facility technology, how was the standard endogenous to innovation? According to a member of EPA staff who was involved in setting the standards, any new compliance technology would not affect EPA regulatory choice, implying that firms did not have an incentive to demonstrate compliance so as to ratchet up the standard.³⁰ However, this is not consistent with the language of the CAAA legislation which instructed the EPA to use an open rule-making process which consisted of collecting information from the facilities. At least one facility which I contacted did consult with the EPA in the commenting process.³¹ Nevertheless, it is unclear whether firm innovation actually affected the standard. In the following empirical analysis, I will work under the assumption that innovation in 1991 did affect the standards promulgated in 1992. However, it is noteworthy that firms may have used innovation strategically as long as they *believed* that innovation would ratchet up the standard.

We estimate a simple linear model for equation (7) to test for the endogeneity of the final regulatory outcome: the number of pre-innovation facilities owned by the parent firm which were subjected to the HON standards. Our linear model takes the form:

$$I_{it} = x_{it+1}^P \beta + W_{it} \gamma + u_{it} \quad (8)$$

where

$$x_{it+1}^P = \text{predicted regulation} = f_2(\cdot) = I_{it} \delta + \sum_{j \neq i} I_{jt} \psi + Z_{it} \lambda = x_{it+1}^* - \epsilon_{it} \quad (9)$$

As discussed previously, a measurement error problem is built into our measure of regulatory stringency. We would like to observe x_{it+1}^P which is the firm's *expectation* of the number of pre-innovation

³⁰ Personal communication, Jan Meyer, 4/30/1999.

³¹ Personal communication, Bruce Barbre, Exxon, Baton Rouge, LA, 3/1999.

facilities subject to the (endogenous) regulatory standard. However, we observe an *EPA estimate* of the number of pre-innovation facilities subject to the standard. Our variable differs from the desired variable by two factors: (1) firm error in forecasting the regulator's best response, and (2) EPA error in assessing whether a pre-innovation facility is impacted. Therefore, least squares using our observed measure of regulatory stringency will not yield consistent estimates of β . However, we can use another estimator for β which is consistent under the built in measurement error but inconsistent under endogeneity. Define

$$Y \equiv [L_t]$$

$$\tilde{X} \equiv [\underline{x}_{t+1}^* \quad \underline{W}_t] = [\underline{x}_{t+1}^P \quad \underline{W}_t] + [\underline{\epsilon}_t \quad \underline{0}]$$

$$\phi \equiv \begin{bmatrix} \beta \\ \gamma \end{bmatrix}$$

$$\hat{\Omega}_\epsilon \equiv \begin{bmatrix} \hat{\sigma}_\epsilon^2 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & & 0 \end{bmatrix}$$

where $\hat{\sigma}_\epsilon^2$ is a consistent estimator for the measurement error. The model is: $Y = [\underline{x}_{t+1}^P \quad \underline{W}_t] \phi + \underline{u}$.

Assume that the measurement error is independent of the unobserved determinants of innovation ($E[\epsilon_i u_i] = 0$). One can verify that the following estimator is consistent for ϕ under exogenous regulation ($E[x_{it+1}^* u_i] = 0$):

$$\hat{\phi}^{ME} \equiv (\tilde{X}' \tilde{X} - N \hat{\Omega}_\epsilon)^{-1} \tilde{X}' Y$$

However, this estimator is not consistent under endogeneity.

As a baseline, we estimate equation (8) using GLS ignoring the built in measurement error and replacing predicted regulation with actual regulation. This would be our model if there were no uncertainty to the firm of the regulator's best response function and the EPA had accurate pre-

innovation data on the pollution-abatement technology of the facilities. As exogenous determinants of innovation, we include in the model measures of firm size (sales, employees), financial status (cash, current assets, current and long-term debt), competition in the output market (4 digit HHI), and an indicator of any innovation in the past 5 years.³² This dummy for previous innovation is intended to capture whether firms which innovate are fundamentally (and unobservably) different from those which do not.^{33, 34} Results are reported in Table 3.

We find that if it owns one more (endogenously) regulated facility, a parent firm will increase R&D expenditures by 3.2%. However, a 95% confidence interval contains the origin suggesting little statistical evidence that (endogenous) regulation has a net effect on innovation. To complete the story, conditioning on whether the firm has performed any innovation in the previous 5 years, a firm is likely to innovate more if it has more cash, current assets, employment, and current and long-term debt, less sales, and operates in a less concentrated industry. Many of these firm characteristics are not statistically significant at standard testing levels but we believe this is due to high explanatory power of whether the firm is 'an innovator' ($EVERRND=1$). Bear in mind that the OLS estimator is inconsistent due to the potential endogeneity and built in measurement error.

Next, we estimate the effect of (exogenous) regulation on innovation by instrumenting for our regulation variable with determinants of regulation which are also not unobservable determinants of innovation. Our IV estimation results are shown in Table 3. The parameter estimates are very similar except for the parameter estimate on regulation ($HONFACS$) which rises fairly substantially. These results would suggest that owning one more facility which is (exogenously) regulated will cause a firm to increase R&D expenditures by 16.8%. The standard error is slightly larger than under OLS however this parameter estimate is statistically different from zero at the 7 percent level.

For the moment let us assume that there is no error in the measurement of regulatory stringency

³²The exogeneity of other firm characteristics may be problematic if a firm jointly determines inputs, output, and research and development.

³³Blundell, et. al [1]

³⁴For example, it may be that 'dirty' industries are low growth industries which simply do not perform much innovation.

(e.g. firms know the regulator’s best response function with certainty and the EPA correctly measures the impact of the standard on facilities). In order to test for endogeneity of regulation, we compare our parameter estimates under OLS and IV. As discussed previously, we view OLS as estimating the effect on innovation of a firm being ‘treated’ with regulation which is (possibly) endogenous to firm behavior. Alternatively, IV will estimate the effect of being ‘treated’ with exogenous regulation. Statistically different parameter estimates would suggest that firms respond differently when they believe regulation is malleable. Our Hausman test results reported in Table 3 provide strong evidence that the parameter estimates are statistically different under OLS and IV.³⁵ Firms innovate more when treated with exogenous rather than endogenous regulation. This result is not only statistically significant but also economically significant: one more endogenously regulated facility will lead a firm to innovate only 3.2% more while an exogenously regulated firm will lead to 16.8% more innovation. This result would be consistent with a firm strategically suppressing innovation to force the regulator to back down on regulation.

We have found evidence that regulation is endogenous to firm behavior. However, one must be cautious in interpreting a Hausman test as evidence of endogeneity. This evidence relies heavily on our instrumental variable estimation ‘creating’ the desired natural experiment of observing firms treated with both endogenous and exogenous regulation. Fortunately, since our model is overidentified, we can formally test whether the conditions for IV to yield consistent estimates are satisfied. Under the null of the model being correctly specified and the instruments being valid, the test statistic $teststat = 4.75$ is distributed $\chi^2(4)$ so we clearly fail to reject.³⁶ Our test of overidentifying restrictions suggests that we have valid instruments to test for the endogeneity of regulation.

Now we will take up the issue of measurement error in our regulatory stringency variable. Under uncertainty we can use $\hat{\phi}^{ME}$ to estimate the average treatment effect of endogenous regulation. We require an estimate of the measurement error σ_ϵ^2 (the variable of the firm forecast error and EPA

³⁵In order to investigate if the apparent endogeneity is a result of functional form, we allow regulation and the instruments to all enter as quadratics but still reject that the OLS and IV parameter estimates are equal.

³⁶This test statistic has a mean of 4 under the null hypothesis and the upper tail area corresponding to our test statistic is 0.314.

measurement error). We do not believe we have any credible way to consistently estimate the firm forecast error. Therefore, we calculate $\hat{\phi}^{ME}$ for various values of σ_ϵ^2 . The results are depicted in Figure 6.

The upward sloping line is the estimated regulation parameter for various values of the firm forecast error (SIGEPS). As a basis for comparison, the bottom horizontal line is the OLS parameter estimate and the top horizontal line is the IV parameter estimate. We compare these $\hat{\phi}^{ME}$ estimates (which are inconsistent under endogeneity) to the instrumental variables estimate which is consistent under both uncertainty and endogeneity. Statistically different coefficient estimates will be interpreted as evidence of endogeneity. I have not developed the Hausman-like test statistics yet³⁷, but we will expect to reject for sufficiently low values of σ_ϵ^2 .³⁸ These results suggest that if firm expectations of the number of regulated facilities are accurately estimated by the EPA's estimate of the impact of standards, we can reject exogeneity of regulation.

This empirical analysis finds evidence of some form of endogeneity between the innovation of chemical manufacturers and regulation under the 1990 Clean Air Act Amendments. Although the results are very speculative, I believe that this evidence is sufficiently strong to suggest that regulation should not necessarily be treated as exogenous in either empirical or theoretical models. If she is particularly concerned with consistency, then the researcher may conclude from this result that empirical studies on the effects of regulation should allow for the possibility of endogeneity.

3.3 Testing for Endogeneity Using a Continuous Treatment Measure

The above empirical analysis suggests that treating a chemical manufacturer with endogenous regulation will lead the firm to suppress innovation. The treatment variable was *binary*: least squares estimated the effect of treatment and IV estimated the effect of no treatment. In this section, I estimate a model where the treatment variable is *continuous*.

³⁷A Hausman test is complicated by the fact that even if one has the asymptotic covariance matrix of $\hat{\phi}^{ME}$, one must show that this estimator is asymptotically efficient to use the Hausman test.

³⁸Of course the Hausman test measures differences of the whole parameter vector rather than just the regulation parameter.

The theoretical model would predict that the strategic use of innovation in response to technology-forcing regulation is relatively larger in more concentrated industries. An individual firm in a more concentrated industry will have a large effect on the total industry innovation and, hence, on the amount of regulation. Therefore, concentration is a good proxy for the amount of continuous treatment of endogenous regulation a firm receives. A complication arises that concentration may act through other mechanisms to affect levels of R&D. Therefore, I employ a difference in differences estimator to tease apart the effects of endogenous regulation and other factors. I do so by analyzing the behavior of firms in the chemical manufacturing industry before and after the 1990 CAAA.

3.3.1 The Model

I assume that in 1987 no chemical manufacturing firms believed that they were to be faced with endogenous technology-forcing regulation. I assume that a firm's R&D choice was given by:

$$RND_{87i} = \alpha_{87} + \beta \cdot X_{87i} + \delta \cdot HHI_{87i} + \epsilon_{87i} \quad (10)$$

where X_{87i} is a measure of exogenous determinants of firm i 's innovation such as measures of size and financial status, and HHI_{87i} is a measure of concentration in the output market.³⁹

In 1992 after the passage of the CAAA but before promulgation of the first set of MACT standards, firms faced a similar relationship for the determination of innovation. However, now some chemical firms were also faced with treatment of endogenous regulation. Each firm in the chemical manufacturing industry faced the possibility of regulation, however the extent to which that regulation was endogenous varied by firm. Firms in more concentrated output markets had more effect on the regulatory outcome through pollution-control innovation than firms in less concentrated markets. Therefore, I will use market concentration as a proxy for the amount of (continuous) 'treatment' of endogenous technology-forcing regulation. These assumptions suggest the following functional form of the 1992 choice of R&D expenditures:

$$RND_{92i} = \alpha_{92} + \beta \cdot X_{92i} + \delta \cdot HHI_{92i} + \theta \cdot HHI_{92i} + \epsilon_{92i} \quad (11)$$

³⁹As with the previous model, the exogeneity of other firm characteristics may be problematic if a firm jointly determines inputs, output, and research and development.

We wish to identify the (selected) average treatment effect parameter θ . In particular, the sign of θ will tell us the effect on innovation of firms being treated with endogenous regulation. If the parameter is significantly different from zero, we might conclude that firms do use innovation strategically while the sign of θ will provide evidence as to which of the strategic effects dominates.

Subtracting equation (5) from equation (6) we obtain:

$$\Delta RND_i = (\alpha_{92} - \alpha_{87}) + \beta \cdot \Delta X_i + \theta \cdot HHI_{92i} + \delta \cdot \Delta HHI_i + \Delta \epsilon_i \quad (12)$$

We see that by using a panel of firm characteristics spanning the time of the CAAA, we can estimate equation (12) and identify the selected average treatment effect of endogenous regulation θ .⁴⁰

3.3.2 Data

Our data for this test is from COMPUSTAT and the Census of Manufacturers. Concentration is measured by HHI as reported by the Census of Manufacturers in 1987 and 1992. Census reports concentration at the 4 digit level. Since some SIC=28 firms in COMPUSTAT only report 2 or 3 digit SIC, we calculate more aggregate concentration measures as the simple average of the more disaggregate measures reported in the Census of Manufacturers. The remaining measures of firm size and financial status come from the appropriate variables in COMPUSTAT's Primary-Supplementary-Tertiary, Full Coverage, and Research files.

3.3.3 Results

Using measures of firm size and financial status as the exogenous regressors, we estimate equation (12) by GLS. In addition, we include an indicator of whether the firm invested in research and development in either 1987 or 1992 in order to capture unobserved determinants of whether firms innovate.⁴¹ Results can be found in Table 4.

We find that θ is negative and statistically different from zero at the 10 percent level. Although this parameter estimate is not significant at a very low testing level, this finding is not necessarily

⁴⁰Note that this specification allows for other effects of concentration to affect R&D in levels but not in differences. Any (unmeasured) effect of concentration on *differences* will be attributed to endogenous regulation.

⁴¹The results are not sensitive to excluding this variable.

weak evidence of strategic behavior since the two strategic effects could be working against one another. Firms in more concentrated industries increase innovation less than firms in less concentrated industries. The negative sign on the θ parameter suggests that firms faced with endogenous technology-forcing regulation will suppress innovation relative to those firms faced with exogenous regulation. This finding is consistent with the IV results which also suggest that firms faced with endogenous regulation suppress innovation relative to exogenous regulation.

4 Conclusions

This paper investigates whether firms in an oligopoly setting use innovation strategically to affect the amount of regulation they face. The model distinguishes between five different incentives and disincentives to innovate and establishes that, in general, firms faced with endogenous regulation may innovate more or less than “regulation-takers”. Further work could investigate which regulatory and industry settings are more likely to have heightened and dampened incentives, and study the welfare consequences. Such an analysis would help us understand when “rules are better than discretion” and provide policy guidance as to where to create or remove commitment mechanisms in regulatory institutions.

Our empirical analysis of chemical manufacturers subject to the 1990 Clean Air Act Amendments finds evidence of endogeneity and tends to suggest these firms suppress innovation due to the endogeneity. A better measure of regulatory stringency would improve the strength of the evidence. This estimation also could be strengthened by better data. I would like data on the “height of the regulatory hurdle” rather than EPA estimates of “firms not clearing the hurdle.” Data on pollution abatement R&D rather than aggregate R&D might allow me to tease out very subtle innovation effects from aggregate R&D data. Other possibilities include assembling a panel of TRI-COMPUSTAT data linked with plant level input/output data from the LRD. Finally, future research might explore other examples of technology-forcing regulation such as CFC regulation under the Montreal Protocol, reformulated gasoline, energy efficiency standards in appliances, and the CAFE standards.

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Table 1: Equilibrium Outcomes for the Numerical Example

	Firms MARKUP Innovation*		Firms MARKDOWN Innovation**	
	Exogenous	Endogenous	Exogenous	Endogenous
Firm 1 Innov	0.10	0.18	0.22	0.16
Firm 2 Innov	0.14	0.20	0.22	0.16
Regulation	0.10	0.20	0.44	0.39
Welfare [†]	0.192	0.191	0.221	0.217
Prod Surplus	0.210	0.187	0.162	0.174
CS-EC	-0.018	0.004	0.059	0.043

Common parameter values for two examples: $\lambda = .09$ $\beta = .35$ $\eta = .00$ $\phi = .25$ $\gamma = .40$ $\delta = .80$ Only α and σ differ.

* α differs by firm: $\alpha_1 = 0.35$ $\alpha_2 = 0.55$ $\sigma = 0.00$.

** $\alpha_1 = \alpha_2 = 0.35$ $\sigma = 0.20$.

† For comparison, we can compare the equilibrium levels of welfare to the social planner's solution and the case of no regulation or innovation. Under both sets of parameter assumptions, the non-regulated (status quo) welfare $W^{SQ} = 0.178$. In the first case of marking up innovation, the social planner's solution yields welfare $W^{SP} = 0.193$. In the second case, $W^{SP} = 0.221$

Table 2: Descriptive Statistics

Variable	Description	Mean	Standard Deviation
T3FAC	T3 facilities contributing to parent	5.39	7.13
CHEMXFAC	facilities*Title III chems for parent	26.79	47.30
T3AIRREL	Lbs fug/stack air rel by parents plants	1049970.70	3590887.81
T3RELTRA	Lbs rel/trans TIII chems by par plants	2394244.24	14259158.50
HONFACS	facilities s.t. HON regulation	0.77	2.15
HONAIRT3	Lbs air rel T3 by HON plants of parent	419027.24	1911040.38
HONTOTT3	Lbs rel/trans T3 by HON plants of par	980946.36	5370903.37
POTENCY	Carcino potency of plants emiss NB: :=0	46.42	187.02
TOXICITY	Chron toxicity of plants emiss NB: :=0	114.64	188.77
CURRASST	Current Assets - Total (MM,100MM)	1340.49	2199.47
LTDEBT	Long-Term Debt - Total (MM,100MM)	714.53	1365.21
EMPLOY	Employees (M,M)	19.92	31.04
CURRDEBT	Debt in Current Liabilities (MM,100MM)	257.61	560.56
RND	RandD Expense(MM,1...)	132.76	289.59
EVERRND	Any Innovation in Past 5 Years?	0.86	0.35
SALESR	Sales (Restated) (MM,100MM)	3928.19	7341.61
CASH	Cash (MM,100MM)	148.76	308.90
RND5YRAV	Constant Dollar RandD Expense(MM,1...)	96.16	211.94
HHI1992	HHI - 4 digit SIC - 1992 Census of Manu	729.18	684.26
PARHON	Any HON facilities owned by parent	0.24	0.43

Table 3: Investment Equation

Dependent Variable: LNRND		
Variable	GLS	IV
HONFACS	.0320 (.0614)	.1684 (.0830)
CONSTANT	-4.5408 (1.419)	-3.9947 (1.4621)
HHI1992	-.0003 (.0002)	-.0003 (.0002)
LNSALES	-.7551 (.3537)	-.7971 (.3607)
LNCURASS	1.1275 (.4289)	1.0838 (.4373)
LNEMPLOY	.2200 (.2671)	.3022 (.2741)
LNLTDEBT	.0919 (.1015)	.0553 (.1044)
LNCURDBT	.0854 (.0790)	.0725 (.0806)
LNCASH	.1623 (.1145)	.1692 (.1167)
EVERRND	4.5971 (.3570)	4.5565 (.3641)
R^2	.785	.777

Standard errors in parentheses

Hausman Test on OLS vs. IV: Test Statistic=16.79, $\chi^2(4)$ Upper tail area: .002

Overidentification Test: Test Statistic=4.75, $\chi^2(4)$ Upper tail area: .314

Table 4: Difference in Differences Estimator

Dependent Variable: Δ RND	
Variable	GLS
CONSTANT	8.121 (11.077)
INNOVATOR?	5.971 (7.794)
HHI1992	-.020 (.012)
Δ HHI	.034 (.024)
Δ EMPLOY	-5.880 (4.796)
Δ SALES	.075 (.025)
Δ CASH	-.073 (.198)
Δ CURAST	.093 (.073)
Δ CURDBT	-.157 (.115)
Δ LTDBT	-.0154 (.032)
R^2	.613

N = 136

Standard errors in parentheses

FIGURE 1

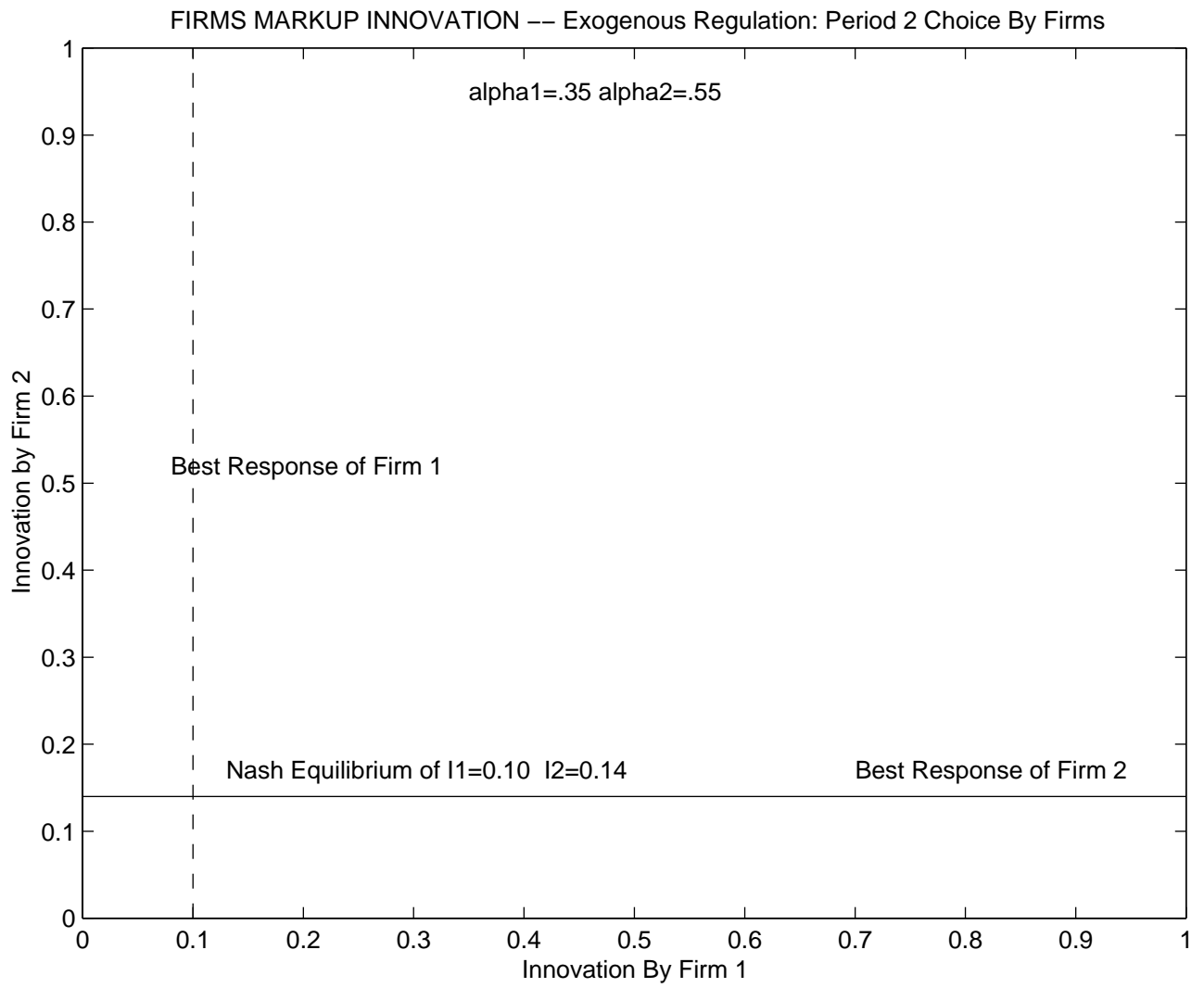


FIGURE 2

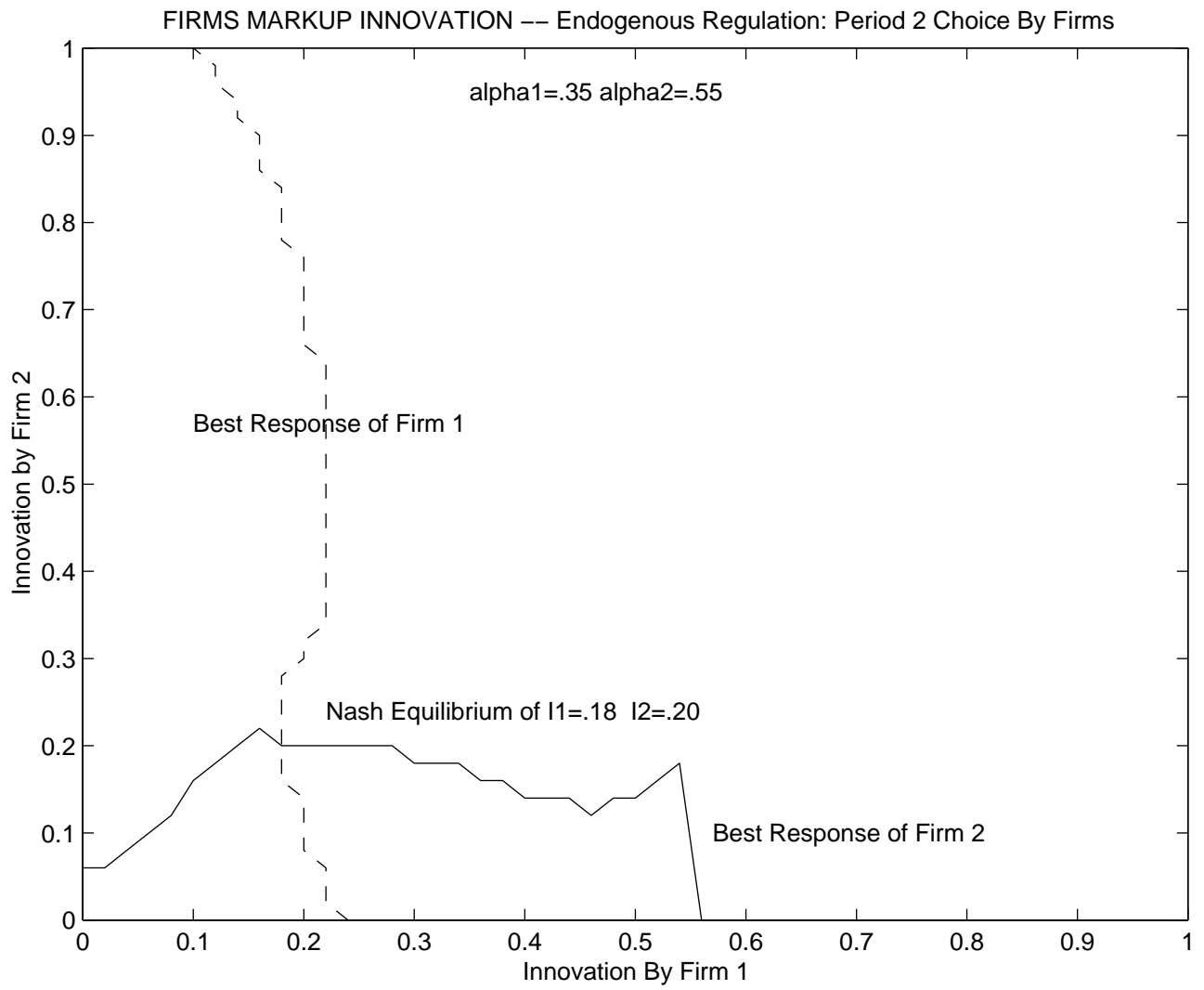


FIGURE 3

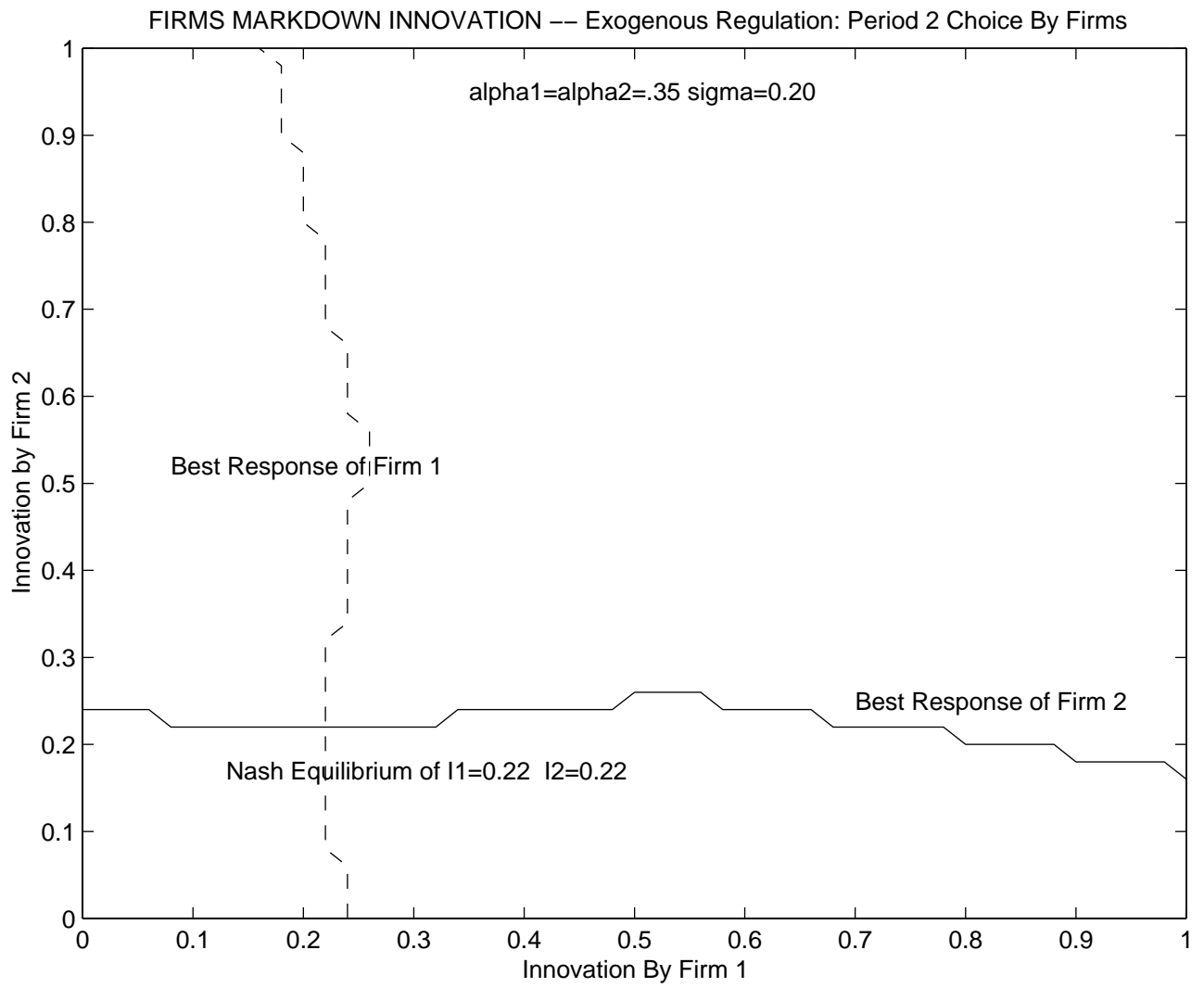


FIGURE 4

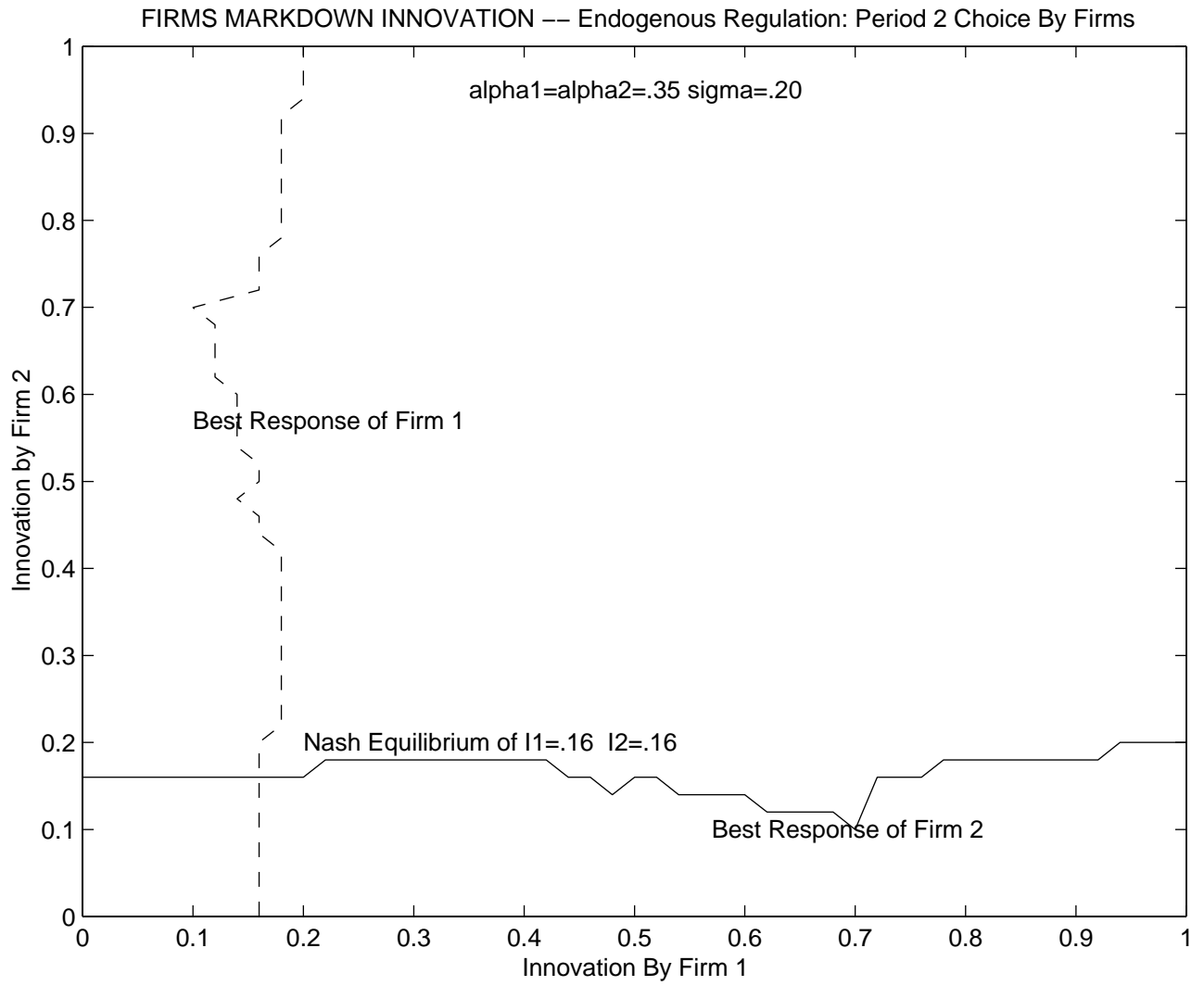


FIGURE 5

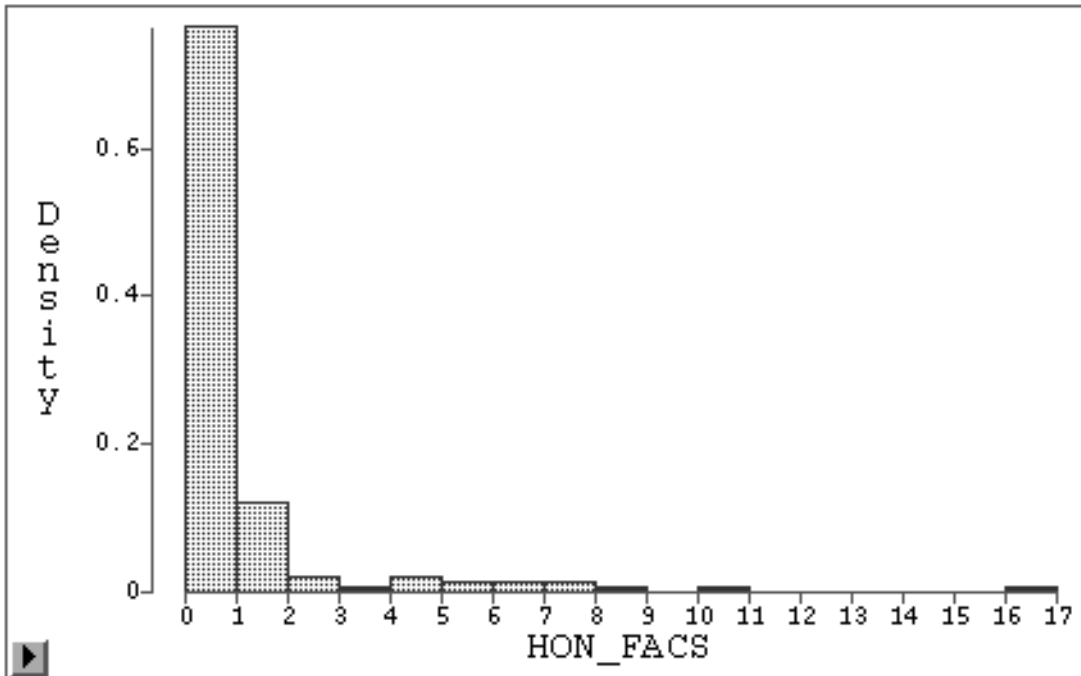
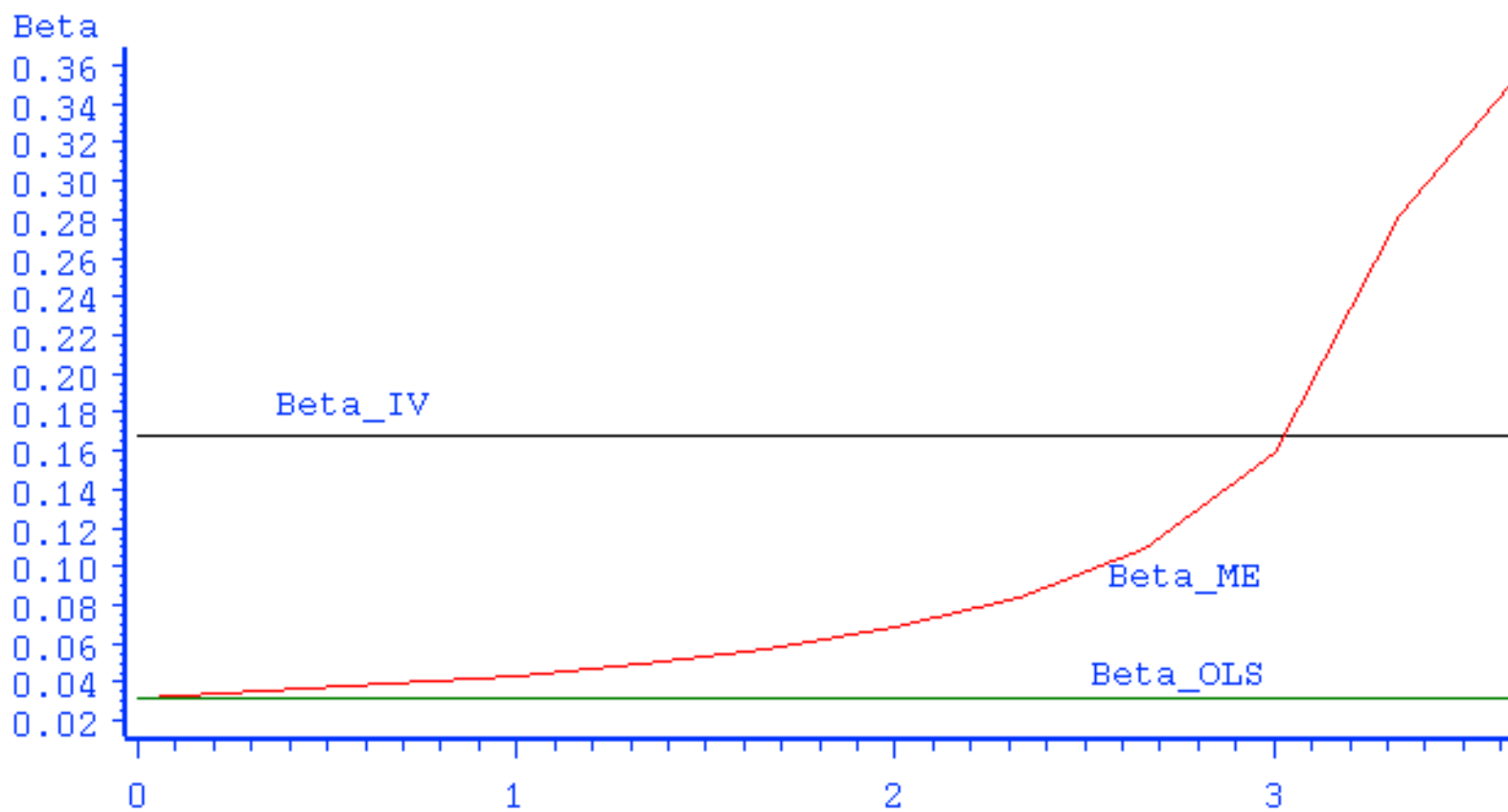


FIGURE 6



APPENDIX

Sufficient Conditions For Regulation To Be Weaking Increasing In Innovation For The Symmetric Equilibrium Case

Holding the nature of competition (θ) constant, we can write welfare as a function of technology \mathbf{T} and regulation x : $W(\mathbf{T}, x)$ where we do not index by firm since we focus on symmetric equilibria. Accordingly, we can write: ⁴²

$$W(\mathbf{T}, x) = \omega_1 \cdot CS(\mathbf{T}, x) + \omega_2 \cdot \Pi(\mathbf{T}, x) + (1 - \omega_1 - \omega_2) \cdot EC(\mathbf{T}, x)$$

Assuming differentiability, if $W_{x\mathbf{T}} \geq 0$, then $W(\mathbf{T}, x)$ is supermodular and Topkis' Monotonicity Theorem says that $x^*(\cdot)$ is weakly increasing in technology. I make assumptions about the signs of the cross-partials of each of the components of welfare: $CS_{x\mathbf{T}} \geq 0$ and $EC_{x\mathbf{T}} = 0$. $CS_{x\mathbf{T}} \geq 0$ says that for higher levels of technology, an increase in regulation will have a lower (negative) impact on marginal cost and thus reduce quantity and CS by less.⁴³ $\pi_{x\mathbf{T}} \geq 0$ says that for higher levels of technology, an increase in regulation will have a smaller (negative) impact on marginal cost and therefore π . Since $R_{Ix}(\cdot) = 0$, $\Pi_{x\mathbf{T}} \geq 0$. Finally, $EC_{x\mathbf{T}} = 0$ says that externality costs are only a function of the regulatory standard and the amount of output, and do not directly depend upon technology.⁴⁴ Using these three assumptions about the signs of the cross-partials and the fact that a linear combination of supermodular functions is supermodular, $W(\mathbf{T}, x)$ is supermodular. By Topkis' Monotonicity Theorem, $x^*(\cdot)$ is weakly increasing in technology.

⁴²Economists differ on how much policymakers actually value these three components. Although the pure welfare economist would value all costs and benefits equally, some argue that the regulator is 'captured' by the industry while others believe that consumers are the major concern. In order to make the model robust to political economy considerations, I add parameters for the relative weights of each components of the objective function.

⁴³For example, this would be satisfied under Cournot competition with marginal cost a second order polynomial of x and I : $c = \tilde{c} + \alpha \cdot x + \lambda \cdot x^2 - \beta \cdot I - \eta \cdot I^2 - \phi \cdot x \cdot I$.

⁴⁴For example, we could specify $EC = \gamma \cdot (1 - x) \cdot Q$ where x is the fraction of external costs which must be eliminated per unit of the good.