Demand-enhancing Innovation

Mika Kato*

Abstract

This paper studies a patent-protected monopolist's optimal innovation problem when its spending on product/quality innovation raises the scale of demand for its product or service. By reducing a monopolist's incentive to innovate, regulation of the firm's price in such a market may reduce consumer welfare in the long run. To study the implied policy tradeoff between static and dynamic consumer surplus, I introduce a simple form of price regulation where a regulator allows a fixed markup over marginal cost. I find that the consumer-welfare-maximizing markup is non-zero and dependent on market-specific parameters. Price regulation is beneficial to consumers only in markets where the existing innovations become obsolete relatively slowly. In other markets regulation will in the long run be harmful.

JEL codes: L12, L21, L22, L41 & L51

Keywords: monopoly, market power, optimal regulation, product/quality innovation, obsolescence of innovations, consumer welfare

1 Introduction

In an R&D-intensive market, a patent-protected firm will generally try to generate new or improved versions of the product, thereby enhancing the demand for its product. If the firm does not innovate, its product will lose value relative to other products and demand will fall. The firm will, in other words, wish to innovate even if it has no effective competitors. Price regulation in such an environment may raise consumer welfare temporarily but in the long run, it may harm consumer welfare by reducing innovative activity. The net effect of price regulation will thus be positive or negative depending on the nature of market.

One of the most relevant markets is pharmaceuticals where monopoly power can legally derive from a patent granted to a firm. Pharmaceutical markets in almost all European countries are subject to some form of price regulation that aims to control medical expenditures. However, the way the price cap is set appears to have

*Department of Economics, Howard University, 2400 6th St., N.W., Academic Support Building B, Rm. 319, Washington, DC 20059; (202)806-6774; (202)806-4896 (fax); mkato@howard.edu.

little basis on rigorous economic reasoning. For example, in Greece, Ireland, Italy, Netherlands, and Portugal, pharmaceutical price control is based on average or lowest price of the same product in a set of countries (Kanavos, 2001).

By contrast to European practice, prices of pharmaceutical products in the U.S. are not regulated. This is due mainly to concerns about the negative impact that such regulation may have on innovation. There have been discussions of the possible dynamic impact of the price regulation on incentives for innovation of new drugs. Studies suggest that price regulation has a negative impact on R&D spending and on both the extent and the timing of the launch of new drugs (Giaccotto, Santerre and Vernon, 2005; Vernon, 2005; Kyle, 2007; Golec and Vernon, 2010).

According to the study by Squires and Anderson (2015), among 13 high-income countries, the United States spends the most per capita on health care. This is not due to more frequent doctor visits or hospital admissions but rather due to a greater use of medical technology and higher health-care prices. There has been an increasing policy debate as to whether the U.S. should implement price regulation of pharmaceutical products. A theoretically grounded level of price regulation that maximizes public welfare should recognize the dynamic trade-off effect between the pharmaceutical product prices and innovation. Understanding the precise nature of this trade-off requires a dynamic model. My model shows that in general, there exists a welfare-maximizing level of price for each market.

The model in this paper focuses on a monopolist's innovation incentives in an infinite-horizon dynamic setting with perfect capital markets. I study a monopolist's innovation decision in a situation in which its innovation spending raises demand for its product or service. I first show that it is optimal for the firm to innovate faster and to charge a smaller markup in a market in which the value of its existing innovations erodes more quickly.

Into this market I then introduce price regulation, and study its effect on consumer welfare in the short and the long run. When a regulator attempts to hold the monopolist's price closer to its competitive level, the effect on consumer welfare is twofold. The resulting price-reduction raises consumer welfare in the short run but it also reduces the firm's incentive to innovate, and this leads it to create fewer new products and services in the long run. And since fewer new products are created, the value of the monopolist's existing product gradually declines. Price regulation may therefore harm consumer welfare in the long run.

Price regulation in my model takes a simple form – a regulator places a cap on the markup over cost so as to maximize the present value of consumer welfare. I derive the consumer-welfare-maximizing markup which is positive and which depends on market-specific parameters. I then show that in a market where existing innovations become obsolete sufficiently slowly, the benefit of price regulation exceeds its harmful effects. On the other hand, in a market where existing innovations become obsolete more quickly, the harm outweighs the benefit.

There exists a threshold obsolescence rate at which the cost and benefit of price-cap regulation are equal. This implies that price-cap regulation is beneficial only for a market that has an obsolescence rate smaller than this threshold rate. I derive this rate explicitly. For obsolescence rates above this cutoff rate, regulation is harmful.

I then analyze how these results may change when shareholders' welfare is also taken into account. One would conjecture in that case that even less regulation should be optimal. I show analytically that the aggregate-welfare-maximizing markup is always greater than the markup that maximizes consumer welfare alone.

In an appendix, I study an imperfect capital market. This raises the possibility of a second harmful effect of price regulation, namely that of depriving the firm of the funds it needs to finance its innovative activity. That is, I study a firm's innovative activity when its innovation is constrained by its internal funds. In this case, regulation slows down or even reduces the firm's access to internal funds and, hence, its ability to finance its innovative activity. This effect only compounds the results obtained in the body of the paper. The results therefore hold regardless of whether capital markets are perfect or not.

The rest of the paper is organized as follows. After a brief description of what this paper contributes to the literature, Section 2 introduces the monopolist's innovation problem. Section 3 discusses the effect of price-cap regulation on the firm's innovative activity and consumer welfare. Section 4 studies optimal price-cap regulation for different markets. Section 5 shows some empirical support of the model's propositions. Section 6 discusses possible extensions of the present analysis. Section 7 concludes the paper. Some proofs, data tables and additional results are in Appendixes.

Contribution to the literature

My paper relates to Cabral and Riordan (1989) who provide a three-stage model of a monopolist's optimal investment in cost-of-production reduction under price-cap regulation. They show that price-cap regulation promotes better incentives for cost reduction than does rate-of -return regulation as long as the cap is not too low. When the cap is too low, the firm's incentive for cost reduction is destroyed. It relates also to Clemenz (1991) who extends Cabral and Riordan (1989)'s model to study the welfare-maximizing price cap; Clemenz confirms Cabral and Riordan's main results but he also shows that price-cap regulation achieves a higher consumer surplus than rate-of-return regulation.

My paper also studies the effect of price-cap regulation on the incentive to innovate and it too derives the optimal price cap in a dynamic setting. It differs, however, from their papers in three important ways.

- First, it studies a monopolist's incentives for *product* or *quality innovation* (which is 'demand-enhancing'), and not process innovation (which is cost-reducing). Schmookler (1966) had stressed the causality from demand to innovation, whereas I introduce a second, reverse channel: Innovation raises demand.

- Second, its results concerning welfare are different; in particular they revolve around the rate of obsolescence of innovations and therefore have implications for how market characteristics such as product turnover should affect the optimal price regulation.

- Third, the paper offers an infinite-horizon model whereas Cabral and Riordan and Clemenz have three-stage models. My argument requires a multi-period treatment because obsolescence takes time.

My model also explains some recent findings that price-cap regulation may incentivize the monopolist to raise the quality of its products. Because my model focuses on demand enhancement, it captures the monopolist's incentive to raise quality so as to raise the demand for its product and raise its profit in spite of the price cap. This is in contrast to the arguments of Armstrong, Cowan and Vickers (1994) and Kwoka (2009) who argue that a firm may respond to price-cap regulation by lowering its investment in product quality. However, Banerjee (2003) finds from data of the U.S. telecom retail industry that price-cap regulation had a positive effect on quality, which supports the quality-enhancement effect that my model captures.

2 The model

Consider a patent-protected monopolist which engages in production and innovation in a perfect capital market. Assume that the firm faces a linear downward-sloping demand curve,

$$q_t = d_t - \varepsilon p_t, \tag{1}$$

where q_t is the production and p_t is the product price. The intercept, d_t, represents the scale of demand of the monopolist's market and $\varepsilon > 0$.

Assume that product innovation, x_t, increases d_t where $x_t \geq 0$ and that the initial scale of demand is given at $d_0 \geq 0$. The existing innovations are assumed to become obsolete at a rate, δ, and therefore d_t also falls at δ with no innovation effort. That is,

$$\dot{d}_t = x_t - \delta d_t. \tag{2}$$

The cost of innovation is the sum of its direct cost, x_t, and the convex adjustment cost, $\varphi(x_t)$ with properties $\varphi'(\cdot) > 0$, $\varphi(0) = \varphi'(0) = 0$, and $\varphi''(\cdot) > 0$. When a unit production cost is constant, c, the firm's cash flow at time t is

$$(p_t - c)\, q_t - x_t - \varphi(x_t). \tag{3}$$

The monopolist's price-setting rule is $(d_t - \varepsilon p_t) - \varepsilon (p_t - c) = 0$ or more explicitly, the monopoly price, p^m, is

$$p^m(d_t) = \frac{d_t + \varepsilon c}{2\varepsilon}. \tag{4}$$

Then the firm's gross profit, π, can be expressed as a function of d_t only. That is,

$$\pi\left(d_t\right) \equiv \left(p^m\left(d_t\right) - c\right)\left\{d_t - \varepsilon p^m\left(d_t\right)\right\}. \tag{5}$$

From eq. (5), we find that the marginal profit is nonnegative,

$$\pi'\left(d_t\right) = \frac{d_t - \varepsilon c}{2\varepsilon} \geq 0, \tag{6}$$

for any $q_t = d_t - \varepsilon p_t \geq 0$ and $p_t \geq c$. The second derivative of eq. (5) is

$$\pi''\left(d_t\right) = \frac{1}{2\varepsilon} > 0. \tag{7}$$

That is, $\pi\left(\cdot\right)$ has increasing returns to scale.

The monopolist's problem is to maximize its present value, V,

$$\max_{x_t \geq 0} V\left(d_t, x_t\right) = \int_0^\infty \left\{\pi\left(d_t\right) - x_t - \varphi\left(x_t\right)\right\} e^{-rt} dt, \tag{8}$$

subject to eq. (2), where r is the discount rate.[1]

To solve this problem, we define the current-value Hamiltonian function, H_t, at time t as

$$\begin{aligned} H_t\left(d_t, x_t\right) \equiv\ & \pi\left(d_t\right) - x_t - \varphi\left(x_t\right) \\ & + \gamma_t\left(x_t - \delta d_t\right), \end{aligned} \tag{9}$$

where γ_t is the costate variable associated with d_t.

Then the optimal innovation, x_t, must satisfy

$$1 + \varphi'\left(x_t\right) = \gamma_t, \tag{10}$$

for all t. The condition simply states that the marginal benefit from a unit of investment, i.e., the right side of eq. (10), must be equal to its marginal cost, i.e., the left side of eq. (10).

The law of motion of γ_t is

$$\dot{\gamma}_t = \left(r + \delta\right)\gamma_t - \pi'\left(d_t\right). \tag{11}$$

Differentiating eq. (10) with respect to time and equating it and eq. (11) yields the law of motion of x_t,

$$\dot{x}_t = \frac{1}{\varphi''\left(x_t\right)}\left[\left(r + \delta\right)\left\{1 + \varphi'\left(x_t\right)\right\} - \pi'\left(d_t\right)\right]. \tag{12}$$

Finally, we impose the transversality condition,

$$\lim_{t \to \infty} \gamma_t e^{-rt} = 0. \tag{13}$$

[1] When a patent expires in T years, monopoly profit π is guaranteed only for $t \in [0, T]$ but not for $t \in (T, \infty)$. For mathematical convenience, I assume that T is sufficiently 'large' such that the solution will be close to the solution for $T \to \infty$. In most patent laws, the term of patent is 20 years with a possible extension.

The optimal innovation strategy

The monopolist's optimal innovation strategy, if it exists, must satisfy the two laws of motion, eqs. (2) and (12), and the transversality condition, eq. (13). An optimal innovation strategy exists if the steady state is a stable saddle point.

Let x^* and d^* be the steady-state values that solve $\dot{x}_t = \dot{d}_t = 0$. That is x^* and d^* satisfy

$$(r+\delta)\{1+\varphi'(x^*)\} = \pi'(d^*), \tag{14}$$

and

$$x^* = \delta d^*. \tag{15}$$

Evaluating the Jacobian matrix, J, in the steady state,

$$J_{x_t=x^*,d_t=d^*} = \begin{bmatrix} r+\delta & -\frac{\pi''(d^*)}{\varphi''(x^*)} \\ 1 & -\delta \end{bmatrix}, \tag{16}$$

where $Tr J_{x_t=x^*,d_t=d^*} = r > 0$, we know that the steady state is a saddle stable point if

$$\det J_{x_t=x^*,d_t=d^*} = -\delta(r+\delta) + \frac{\pi''(d^*)}{\varphi''(x^*)} < 0. \tag{17}$$

Since $\pi'' = (2\varepsilon)^{-1} > 0$ from eq. (7), eq. (17) states that the firm's optimal innovation strategy exists if

$$\varphi''(x^*) > \frac{1}{2\varepsilon\delta(r+\delta)}. \tag{18}$$

I assume that eq. (18) is satisfied.

Numerical examples

Of the parameters that affect the monopolist's innovative activity, the obsolescence rate, δ, of existing innovations probably varies over markets the most. The parameter δ may capture depreciation of the value of existing products and services. For example, δ can be measured by patent renewal rates (Pakes and Simpson, 1989; Schankerman, 1998), R&D capital depreciation rates (Hall, 2007), or product-price declines (Cummins and Violante, 2002) across different markets. Also, a market's δ can be large when potential competitors produce close substitute goods. In this sense, δ may also capture the degree of market's contestability discussed in Baumol (1983). Product-substitution rates can be measured by diffusion speed (Mansfield, 1968; Romeo, 1977).

When δ is large, maintaining its market size requires the monopolist to innovate faster. In the subsequent numerical examples, I study the monopolist's innovative activity in markets characterized by various δs and show that the monopolist actually does innovate faster but charges a smaller markup in a large-δ market.

Let $\varphi(\cdot)$ be

$$\varphi(x_t) = x_t^\alpha;\ \alpha > 1. \tag{19}$$

	r	ε	c	α
value	0.05	1.00	1.00	3.00

Table 1: baseline parameters

I set the baseline parameters in Table 1. These values are common to examples (i) and (ii). The obsolescence rate of the existing innovations is $\delta = .05$ in example (i) and $\delta = .10$ in example (ii). Figure 1 shows the local dynamics of these examples in the (d_t, x_t)-vector-field. The solid line shows the firm's optimal innovation strategy, i.e., the optimal x_t for a given scale of demand, d_t, of its market. The dotted lines are the demarcation curves, on which $\dot{x}_t = 0$ and $\dot{d}_t = 0$. The arrows in the vector field shows the law of motion from eqs. (2) and (12).

ex.	δ	properties
(i)	0.05	x_t is increasing in d_t; steady-state x^*/d^* is low; $p^m(d^*)$ is high; d^* is high
(ii)	0.10	x_t is increasing in d_t; steady-state x^*/d^* is high; $p^m(d^*)$ is low; d^* is low

Table 2: numerical examples

First, we find that optimal innovation, x_t, is monotonically increasing in the scale of demand, d_t (*Schmookler effect*).[2] Second, in steady states, then in a larger-δ market where innovations become obsolete more quickly, we find that a monopolist innovates faster (i.e., more innovation relative to the scale of demand, x^*/d^*), that it charges a smaller markup over production cost (i.e., lower $p^m(d^*)$), and that it achieves a smaller scale of demand, d^*. These results are summarized in Table 2.

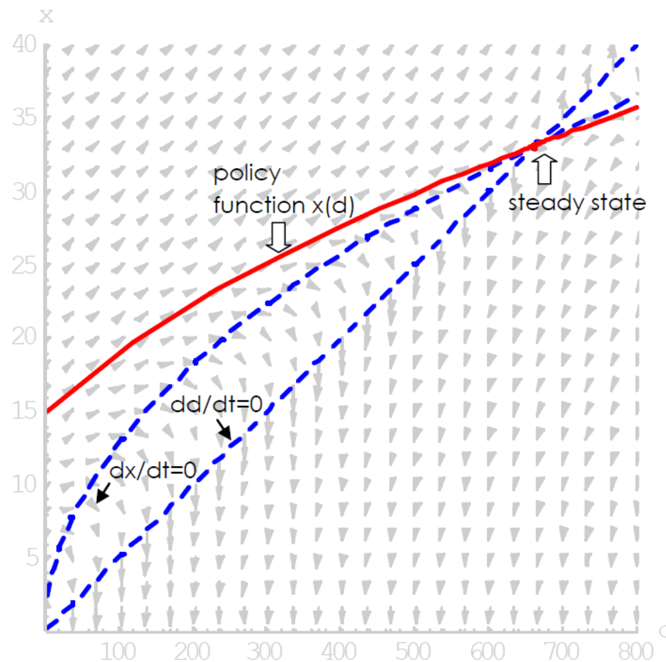
If we confine our attention to steady states, then it is easy to show the above results analytically. The following proposition deals with:

$$\begin{aligned} x^*/d^* &= \text{innovation relative to the scale of demand,} \\ \mu^m &= \text{monopoly markup,} \\ \delta &= \text{obsolescence rate of innovations,} \end{aligned}$$

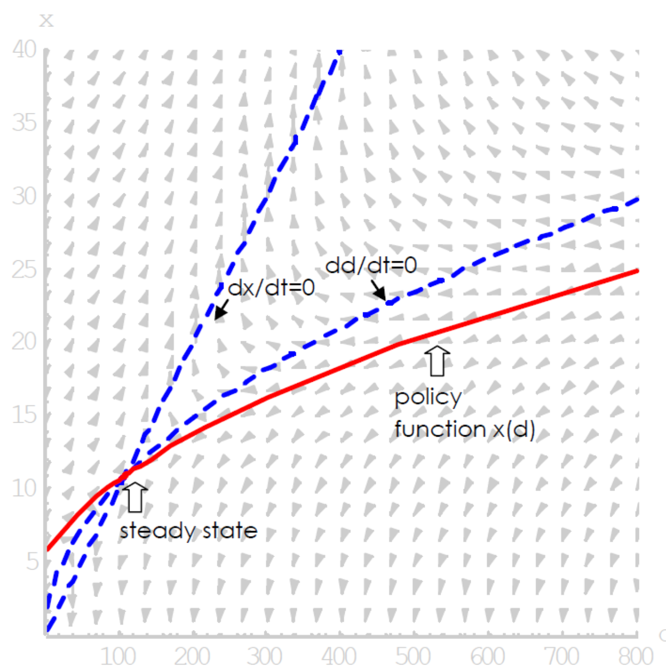
where the markup, μ^m, should satisfy $(1 + \mu^m)\, c = p^m(d^*(\delta))$.

Proposition 1 *In a larger-δ market, the monopolist's x^*/d^* is larger, and its μ^m and d^* are smaller.*

[2] Schmookler (1966) argues that inventive activity rises with market size.



(i) Demand depreciates at 5%



(ii) Demand depreciates at 10%

Figure 1: monopolist's optimal innovation in small-δ and large-δ markets

Proof. In a steady state, eqs. (14) and (15) hold. From eq. (15), obviously $\delta = x^*/d^*$. Thus,

$$\frac{\partial}{\partial \delta}\left(\frac{x^*}{d^*}\right) = 1 > 0. \tag{20}$$

From eq. (4), the steady-state monopoly price, $p^m(d_t)$, is an increasing function of d_t. Therefore, the effect of an increase in δ on μ^m is

$$\frac{\partial \mu^m}{\partial \delta} = \frac{p^{m\prime}(d^*)\left(\partial d^*/\partial \delta\right)}{c} < 0. \tag{21}$$

Note that from eqs. (14) and (15), the effect of an increase in δ on d^* is

$$\frac{\partial d^*}{\partial \delta} = -\frac{1 + \varphi'(x^*) + (r+\delta)\varphi''(x^*)\, d^*}{D} < 0, \tag{22}$$

where $D \equiv \delta(r+\delta)\varphi''(x^*) - (2\varepsilon)^{-1}$ is positive from eq. (18). ■

Figures 2 and 3 numerically illustrates Proposition 1's claim that x^*/d^* is increasing in δ and that μ^m is decreasing in δ. The simulation uses the baseline parameters shown in Table 1.

Consumer welfare in the monopoly market

When a monopolist sets the profit-maximizing price, eq. (4), the present value of consumer welfare, w, is computed as

$$w_c \equiv \frac{1}{8\varepsilon}\int_0^\infty (d_t - \varepsilon c)^2 e^{-rt} dt. \tag{23}$$

3 The effect of price regulation on innovation

In the 1980s, regulatory agencies in the United States and the United Kingdom moved away from rate-of-return regulation and towards price-cap regulation. Examples are telecommunications (British Telecom in 1984, AT&T in 1989), energy (British Gas in 1986), and transportation (British Airports Authority in 1986).[3][4] Much of the subsequent theoretical development focuses on how different forms of regulation may distort

[3] A clarification on the terminology: By "Rate-of-return regulation," we mean that a regulator sets a rate of return on capital based on the firm's operating costs and its capital stock, given estimates of the firm's cost of capital and its demand. A regulator conducts a review every time the firm changes its price.

By "Price-cap regulation" we mean that a regulator sets a ceiling on the rate to be charged. A firm can make any change of its price as long as its price doesn't exceed the cap. No limit is set on the rate of return that a firm can earn. Littlechild (1983) introduced the concept, which is also known as RPI-X regulation.

[4] Experience with the adoption of price-cap regulation for various industries in the United Kingdom is documented by Beesley and Littlechild (1989), and in the U.S. for the case of AT&T by Braeutigam and Panzar (1993).

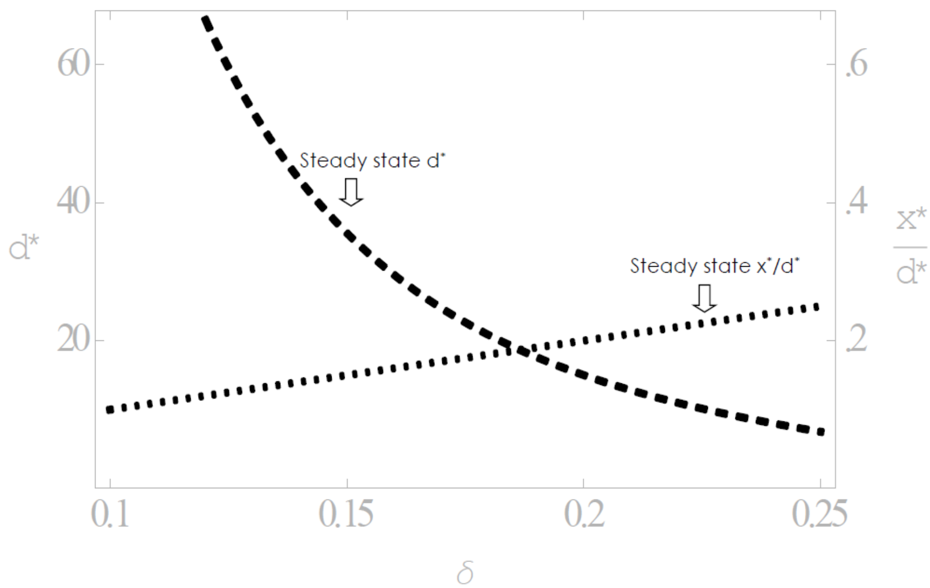


Figure 2: effect of δ on steady-state values of d^* and x^*/d^*

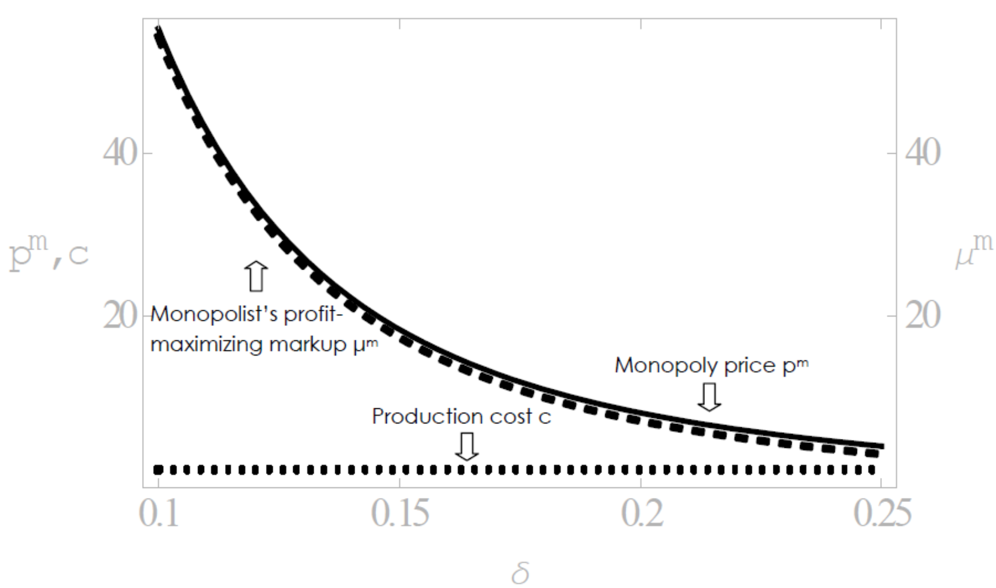


Figure 3: effect of δ on steady-state values of μ^m and p^m

a monopolist's incentive to invest and innovate.[5] Several studies find that price-cap regulation is a better than rate-of-return regulation. The two often-emphasized reasons for why price-cap regulation provides better incentives for a firm to invest and innovate are its effect on cost-reducing innovation[6] and the *Averch-Johnson effect.*[7]

In this section, a simple form of price regulation that can reduce the monopolist's excess profit is introduced into the market described in Section 1. I then study the effect on consumer welfare in the short and the long run.

Consider the following form of price-cap regulation,

$$p_t \leq (1+\mu)\, c, \tag{24}$$

where μ is the markup allowance set by a regulator over the marginal cost.

The monopolist's new gross profit, $\hat{\pi}$, is defined as

$$\hat{\pi}(d_t) \equiv \mu c \left\{ d_t - \varepsilon (1+\mu)\, c \right\}, \tag{25}$$

where $\hat{\pi}$ exhibits constant returns to scale, i.e.,

$$\hat{\pi}' = \mu c \text{ and } \hat{\pi}'' = 0. \tag{26}$$

With the price-cap regulation, the current-value Hamiltonian function, $\hat{H}_t$, at time t is

$$\begin{aligned} \hat{H}_t \equiv\ & \hat{\pi}(d_t) - x_t - \varphi(x_t) \\ & + \nu_t (x_t - \delta d_t), \end{aligned} \tag{27}$$

where ν_t denotes the new costate variable associated with d_t.

The following transversality condition should be met in the optimal path,

$$\lim_{t\to\infty} \nu_t e^{-rt} = 0. \tag{28}$$

[5] See, for example, Vogelsang (2002) for reviews of recent key studies.

[6] *Incentive of cost-reducing innovation*: Cabral and Riordan (1989) and Clemenz (1991) show that price-cap regulation generally provides better incentives for cost-reducing innovation. This is because a monopolist's cost-reducing innovation under rate-of-return regulation may not be properly rewarded. Under rate-of-return regulation, the firm can keep its extra profit from cost-reducing innovation temporarily until the next review but not necessarily for a long period. At the review, if the regulator cannot distinguish whether the firm's increased earnings are due to its cost-reducing effort or due to an exercise of its market power, the rate of return will be reset to cancel the firm's increased earnings. Under price-cap regulation, by contrast, a monopolist can keep its extra profits from cost-reducing effort permanently or for a longer period. Empirical support for this claim has been found by Greenstein *et al.* (1995) and by Ai and Sappington (2002).

[7] *The Averch-Johnson effect*: Averch and Johnson (1962) show that when the rate of return on capital is set above its market cost, rate-of-return regulation induces a monopolist to accumulate excess capital and therefore to produce inefficiently so as to maximize its total profit.

The optimal innovation strategy under price regulation

Accordingly, the law of motion of x_t is

$$\dot{x}_t = \frac{1}{\varphi''(x_t)} \left[(r+\delta) \{1 + \varphi'(x_t)\} - \mu c \right]. \tag{29}$$

Let x^{**} and d^{**} be the new steady state values that solve $\dot{x}_t = \dot{d}_t = 0$. That is, from eqs. (2) and (29), x^{**} and d^{**} satisfy

$$(r+\delta) \{1 + \varphi'(x^{**})\} = \mu c, \tag{30}$$

and

$$x^{**} = \delta d^{**}. \tag{31}$$

If we confine our attention to steady states, then it is easy to show analytically that when a greater markup is allowed, the monopolist innovates more (i.e., larger x^{**}), that it reaches a higher scale of demand (i.e., larger d^{**}), but that the ratio of the two, x^{**}/d^{**}, is not affected. The following proposition deals with:

$$\begin{aligned} x^{**} &= \text{innovation (under price cap)}, \\ d^{**} &= \text{scale of demand (under price cap)}, \\ x^{**}/d^{**} &= \text{innovation relative to the scale of demand (under price cap)}, \\ \mu &= \text{markup allowance set by a regulator.} \end{aligned}$$

Proposition 2 *With a greater μ, the monopolist's x^{**} and d^{**} are larger while x^{**}/d^{**} is not affected.*

Proof. In a steady state, eqs. (30) and (31) hold. From eq. (30), the effect of an increase in μ on x^{**} is

$$\frac{\partial x^{**}}{\partial \mu} = \frac{c}{(r+\delta)\varphi''(x^{**})} > 0. \tag{32}$$

From eq. (31), the effect of an increase in μ on d^{**} is

$$\frac{\partial d^{**}}{\partial \mu} = \frac{1}{\delta} \frac{\partial x^{**}}{\partial \mu} > 0, \tag{33}$$

and its effect on x^{**}/d^{**} is zero. ■

Figures 4 and 5 numerically illustrate Propositions 2's claim that both x^{**} and d^{**} are increasing in μ. The simulation uses the baseline parameters shown in Table 1.

Evaluating the Jacobian matrix, $\hat{J}$, of eqs. (2) and (29) in the steady state,

$$\hat{J}_{x_t = x^{**}, d_t = d^{**}} = \begin{bmatrix} r+\delta & 0 \\ 1 & -\delta \end{bmatrix}, \tag{34}$$

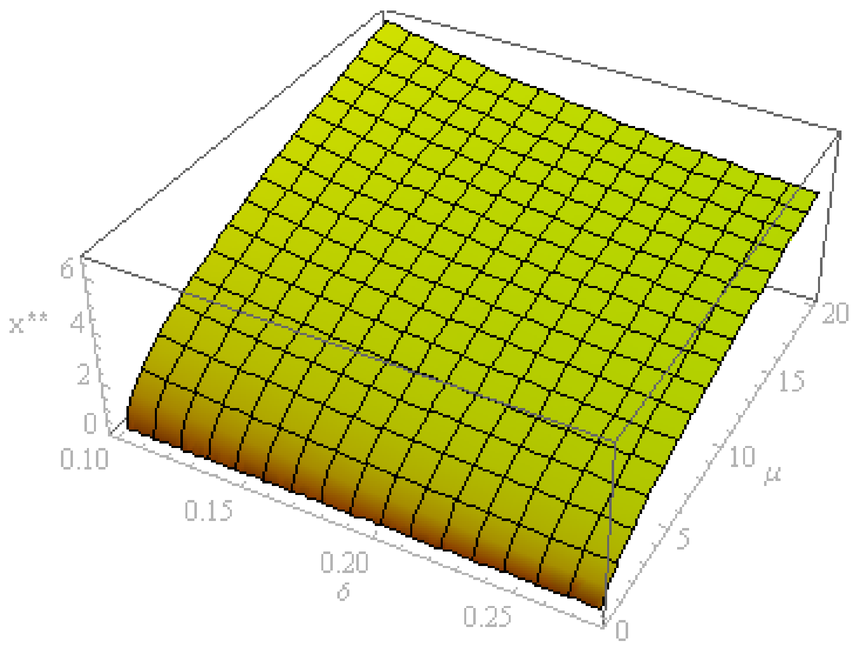


Figure 4: effect of δ and μ on steady state value of x^{**}

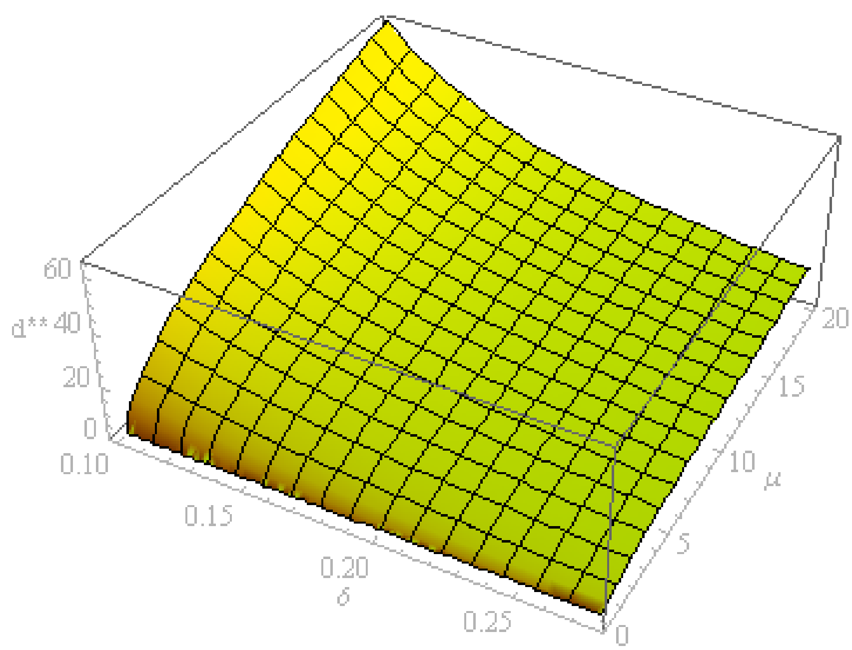


Figure 5: effect of δ and μ on steady state value of d^{**}

where $Tr\hat{J}_{x_t=x^{**},d_t=d^{**}} = r > 0$ and $\det\hat{J}_{x_t=x^{**},d_t=d^{**}} = -\delta(r+\delta) < 0$, we know that the steady state is a saddle-stable point and therefore, the optimal innovation strategy exists.

With a price cap, the new law of motion of ν_t is

$$\dot{\nu}_t = (r+\delta)\nu_t - \mu c. \tag{35}$$

Solving this differential equation, we get[8]

$$\nu_t = \frac{\mu c}{r+\delta}. \tag{36}$$

Thus, ν_t is constant for all t. Then, x_t also must be constant for all t because the optimal x_t must satisfy $1+\varphi'(x_t) = \nu_t$ and $\varphi(\cdot)$ is strictly convex. Moreover, the optimal x_t must approach its steady state, x^{**}, to satisfy the transversality condition. From eq. (28),

$$\lim_{t\to\infty}\{1+\varphi'(x_t)\}e^{-rt} = 0. \tag{37}$$

Therefore, the optimal x_t is constant for all t at

$$x_t = x^{**}. \tag{38}$$

Proposition 3 *With a greater μ, the monopolist's x_t is larger both in and out of steady state.*

Proof. From eqs. (32) and (38), the effect of an increase in μ on x_t is

$$\frac{\partial x_t}{\partial \mu} = \frac{\partial x^{**}}{\partial \mu} > 0. \tag{39}$$

■

Since eq. (38) finds that the firm's optimal innovation is constant at x^{**} for all t, the law of motion of d_t, eq. (2), can reduce to

$$\dot{d}_t = x^{**} - \delta d_t. \tag{40}$$

[8] Integrating eq. (35), we get

$$\begin{aligned}\int_t^\infty [\dot{\nu}_\tau - (r+\delta)\nu_\tau] e^{-(r+\delta)\tau} d\tau &= -\mu c \int_t^\infty e^{-(r+\delta)\tau} d\tau \\ \lim_{\tau\to\infty} \nu_\tau e^{-(r+\delta)\tau} - \nu_t e^{-(r+\delta)t} &= -\frac{\mu c}{r+\delta} e^{-(r+\delta)t}.\end{aligned}$$

From eq. (28), the first term of the left-hand-side is zero. Therefore, the solution of eq. (35) is

$$\nu_t = \frac{\mu c}{r+\delta}.$$

Solving eq. (40), we get[9]

$$d_t = d^{**} + (d_0 - d^{**})\, e^{-\delta t}, \tag{41}$$

which simply states that the scale of demand, d_t, asymptotically approaches to its steady state level, d^{**}.

Consumer welfare under price regulation

The present value of consumer welfare, $\hat{w}_c$, under price-cap regulation is computed as

$$\hat{w}_c = \frac{1}{2\varepsilon}\int_0^\infty \{d_t - \varepsilon\,(1+\mu)\,c\}^2\, e^{-rt} dt. \tag{42}$$

4 Optimal price regulation

Should regulatory agencies aim to maximize the consumer welfare only, or to maximize the aggregate economic welfare?[10] This still is a much debated question. In case of merger, for example, which is the most debated context, the argument can be summarized as follows: while a merger can reduce consumer welfare (as a result of less competition and a post-merger price increase), it can increase shareholders' welfare (as a result of an efficiency increase of the merged firms). On net, aggregate economic welfare may then increase. This implies that under the two different welfare standards, opposite policy conclusions can be drawn, so that maximization of consumer welfare calls for blocking the merger, whereas maximizing aggregate economic welfare would call for allowing the merger.

In case of monopoly, regulating the price reduces shareholders' welfare. Unlike the merger case, however, its effect on consumer welfare is not necessarily positive in a dynamic situation. Consumers, in general, benefit from both a lower price and from more innovation; regulating a monopolist's price can reduce its incentive to innovate, implying that shareholders' and consumer welfare may *both* decline. Price regulation then reduces aggregate welfare.

---

[9] Integrating eq. (40), we get

$$\begin{aligned}
\int_0^t \left[\dot{d}_\tau + \delta d_\tau\right] e^{\delta\tau} d\tau &= x^{**}\int_0^t e^{\delta\tau} d\tau \\
\left[d_\tau e^{\delta\tau}\right]_0^t &= x^{**}\left[\frac{e^{\delta\tau}}{\delta}\right]_0^t \\
d_t e^{\delta t} - d_0 &= \frac{x^{**}}{\delta}\left(e^{\delta t} - 1\right).
\end{aligned}$$

From eq. (31), $x^{**}/\delta = d^{**}$. Thus,

$$d_t = d^{**}\left(1 - e^{-\delta t}\right) + d_0 e^{-\delta t}.$$

[10] See Salop (1995, 2005), Farrell and Katz (2006), Pittman (2007), and Kaplow (2011).

In this section, I show the above-stated points analytically and numerically. That is, even under the pure consumer welfare standard, bringing the market's price to its competitive level is never optimal. Moreover, in some high-δ markets, no intervention is optimal. I also analyze how these results may change under the aggregate economic welfare standard. I show that when shareholders' welfare is also taken into account, even less regulation should be optimal for all markets.

Price-cap regulation benefits consumers only if $w_c < \hat{w}_c$, otherwise it harms them in the long run. From eqs. (23) and (42), we may have $w_c \lesseqgtr \hat{w}_c$ depending on parameters. Let us now focus on two parameters, δ and μ, as key determinants of w_c and $\hat{w}_c$, with all other parameters being held constant. The effect of an increase in the markup allowance, μ, in a given-δ market, on consumer welfare, $\hat{w}_c$, is twofold. A higher markup allowance immediately increases the monopolist's product price and thus reduces consumer welfare in the short run. On the other hand, a higher markup allowance can raise the monopolist's incentive to innovate. As innovation enhances the scale of demand, in the long run, consumer welfare may rise.

I also show that there exists a unique markup allowance rate, μ^o, for a given δ, that maximizes $\hat{w}_c$. However, imposing the markup allowance, μ^o, may not benefit for consumers if it does not improve consumer welfare. I show that there exists a threshold obsolescence rate, $\tilde{\delta}$, so that price-cap regulation is beneficial only for a market that has a obsolescence rate smaller than $\tilde{\delta}$ and that otherwise it is harmful.

To simplify the argument, I assume that at the moment that regulation is imposed market is in its steady state, i.e., $d_0 = d^*$. If the regulation is not imposed, the present value of consumer welfare, eq. (23), is

$$w_c(\delta) \equiv \frac{1}{8\varepsilon} \int_0^\infty (d^*(\delta) - \varepsilon c)^2 e^{-rt} dt. \tag{43}$$

On the other hand, if the regulation is imposed, the present value of consumer welfare, eq. (42), is

$$\hat{w}_c(\delta, \mu) \equiv \frac{1}{2\varepsilon} \int_0^\infty \{d_t - \varepsilon (1+\mu) c\}^2 e^{-rt} dt. \tag{44}$$

Suppose that a regulator represents consumer welfare only. Then its problem is to find the markup-allowance, μ^o, that maximizes the consumer welfare, i.e.,

$$\mu^o = \arg\max \text{eq. (44)}. \tag{45}$$

The first-order necessary condition for maximization of consumer welfare is $\partial \hat{w}_c / \partial \mu = 0$. Rearranging the condition and from eq. (41), we get

$$\begin{aligned} &\underbrace{\frac{\partial d^{**}(\delta, \mu^o)}{\partial \mu} \frac{1}{\varepsilon} \int_0^\infty \{d_t - \varepsilon (1+\mu^o) c\} \left(1 - e^{-\delta t}\right) e^{-rt} dt}_{\equiv \Delta^1(\delta,\mu)} \\ = &\underbrace{c \int_0^\infty \{d_t - \varepsilon (1+\mu^o) c\} e^{-rt} dt.}_{\equiv \Delta^2(\delta,\mu)} \end{aligned} \tag{46}$$

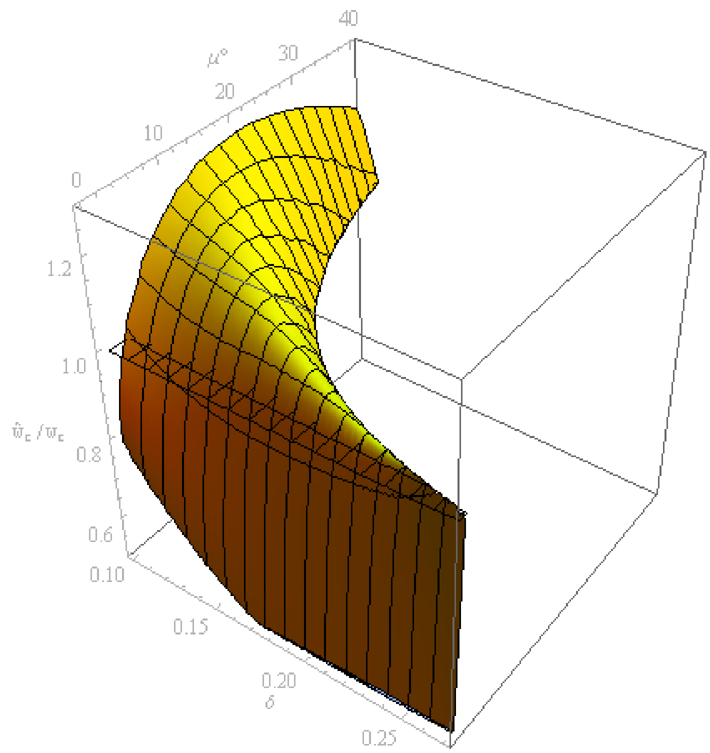


Figure 6: consumer welfare ratio Γ ($\hat{w}_c/w_c$, with and w/o price-cap regulation)

That is, the markup allowance, μ, in a given-δ market, should be raised until its marginal benefit, Δ^1, from demand enhancement becomes equal to its marginal cost, Δ^2, due to the price increase. The next proposition deals with:

$$\begin{aligned} \hat{w}_c(\delta, \mu) &= \text{present value of consumer welfare (under price cap)}, \\ \mu^o &= \text{markup allowance that maximizes } \hat{w}_c. \end{aligned}$$

Proposition 4 *There exists μ^o, for a given δ, that maximizes $\hat{w}(\delta, \mu)$.*

Proof. See Appendix 1. ■

Figure 6 numerically illustrates Proposition 4's claim. The simulation uses the baseline parameters shown in Table 1. The vertical axis is the consumer-welfare ratio, defined as $\hat{w}_c(\delta, \mu)/w_c(\delta) \equiv \Gamma(\delta, \mu)$. The welfare-maximizing markup, μ^o, for a given δ-market, occurs along the peak of the function $\Gamma(\delta, \mu)$. The price-cap regulation is beneficial to consumers only if $\Gamma(\delta, \mu^o(\delta)) > 1$. Note that the domain of the function $\Gamma(\delta, \mu)$ is restricted to be $\mu < \mu^m(\delta)$, where $\mu^m(\delta)$ is the monopolist's profit-maximizing markup.[11] This is simply because any price-cap regulation that

[11] The monopolist's markup, μ^m, satisfies $p^m(d^*) = (1 + \mu^m)c$, where from eq. (4), $p^m(d^*) = \{d^*(\delta) + \varepsilon c\}/2\varepsilon$. By solving this for μ^m, we get $\mu^m(\delta) = \{d^*(\delta) - \varepsilon c\}/2\varepsilon c$.

allows a higher markup than $\mu^m(\delta)$ will no longer be binding and therefore $\Gamma(\delta, \mu) = 1$ for $\mu \geq \mu^m(\delta)$. In Figure 6, a unique value, $\tilde{\delta} > 0$, at which $\Gamma\left(\tilde{\delta}, \mu^o\left(\tilde{\delta}\right)\right) = 1$ exists. This implies that, in a market where the existing innovations become obsolete at a faster rate than $\tilde{\delta}$, price-cap regulation no longer raises consumer welfare. Moreover, reducing the monopolist's markup in this case will harm the consumer welfare. The next proposition will clarify this point. We deal with:

$$
\begin{aligned}
\Gamma(\delta, \mu^o(\delta)) &\equiv \frac{\hat{w}_c(\delta, \mu^o(\delta))}{w_c(\delta)} \\
&= \frac{\text{consumer welfare (under \textit{optimal} price-cap)}}{\text{consumer welfare (w/o regulation)}}, \\
\tilde{\delta} &= \text{threshold obsolescence-rate where } \Gamma \gtreqless 1 \text{ for } \delta \lesseqgtr \tilde{\delta}.
\end{aligned}
$$

Proposition 5 *There exists $\tilde{\delta}$ at which $\Gamma\left(\tilde{\delta}, \mu^o\left(\tilde{\delta}\right)\right) = 1$.*

Proof. See Appendix 2. ■

Figure 7 numerically confirms Proposition 5's claim. The simulation uses the baseline parameters shown in Table 1. Price-cap regulation is beneficial only for a market that has a obsolescence rate less than $\tilde{\delta}$. Figure 8 shows the optimal rate of reduction, $\alpha = 1 - (\mu^o/\mu^m)$, of the monopolist's markup. It confirms that a smaller markup reduction is optimal in a market where the existing innovations become obsolete at a faster rate.

Suppose now that a regulator represents both consumer welfare, $\hat{w}_c$, and shareholders' welfare, $\hat{w}_s$. The present value of shareholders' welfare is

$$\hat{w}_s(\delta, \mu) \equiv \int_0^\infty \mu c \left(d_t - \varepsilon (1 + \mu) c\right) e^{-rt} dt. \tag{47}$$

Then its problem is to find the markup-allowance, μ', that maximizes the aggregate welfare, i.e.,

$$\mu' = \arg\max \hat{w}_c(\delta, \mu) + \hat{w}_s(\delta, \mu). \tag{48}$$

The next proposition shows that when shareholders' welfare is also taken into account, even less regulation should be optimal for all markets. We deal with:

$$
\begin{aligned}
\hat{w}_s(\delta, \mu) &= \text{present value of shareholders' welfare (under price cap)}, \\
\mu' &= \text{markup allowance that maximizes } \hat{w}_c + \hat{w}_s.
\end{aligned}
$$

Proposition 6 *The aggregate-welfare-maximizing μ' is larger than the consumer-welfare-maximizing μ^o for all markets.*

Proof. See Appendix 3. ■

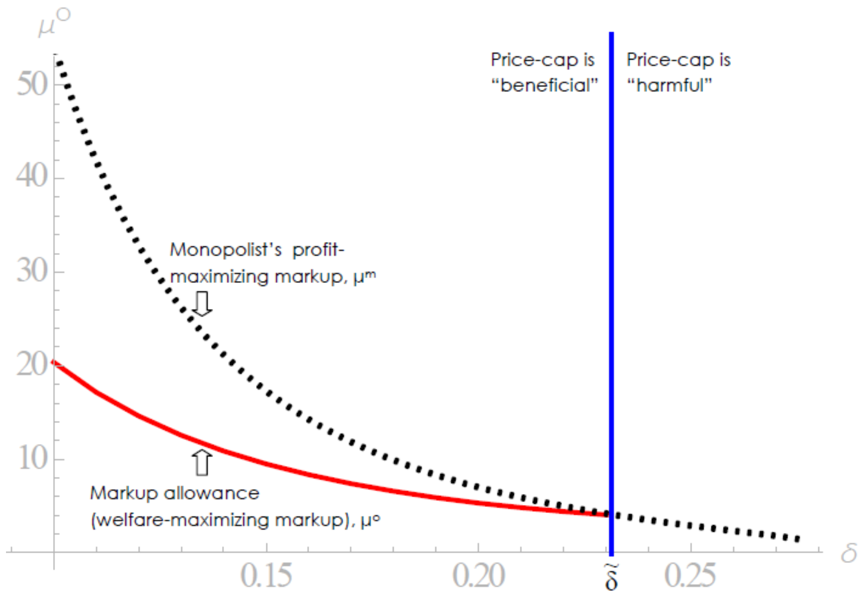


Figure 7: optimal markup allowance (μ^o) and threshold ($\tilde{\delta}$)

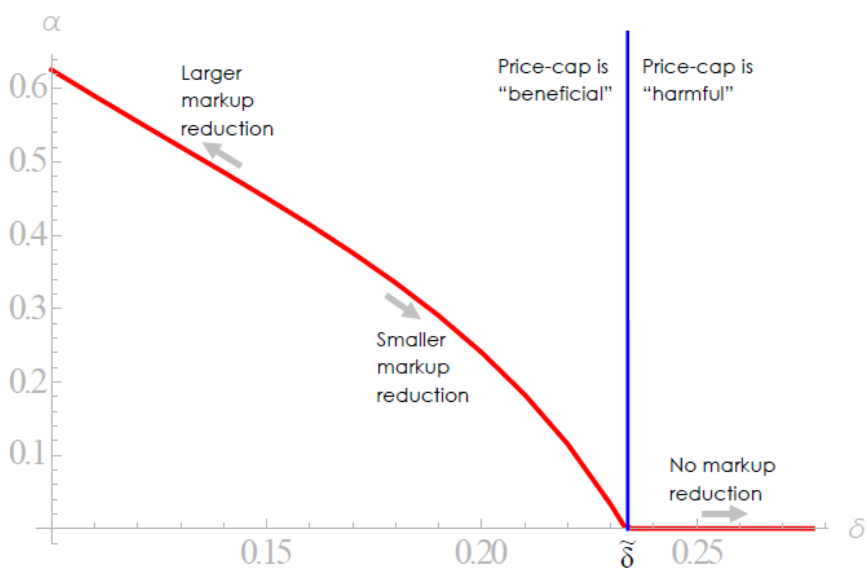


Figure 8: optimal markup reduction (α) and threshold ($\tilde{\delta}$)

5 Some evidence

The purpose of this section is to report some empirical observations which are relevant to the model's predictions, but not to give a formal empirical analysis.

As shown in Proposition 1, the model predicts a positive relation between δ and x^*/d^*. That is, in markets that have a higher rate of obsolescence of innovations, a monopolist should innovate at a faster rate. Since the monopolist's current scale of demand is as a result of its cumulative past innovation effort, we may measure the scale of demand by the firm's R&D capital and δ by the depreciation rate of that capital. Hall (2007) estimates the depreciation rate of the R&D capital using firm market value for six U.S. manufacturing sectors (chemicals, rubber, and plastics; pharmaceuticals and medical instruments; electrical machinery; computers and scientific instruments; metals, machinery, and transport equipment; and miscellaneous manufacturing) for the period 1999-2003. I shall use Hall's depreciation rate as a proxy for the model's δ. As a proxy for x^*/d^*, I use average R&D funds (company and other nonfederal) for the period 1999-2003 as a percent of net sales. The data are available for the U.S. manufacturing industries at the North American Industry Classification System (NAICS)'s 4-digit-level from the NSF's Industrial R&D Information System. Table A1 in Appendix 5 provides the summary of the data. Figure 9 shows the relation between the constructed depreciation rates and the innovation ratios.

As Proposition 1 also shows, the model predicts a negative relation between δ and μ^*, that is a monopolist in markets where the existing innovations become obsolete at a faster rate should charge a smaller markup. Hall (1988) estimates markup ratios at the Standard Industrial Classification (SIC)'s 2-digit-level U.S. manufacturing industry for the period 1953-1984. Roeger (1995) re-estimates them in a different way to overcome identification problems recognized in Hall (1988). I use Roeger (1995)'s markup estimates as a proxy for the model's μ^*. As a proxy for δ, I use a patent renewal rate as a negative indicator of the rate at which R&D capital depreciates.[12] Pakes and Simpson (1989) estimate patent renewal rates using Finnish manufacturing data at the 2-digit level for the period 1969-1987. The period they study appears to have a significant overlap with Roeger's. Pakes and Simpson cluster industries into the highest-patent-renewal-rate Group 1, and so on down to the lowest-patent-renewal rate Group 5. I interpret high rates of renewal to mean low rates of depreciation, and low renewal rates to mean high rates of depreciation of patent value. Column 2 and 4 of Table A2 in Appendix 5 provides the summary of the data. Figure 10 shows the relation between the depreciation rate and the markup ratio. The depreciation of patent value is on the x-axis and is ranked from 1 (the lowest depreciation) to 5 (the highest depreciation).

[12] I do not use, in this case, Hall (2007)'s market-value-based depreciation rate as a proxy for δ because Hall's study period, 1999-2003, has no overlap with Roeger's study period, 1953-1984.

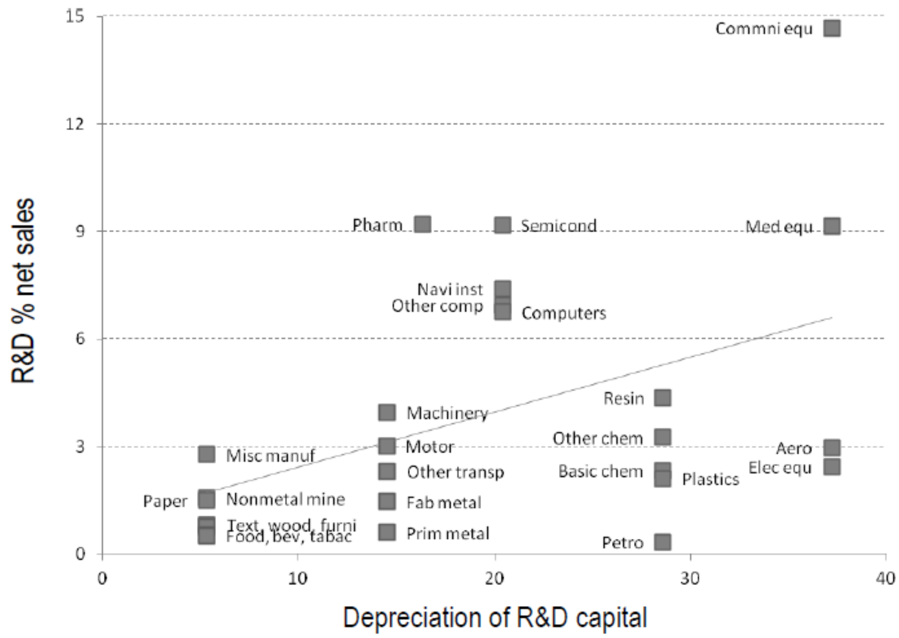


Figure 9: R&D capital depreciation rate and R&D % of net sales

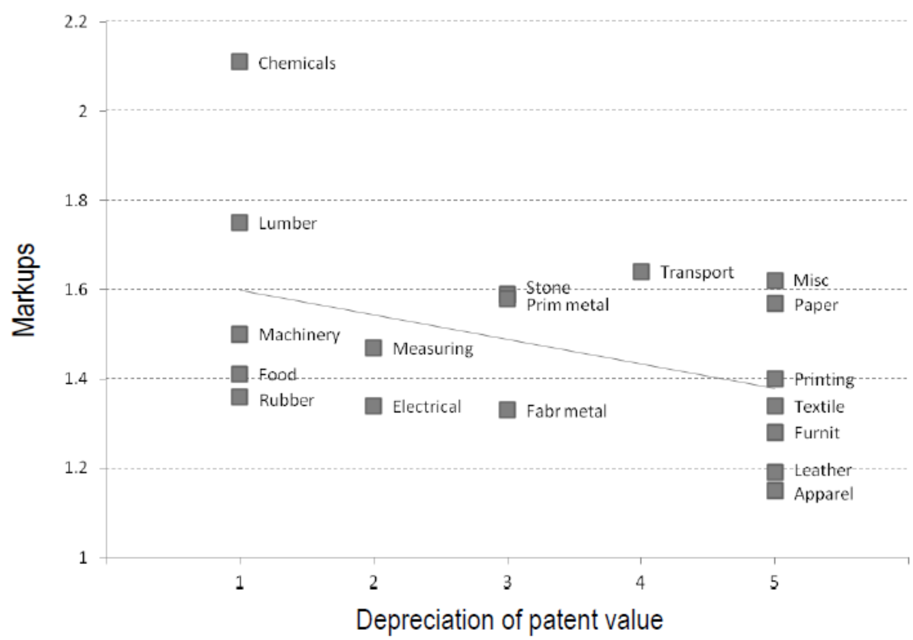


Figure 10: patent depreciation rate and markup

6 Remarks on Literature

A possible extension of the model would be to cast the regulatory agency's welfare-maximizing problem as one of determining an optimal patent length, instead of an optimal markup allowance. This can be done market by market. For early studies on optimal patent lives, see Nordhaus (1969) and Scherer (1972). More recently, a paper by Horowitz and Lai (1996) studies the effect of patent length on the size and frequency of innovation and derives the consumer-welfare-maximizing patent length. Given the model's features, one would expect similar conclusions to obtain. That is, tougher regulation would take the form of a shorter patent life, and a short patent length would be optimal in a market where the existing innovations become obsolete more slowly. Conversely, in a market where the existing innovations become obsolete more quickly, it would be optimal to have less regulation which then would translate into a longer patent life.

Another extension would follow Armstrong and Sappington (2007) who argue that the frequency of regulatory review (also referred to as the regulatory lag) affects the level of the monopolist's cost-reduction effort: The more frequently the cap is revised, the less cost reduction the monopolist will undertake. In my model the firm engages in demand-enhancing innovation but it does not reduce its cost which remains constant throughout. Therefore, in the present analysis, the frequency of review affects neither the regulator's choice of optimal price cap nor the monopolist's incentive to enhance its demand. However, if we did include in the monopolist's problem a cost-reduction effort, Δ (but no ability to enhance demand), the following conjecture holds, at least in a simple example worked out below:

Conjecture. *In a market that has a high δ, the monopolist's Δ is small, and so is the deadweight loss. Thus infrequent review should be optimal.*

Example. A monopolist faces a demand curve, $q_t = d_t - \varepsilon p_t$, where the intercept

$$d_t = d_0 e^{-\delta t} \tag{e1}$$

shrinks at the rate δ. Suppose that at $t = 0$, a regulator has just set the price cap equal to the marginal cost, c, to eliminate the monopolist's profit. The review horizon is assumed to be $T > 0$ periods. Then $p_t = c$ for $t \in [0, T]$. The monopolist chooses the level of cost-reduction effort, $\Delta \geq 0$, at $t = 0$ to maximize the present value of the net surplus. I.e.,

$$\max_{\Delta \geq 0} \int_0^T \Delta \max\left\{0, d_0 e^{-\delta t} - \varepsilon c\right\} e^{-rt} dt - \varphi(\Delta), \tag{e2}$$

where $\varphi(\cdot)$ is a cost of effort function with properties, $\varphi(0) = \varphi'(0) = 0$, $\varphi' > 0$, $\varphi'' > 0$, and $r > 0$ is the discount rate. The optimal cost-reduction effort, Δ^*, satisfies

$$\frac{d_0}{\delta + r}\left(1 - e^{-(\delta+r)T}\right) - \frac{\varepsilon c}{r}\left(1 - e^{-rT}\right) = \varphi'(\Delta^*). \tag{e3}$$

Thus we find that (i) the longer the review horizon, T, is, the larger the monopolist's cost-reduction effort, Δ^*, is:

$$\frac{\partial \Delta^*}{\partial T} = \frac{1}{\varphi''(\cdot)} \max\left\{0, d_0 e^{-\delta T} - \varepsilon c\right\} e^{-rT} \geq 0, \tag{e4}$$

and (ii) the higher the market's δ is, the smaller the monopolist's cost-reduction effort, Δ^*, is:

$$\frac{\partial \Delta^*}{\partial \delta} = -\frac{d_0}{\varphi''(\cdot)(\delta + r)^2} \left\{1 - \frac{1 + (\delta + r)T}{e^{(\delta + r)T}}\right\} < 0. \tag{e5}$$

When Δ^* is small, the price permitted, c, diverges only little from the realized marginal cost, $c - \Delta^*$, so there should be only little deadweight loss. Thus in a high-δ market, it is optimal to have infrequent review, i.e., a long lag, T.

Another possible extension would study a setting where δ is private information to the firm and unknown to a regulator. In that case the firm may wish to overstate its δ because the regulator may then permit a larger markup. To assign the correct markup, the regulator need to learn the true δ. One way would be to try to infer it from the monopolist's innovation spending relative to its market size; this can be measured by R&D spending as a percent of net sales. My model predicts that in markets with larger δ, a monopolist will innovate at a faster rate (Proposition 1). Another way to elicit δ would be to design an incentive-compatible mechanism under which the firm will want to reveal the true value. Riordan (1984) and Lewis and Sappington (1988) study Bayesian incentive-compatible subsidy policies in a static environment where a monopolist knows its demand better than does the regulator.

7 Conclusions

This paper has analyzed the effect of price regulation on a patent-protected monopolist's innovative activity and its effect on welfare in an infinite-horizon dynamic model. Price regulation in the model takes a simple form – a regulator allows a certain markup over the marginal cost. Such regulation may improve consumer welfare temporarily. However, it also can reduce the monopolist's incentive to innovate in the long run. In that case, consumers will receive less benefit from future innovations.

The paper studied a consumer-welfare-maximizing level of price regulation for each market characterized by its obsolescence rate of innovations. The main finding is that a greater reduction of the monopolist's markup is optimal in markets where the existing innovations become obsolete more slowly and that a smaller or even a zero reduction of the monopolist's markup is optimal in markets where the existing innovations become obsolete more quickly. The paper also found that there is a unique threshold obsolescence rate of innovations that describes the nature of the optimal policy. That is, regulation is on net beneficial if innovations become obsolete more slowly than the threshold rate: If the existing innovations become obsolete more slowly than this rate, price regulation raises consumer welfare, and the regulator should therefore step in to impose a cap on the monopolist's price. On the other hand, if the existing innovations become obsolete at a faster rate than the threshold rate, price-cap regulation reduces consumer welfare. The paper also studied how these results may change when shareholders' welfare is also taken into account and it found that in that case even less regulation should be optimal for all markets.

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Appendix 1: Proof of proposition 4

Proof. We know that $\hat{w}_c$ has a local maximum at μ^o if $\hat{w}_c$ is concave down at μ^o, i.e.,

$$\text{if } \frac{\partial^2 \hat{w}_c}{\partial \mu^2} = \frac{\partial \Delta^1}{\partial \mu} - \frac{\partial \Delta^2}{\partial \mu} < 0 \Rightarrow \hat{w}_c \text{ has a local maximum at } \mu^o. \tag{a1}$$

Taking a derivative of the marginal benefit, Δ^1, with respect to μ gives

$$\begin{aligned} \frac{\partial \Delta^1}{\partial \mu} &= \underbrace{\frac{\partial^2 d^{**}(\delta,\mu^o)}{\partial \mu^2}\frac{1}{\varepsilon}\int_0^\infty \{d_t - \varepsilon(1+\mu^o)c\}\left(1-e^{-\delta t}\right)e^{-rt}dt}_{term\ 1} \\ &\quad \underbrace{+\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu}\frac{1}{\varepsilon}\int_0^\infty \left\{\left(1-e^{-\delta t}\right)\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu} - \varepsilon c\right\}\left(1-e^{-\delta t}\right)e^{-rt}dt.}_{term\ 2} \end{aligned} \tag{a2}$$

From eqs. (32) and (33), $\partial^2 d^{**}/\partial \mu^2$ in *term* 1 is negative.[13] Note that $\{\cdot\}$ in *term* 1 is the monopolist's production level under price-cap regulation and $\{\cdot\} > 0$. Thus, *term* 1 of eq. (a2) is negative.

Let *term* 2 of eq. (a2) be expanded as[14][15]

$$term\ 2 = \frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu}\frac{1}{\varepsilon}\frac{2\delta^2}{r(r+\delta)(r+2\delta)}\left\{\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu} - \frac{r+2\delta}{2\delta}\varepsilon c\right\}. \tag{a3}$$

where from eq. (33), $\partial d^{**}/\partial \mu > 0$ and thus the sign of *term* 2 depends solely on the sign of $\{\cdot\}$ in eq. (a3).

Now, recall the first-order necessary condition, eq. (46) and rewrite it as

$$\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu} = \Phi \varepsilon c, \tag{a4}$$

---

[13] From eqs. (32) and (33),

$$\begin{aligned} \frac{\partial^2 d^{**}}{\partial \mu^2} &= \frac{-c\varphi'''}{\delta(r+\delta)\varphi''^2}\frac{\partial x^{**}}{\partial \mu} \\ &= \frac{-c^2\varphi'''}{\delta(r+\delta)^2\varphi''^3} < 0. \end{aligned}$$

[14] Useful expansions: $\int_0^\infty e^{-rt}dt = \frac{1}{r}$. $\int_0^\infty e^{-(r+\delta)t}dt = \frac{1}{r+\delta}$. $\int_0^\infty \left(1-e^{-\delta t}\right)e^{-rt}dt = \frac{\delta}{r(r+\delta)}$. $\int_0^\infty \left(1-e^{-\delta t}\right)e^{-(r+\delta)t}dt = \frac{\delta}{(r+\delta)(r+2\delta)}$. $\int_0^\infty \left(1-e^{-\delta t}\right)^2 e^{-rt}dt = \frac{2\delta^2}{r(r+\delta)(r+2\delta)}$.

[15] Rewrite *term* 2 in eq. (a2) as $\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu}\frac{1}{\varepsilon}\left[\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu}\int_0^\infty \left(1-e^{-\delta t}\right)^2 e^{-rt}dt - \varepsilon c\int_0^\infty \left(1-e^{-\delta t}\right)e^{-rt}dt\right]$. Then apply expansions listed in footnote 14.

where

$$\Phi \equiv \frac{\displaystyle\int_0^{\infty} \{d_t - \varepsilon (1+\mu^o) c\} e^{-rt} dt}{\displaystyle\int_0^{\infty} \{d_t - \varepsilon (1+\mu^o) c\} \left(1 - e^{-\delta t}\right) e^{-rt} dt} > 1. \tag{a5}$$

Then by plugging eq. (a4) into eq. (a3), we may rewrite *term* 2 as

$$term\ 2 = \frac{\partial d^{**}(\delta, \mu^o)}{\partial \mu} \frac{1}{\varepsilon} \frac{2\delta^2}{r(r+\delta)(r+2\delta)} \left\{ \Phi - \frac{r+2\delta}{2\delta} \right\} \varepsilon c. \tag{a6}$$

We find from eq. (a6) that *term* 2 is negative if $\frac{r+2\delta}{\delta} > \Phi$.

Then we may state that:

$$\text{if } \frac{r+2\delta}{\delta} > \Phi \Rightarrow \frac{\partial \Delta^1}{\partial \mu} < 0. \tag{a7}$$

By the way, Φ in eq. (a5) can be further expanded as[16]

$$\Phi = \frac{d^{**}(\delta, \mu^o)\left(\frac{\delta}{r(r+\delta)}\right) + d^*(\delta)\left(\frac{1}{r+\delta}\right) - \varepsilon(1+\mu^o) c \left(\frac{1}{r}\right)}{d^{**}(\delta, \mu^o)\left(\frac{2\delta^2}{r(r+\delta)(r+2\delta)}\right) + d^*(\delta)\left(\frac{\delta}{(r+\delta)(r+2\delta)}\right) - \varepsilon(1+\mu^o) c \left(\frac{\delta}{r(r+\delta)}\right)} \tag{a8}$$

Dividing both sides of eq. (a8) by $\frac{r+2\delta}{\delta}$ gives

$$\begin{aligned} \frac{\Phi}{\frac{r+2\delta}{\delta}} &= \frac{d^{**}(\delta, \mu^o)\left(\frac{\delta}{r(r+\delta)}\right) + d^*(\delta)\left(\frac{1}{r+\delta}\right) - \varepsilon(1+\mu^o) c \left(\frac{1}{r}\right)}{d^{**}(\delta, \mu^o)\left(\frac{2\delta}{r(r+\delta)}\right) + d^*(\delta)\left(\frac{1}{r+\delta}\right) - \varepsilon(1+\mu^o) c \left(\frac{r+2\delta}{r(r+\delta)}\right)} \\ &\equiv \frac{f_1}{f_2}, \end{aligned} \tag{a9}$$

where

$$f_1 - f_2 = \frac{-\delta}{r(r+\delta)} \{d^{**}(\delta, \mu^o) - \varepsilon(1+\mu^o) c\} < 0. \tag{a10}$$

Note that $\{\cdot\}$ of eq. (a10) is the monopolist's steady-state production level and $\{\cdot\} > 0$.

Thus at μ^o,

$$\frac{\Phi}{\frac{r+2\delta}{\delta}} = \frac{f_1}{f_2} < 1 \Rightarrow \frac{r+2\delta}{\delta} > \Phi. \tag{a11}$$

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[16] Rewrite Φ in eq. (a6) as $\frac{d^{**}(\delta,\mu^o)\int_0^{\infty}\left(1-e^{-\delta t}\right)e^{-rt}dt + d^*(\delta)\int_0^{\infty} e^{-(r+\delta)t}dt - \varepsilon(1+\mu^o)c\int_0^{\infty} e^{-rt}dt}{d^{**}(\delta,\mu^o)\int_0^{\infty}(1-e^{-\delta t})^2 e^{-rt}dt + d^*(\delta)\int_0^{\infty}(1-e^{-\delta t})e^{-(r+\delta)t}dt - \varepsilon(1+\mu^o)c\int_0^{\infty}(1-e^{-\delta t})e^{-rt}dt}$.
Then apply expansions listed in footnote 14.

Then, from the statement (a7), we may conclude that at μ^o,

$$\frac{\partial \Delta^1}{\partial \mu} < 0. \tag{a12}$$

Similarly, taking a derivative of the marginal cost, Δ^2, with respect to μ gives

$$\frac{\partial \Delta^2}{\partial \mu} = c\int_0^\infty \left\{ \left(1 - e^{-\delta t}\right) \frac{\partial d^{**}(\delta, \mu^o)}{\partial \mu} - \varepsilon c \right\} e^{-rt} dt. \tag{a13}$$

We can expand eq. (a14) as[17]

$$\frac{\partial \Delta^2}{\partial \mu} = \frac{c\delta}{r(r+\delta)} \left\{ \frac{\partial d^{**}(\delta, \mu^o)}{\partial \mu} - \frac{r+\delta}{\delta} \varepsilon c \right\}. \tag{a14}$$

By plugging the first-order necessary condition, eq. (a4), into eq. (a14), we get

$$\frac{\partial \Delta^2}{\partial \mu} = \frac{c\delta}{r(r+\delta)} \left\{ \Phi - \frac{r+\delta}{\delta} \right\} \varepsilon c. \tag{a15}$$

Then we may state that:

$$\text{if } \frac{r+\delta}{\delta} < \Phi \Rightarrow \frac{\partial \Delta^2}{\partial \mu} > 0. \tag{a16}$$

Dividing both sides of eq. (a8) by $\frac{r+\delta}{\delta}$ gives

$$\begin{aligned} \frac{\Phi}{\frac{r+\delta}{\delta}} &= \frac{d^{**}(\delta, \mu^o)\left(\frac{\delta}{r(r+\delta)}\right) + d^*(\delta)\left(\frac{1}{r+\delta}\right) - \varepsilon(1+\mu^o)c\left(\frac{1}{r}\right)}{d^{**}(\delta, \mu^o)\left(\frac{2\delta}{r(r+2\delta)}\right) + d^*(\delta)\left(\frac{1}{r+2\delta}\right) - \varepsilon(1+\mu^o)c\left(\frac{1}{r}\right)} \\ &\equiv \frac{f_3}{f_4}. \end{aligned} \tag{a17}$$

where

$$f_3 - f_4 = \frac{\delta}{(r+\delta)(r+2\delta)} \left\{ d^*(\delta) - d^{**}(\delta, \mu^o) \right\} > 0. \tag{a18}$$

Note that the monopolist's steady-state scale of demand, d^*, in the absence of price-cap regulation is always greater than d^{**} under price-cap regulation. Thus $\{\cdot\}$ of eq. (a18) is positive.

Thus at μ^o,

$$\frac{\Phi}{\frac{r+\delta}{\delta}} = \frac{f_3}{f_4} > 1 \Rightarrow \frac{r+\delta}{\delta} < \Phi. \tag{a19}$$

Then, from the statement (a16), we may conclude that at μ^o,

$$\frac{\partial \Delta^2}{\partial \mu} > 0. \tag{a20}$$

From the two findings, (a12) and (a20), we may conclude that $\partial^2 \hat{w}_c / \partial \mu^2 < 0$ and thus that $\hat{w}_c$ has a local maximum at μ^o. ■

[17] Rewrite eq. (a13) as $c\left[\frac{\partial d^{**}(\delta,\mu^o)}{\partial \mu}\int_0^\infty \left(1-e^{-\delta t}\right)e^{-rt}dt - \varepsilon c\int_0^\infty e^{-rt}dt\right]$. Then apply expansions listed in footnote 14.

Appendix 2: Proof of proposition 5

Proof. The first-order condition, eq. (46), should hold also at $\tilde{\delta}$, i.e., $\Delta^1\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right) = \Delta^2\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right)$. At $\tilde{\delta}$, by definition, $\hat{w}_c\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right) = w_c\left(\tilde{\delta}\right)$, $p^m\left(d^*\left(\tilde{\delta}\right)\right) = \left(1+\mu^o\left(\tilde{\delta}\right)\right)c$ and $d^*\left(\tilde{\delta}\right) = d^{**}\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right)$. Then from eqs. (32) and (33) and footnote 14, eq. (46) at $\tilde{\delta}$ reduces to[18]

$$\varphi''\left(x^*\left(\tilde{\delta}\right)\right) = \frac{1}{\varepsilon\left(r+\tilde{\delta}\right)^2}. \tag{a21}$$

A unique value of $\tilde{\delta}$ solves eq. (a21). ■

Appendix 3: Proof of Proposition 6

Proof. For a given δ, we take a derivative of the present value of the aggregate welfare, $\hat{w}_c + \hat{w}_s$, with respect to μ and evaluate it at $\mu = \mu^o$. Since $\partial\hat{w}_c/\partial\mu = 0$ at μ^o by definition, $\partial\left\{\hat{w}_c+\hat{w}_s\right\}/\partial\mu = \partial\hat{w}_s/\partial\mu$ at μ^o.

Then from eqs. (47) and (41), we have

$$\frac{\partial}{\partial\mu}\left\{\hat{w}_c+\hat{w}_s\right\} = \underbrace{c\int_0^\infty \left\{d_t - \varepsilon\left(1+\mu^o\right)c\right\}e^{-rt}dt}_{term\ 3} + \underbrace{\mu^o c\int_0^\infty \left(\left(1-e^{-\delta t}\right)\frac{\partial d^*}{\partial\mu} - \varepsilon c\right)e^{-rt}dt}_{term\ 4}. \tag{a22}$$

Note that $\{\cdot\}$ in *term* 3 is the monopolist's production level under price-cap regulation and $\{\cdot\} > 0$. Thus, the sign of *term* 3 is positive.

Let *term* 4 of eq. (a22) be expanded as[19]

$$term\ 4 = \mu^o c\frac{\delta}{r\left(r+\delta\right)}\left\{\frac{\partial d^{**}\left(\delta,\mu^o\right)}{\partial\mu} - \frac{r+\delta}{\delta}\varepsilon c\right\}, \tag{a23}$$

where from eq. (33), $\partial d^{**}/\partial\mu > 0$ and thus the sign of *term* 4 depends solely on the sign of $\{\cdot\}$ in eq. (a23).

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[18] From eqs. (32) and (33) and footnote 14,

$$\Delta^1\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right) = \frac{c}{\varepsilon r\left(r+\tilde{\delta}\right)^2\varphi''\left(x^*\left(\tilde{\delta}\right)\right)}\left\{d^*\left(\tilde{\delta}\right) - \varepsilon p^m\left(d^*\left(\tilde{\delta}\right)\right)\right\},$$

and

$$\Delta^2\left(\tilde{\delta},\mu^o\left(\tilde{\delta}\right)\right) = \frac{c}{r}\left\{d^*\left(\tilde{\delta}\right) - \varepsilon p^m\left(d^*\left(\tilde{\delta}\right)\right)\right\}.$$

[19] Rewrite *term* 4 in eq. (a22) as $\mu^o c\left[\frac{\partial d^{**}}{\partial\mu}\int_0^\infty\left(1-e^{-\delta t}\right)e^{-rt} - \varepsilon c\int_0^\infty e^{-rt}dt\right]$. Then apply expansions listed in footnote 14.

At $\mu = \mu^o$, eq. (a4) should hold. By plugging eq. (a4) into eq. (a23), we may rewrite *term* 4 as

$$term\ 4 = \mu^o c \frac{\delta}{r(r+\delta)} \left\{ \Phi - \frac{r+\delta}{\delta} \right\} \varepsilon c \tag{a24}$$

where from eq. (a19), $\frac{r+\delta}{\delta} < \Phi$. Thus *term* 4 is also positive.

Then from eq. (a22), we find that

$$\frac{\partial}{\partial \mu} \{\hat{w}_c + \hat{w}_s\} > 0 \text{ at } \mu = \mu^o, \tag{a25}$$

implying that the aggregate welfare for any given δ should improve by raising μ above the consumer-welfare-maximizing level, μ^o. ■

Appendix 4: The case with imperfect capital market

In this appendix, I study the firm's innovative activity in an imperfect capital market in which its innovation is constrained by its internal funds.[20] Under this assumption, the firm's accumulation of internal funds from monopoly profit can slow down or even decline when the regulator attempts to keep the monopolist's price close to its competitive level. This then reduces the firm's ability to finance its innovative activity. I follow Schworm (1980) and assume that the cost of innovation can be financed only through the firm's accumulated retained earnings, k_t, but not through borrowing. Given the firm's initial endowment of retained earnings, $k_0 > 0$, the law of motion of k_t is

$$\dot{k}_t = (p_t - c)\, q_t - x_t - \varphi(x_t) + r k_t, \tag{a26}$$

where no borrowing is allowed, i.e.,

$$-k_t \leq 0, \tag{a27}$$

but the firm can lend its funds at the rate of return, r.

The non-negativity constraint can be rewritten as

$$z_t \equiv -k_t \Longrightarrow \dot{z}_t = -\dot{k}_t = -\left\{(p_t - c)\, q_t - x_t - \varphi(x_t) + r k_t\right\}, \tag{a28}$$

and

$$\dot{z}_t \leq 0 \text{ whenever } z_t = 0. \tag{a29}$$

The monopolist's new problem is to maximize its present value, eq. (8), subject to eqs. (2) and (a26)-(a29).

[20] A number of studies find a statistically significant relationship between R&D investment and internal finance, e.g., Himmelberg and Petersen (1994).

The current-value Lagrangian function, L_t, at time t is

$$\begin{aligned} L_t \equiv\ & \{\pi(d_t) - x_t - \varphi(x_t)\} e^{-rt} \\ & + \gamma_t (x_t - \delta d_t) \\ & + (\eta_t + \theta_t) \{\pi(d_t) - x_t - \varphi(x_t) + r k_t\}, \end{aligned} \tag{a30}$$

where η_t is the shadow value of k_t and θ_t is the Lagrangian multiplier that is active only when $k_t = 0$, i.e.,

$$-k_t \leq 0 \quad \theta_t k_t = 0. \tag{a31}$$

The optimal innovation, x_t, must satisfy the condition, $\partial L_t / \partial x_t = 0$, or

$$\{1 + \varphi'(x_t)\} \left(e^{-rt} + \eta_t + \theta_t\right) = \gamma_t, \tag{a32}$$

for all t. The condition simply states that the marginal benefit from a unit of investment, i.e., the right side of eq. (a32), must be equal to its marginal cost, i.e., the left side of eq. (a32).

The the law of motion of the costate variable, γ_t, is

$$\dot{\gamma}_t = \delta \gamma_t - \pi'(d_t) \left(e^{-rt} + \eta_t + \theta_t\right), \tag{a33}$$

and the law of motion of the costate variable, η_t, is

$$\dot{\eta}_t = -r(\eta_t + \theta_t). \tag{a34}$$

Differentiating eq. (a32) with respect to time and inserting it into eq. (a33) yields

$$\begin{aligned} \dot{\gamma}_t &= \{1 + \varphi'(x_t)\} \left(-r e^{-rt} + \dot{\eta}_t + \dot{\theta}_t\right) + \varphi''(x_t) \left(e^{-rt} + \eta_t + \theta_t\right) \dot{x}_t \\ &= -r \{1 + \varphi'(x_t)\} \left(e^{-rt} + \eta_t + \theta_t\right) + \{1 + \varphi'(x_t)\} \dot{\theta}_t + \varphi''(x_t) \left(e^{-rt} + \eta_t + \theta_t\right) \dot{x}_t. \end{aligned} \tag{a35}$$

By equating eqs. (a33) and (a35), we get

$$\begin{aligned} & \delta \{1 + \varphi'(x_t)\} \left(e^{-rt} + \eta_t + \theta_t\right) - \pi'(d_t) \left(e^{-rt} + \eta_t + \theta_t\right) \\ = & -r \{1 + \varphi'(x_t)\} \left(e^{-rt} + \eta_t + \theta_t\right) + \{1 + \varphi'(x_t)\} \dot{\theta}_t + \varphi''(x_t) \left(e^{-rt} + \eta_t + \theta_t\right) \dot{x}_t. \end{aligned} \tag{a36}$$

Rearranging eq. (a36) gives the law of motion of x_t,

$$\dot{x}_t = \frac{1}{\varphi''(x_t)} \left[(r + \delta) \{1 + \varphi'(x_t)\} - \pi'(d_t)\right] + \frac{1 + \varphi'(x_t)}{\varphi''(x_t)} \frac{-\dot{\theta}_t}{e^{-rt} + \eta_t + \theta_t}. \tag{a37}$$

In the case when the monopolist's retained earnings are positive, i.e., $k_t > 0$, the financial constraint is not active, i.e., $\theta_t = \dot{\theta}_t = 0$. Then eq. (a37) reduces to eq. (12). The monopolist in this case behaves the same as the one in a perfect capital market. On the other hand, when the retained earnings dry up, i.e., $k_t = 0$, the financial constraint is active, i.e., $\partial L_t / \partial \theta_t = 0$. Then, the optimal innovation is

$$x_t = \pi(d_t) - \varphi(x_t). \tag{a38}$$

That is, the optimal innovation, x_t, is just as large as the firm's current gross profit. In this case, it is clear that any price-cap regulation has an immediate and negative effect on x_t.

Appendix 5: Data

Industry sector	Hall (2007)'s depreciation rats	SIC codes	NAICS codes	Industry	R&D % net sales
Chemicals	28.6	28	3252	-Resin, synthetic rubber, fibers, and filament	4.4
		28	other 325	-Other chemicals	3.3
		28	3251	-Basic chemicals	2.3
		30	326	Plastics and rubber products	2.1
		29	324	Petroleum and coal products	0.3
Computers & inst	20.4	367	3344	-Semiconductor and other electronic components	9.2
		38	3345	-Navigational, measuring, electromedical, and control instruments	7.4
		365	other 334	-Other computer and electronic products	6.9
		357	3341	-Computers and peripheral equipment	6.8
Drugs & med inst	16.3	283	3254	-Pharmaceuticals and medicines	9.2
Electrical	37.2	366	3342	-Communications equipment	14.7
		384	3391	-Medical equipment and supplies	9.2
		372 376	3364	-Aerospace products and parts	3.0
		36	335	Electrical equipment, appliances, and components	2.4
Metals & machinery	14.5	35	333	Machinery	4.0
		371	3361–63	-Motor vehicles, trailers, and parts	3.0
		37	other 336	-Other transportation equipment	2.3
		34	332	Fabricated metal products	1.5
		33	331	Primary metals	0.6
Miscellaneous	5.3	39	other 339	-Other miscellaneous manufacturing	2.8
		32	327	Nonmetallic mineral products	1.6
		26 27	322, 323	Paper, printing, and support activities	1.5
		22 23 31	313–16	Textiles, apparel, and leather	0.8
		25	337	Furniture and related products	0.8
		24	321	Wood products	0.8
		20 21	312	Beverage and tobacco products	0.5
		20	311	Food	0.5

Table A1: R&D capital depreciation rates and R&D % of net sales

Column 1: names of six manufacturing sectors studied in Hall (2007)
Column 2: market-value-based depreciation rates of R&D capital in Hall (2007)
Column 3: SIC codes
Column 4: NAICS codes
Column 5: names of industries
Column 6: R&D funds as a percent net sales

PS (1989)'s patent renewal rates		SIC codes	Roeger (1995)'s markups
Group 1	Food and kindred products	20 Food And Kindred Products	1.5
	Chemicals and allied products	28 Chemicals And Allied Products	2.11
	Machinery	35 Industrial And Commercial Machinery And Computer Equipment	1.41
	Drugs and medicines	28 Chemicals And Allied Products	2.11
	Rubber and plastic products	30 Rubber And Miscellaneous Plastics Products	1.36
	Lumber, wood, and paper	24 Lumber And Wood Products, Except Furniture	1.75
Group 2	Communication equipment	36 Electronic And Other Electrical Equipment And Components, Except Computer Equipment	1.34
	Professional, scientific, and electrical equipment	38 Measuring, Analyzing, And Controlling Instruments; Photographic, Medical And Optical Goods; Watches And Clocks	1.47
Group 3	Primary metals	33 Primary Metal Industries	1.58
	Fabricated metals	34 Fabricated Metal Products, Except Machinery And Transportation Equipment	1.33
	Stone, clay, and glass	32 Stone, Clay, Glass, And Concrete Products	1.59
Group 4	Farm, motor, and air	37 Transportation Equipment	1.64
Group 5	Other	21 Tobacco Products	excl.
	Other	23 Apparel And Other Finished Products Made From Fabrics And Similar Materials	1.15
	Other	31 Leather And Leather Products	1.19
	Other	25 Furniture And Fixtures	1.28
	Other	26 Paper And Allied Products	1.57
	Other	27 Printing, Publishing, And Allied Industries	1.4
	Other	39 Miscellaneous Manufacturing Industries	1.62
	Textiles, apparel, and leather	22 Textile Mill Products	1.34

Table A2: patent renewal rates and markups

Column 1: patent renewal rate Group 1 (highest) to Group 5 (lowest) in Pakes and Simpson (1989)

Column 2: names of industries

Column 3: SIC codes

Column 4: markup ratios in Roeger (1995)[21]

[21] Tobacco (SIC code: 21) and petroleum (SIC code: 29) are excluded as high taxes on these products make the markup estimates for these industires more complicated.