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From experience, regulated monopolists learn to employ cost-reducing innovations. We characterize the optimal regulation of an innovating monopolist with unknown costs. Regulatory policy is designed to minimize current costs of service while encouraging development of cost-saving innovations. We find that under optimal regulation, (i) innovation is encouraged by light-handed regulation allowing the monopolist to earn greater information rents while providing greater service, (ii) innovation occurs in the absence of long-term agreements when private information is recurring, and (iii) innovation is more rapid in a durable franchise, and the regulator prefers durable franchises for exploiting learning economies.

1. Introduction

■ Beginning with the seminal article by Baron and Myerson (1982), an elegant theory of incentive regulation has developed that outlines how a regulator optimally directs a service provider, who is privately informed about the cost of service. This theory generates a rich set of regulatory prescriptions for a wide variety of procurement and franchise environments.[1] However, the extant theory mostly pertains to stationary settings in which technology and the expected cost and value of service do not change systematically with time.[2] An important omission of current theory is that one expects technology improvements to systematically alter the cost and value of service in regulated industries like telecommunications and electricity.[3] Further, current and

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[1] The theory of incentive regulation and a comprehensive review of the literature are summarized nicely in Laffont and Tirole (1993).

[2] Important exceptions are Baron and Besanko (1984) and Laffont and Tirole (1993). See the latter work, Chapters 1, 9, and 10 and the references cited therein, for an overview of this theory.

[3] In electricity markets, the development of alternating current, improvements in controlling generation and transmission, and the introduction of load control and conservation measures have significantly reduced the cost of service. In telecommunications markets, the development of advanced wire and wireless technologies, the improvement of switches, and advances in data processing have created lower-cost service.

future regulations affect the pace of innovation. Therefore we expect regulators to enact current policy anticipating its impact on the rate of innovation and the future expected cost and value of service.

This article examines the optimal regulation of a privately informed service provider in a setting where the expected cost of future service depends on the level of previous service provided. The volume of previous service supplied is a measure of the supplier's "experience" or "knowledge." More experienced producers may reduce their future cost of service by employing superior technologies and better procedures to generate, coordinate, and deliver service to their customers.[4] The regulated firm enjoys learning economies that enable it to reduce the future cost of service to consumers. The primary focus of our analysis is to study how incentive regulation should be designed for encouraging suppliers to develop and adopt cost-saving technologies.

The setting we analyze consists of a monopoly service supplier that is regulated by a commission acting on behalf of consumers. The monopolist's total unit cost of service comprises an intrinsic cost, determined by the current technology, and a temporal cost, which varies each period according to economic and market conditions. We assume the intrinsic cost is publicly known, since one can readily observe the firm's technology for generating service. However, only the supplier knows the current temporal cost reflecting existing supply conditions.[5] Periodic changes in intrinsic costs arising from the implementation of a new technology occur with a probability that is increasing in the service level previously offered.

In practice, long-term regulatory agreements are infeasible. This reflects the inability of regulatory bodies to legally commit to multiyear franchise arrangements.[6] Consequently, the regulator offers short-term agreements that are renegotiated periodically. To model the regulator's limited commitment ability most simply, we assume regulatory agreements are renegotiated each period. Aside from being realistic, this assumption permits us to examine the stability of franchise arrangements and to discover how investments in innovation may exist without binding long-term agreements.[7]

Section 2 presents the formal model. We assume the regulator and monopolist select strategies based on the payoff-relevant history of play. History is completely summarized by the existing supply technology. Technology evolves stochastically through time, determined by the previous sequence of regulatory agreements. We employ dynamic programming arguments to analyze the parties' selection of strategies to maximize their immediate expected return plus future expected continuation value of the franchise. This enables us to generate the players' dynamic decision rules and to characterize the unique Markov-perfect equilibrium (MPE) of this regulation game.

Section 3 investigates how franchise agreements are optimally tailored to promote innovation. We find the supplier and regulator both make concessions to hasten the arrival of cost-reducing technology. Innovation is more rapid when current service is increased, enabling the supplier to accelerate his rate of learning. To facilitate learning, the supplier agrees to provide service at lower cost, and the regulator offers greater compensation for service provided. It is noteworthy that

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[4] Evidence of productivity gains in regulated industries is reflected in the productivity offsets required under price-cap regulation. Productivity offsets reduce rates to correspond to productivity gains the firm is expected to achieve each year. Berndt (1991) contains a nice survey of empirical evidence and techniques for documenting the importance of experience in reducing production costs.

[5] For instance, it seems reasonable to assume that regulators can observe a new technology for generating electricity installed by the monopoly supplier. However, current supply conditions affecting the availability and price of fuel are likely to be privately known by the regulated monopolist.

[6] The inability of regulatory commissions to commit future commissions to a regulatory policy is well documented. Levy and Spiller (1996) provide an enlightening summary of the various ways that regulators abuse their administrative discretion. Nonetheless, regulators do attempt to establish intermediate-term commitments to follow pricing policies, such as multiyear price-cap agreements.

[7] If long-term regulatory agreements were feasible, it would be possible "in theory" for the regulator to achieve the first-best, full-information optimum for our setting (see d'Aspremont and GérardVaret (1979) and Rogerson (1992)). This would require the firm to sign a long-term contract stipulating all payments and supplies of service to be delivered currently and in the future conditional upon future supply conditions. The contract would be negotiated before the firm was privately informed about its costs of production. We note that although such optimal contracts exist, they require strong (and unrealistic) conditions to be satisfied.

concessions arise in equilibrium without long-term agreements for dividing the surplus arising from innovation between the firm and consumers.

Section 3 also illustrates, as expected, that the regulator does lower the firm's payment to coincide with its reduction in supply costs. However, this ratcheting down of service payments does not eliminate the firm's incentives to invest and implement cost-saving technology. The firm's private information about current supply conditions enables it to earn greater information rents when supply costs fall and the regulator demands more service. This is a noteworthy finding that contrasts with several earlier studies suggesting that regulators' opportunistic behavior may preclude utilities from investing.[8] This finding also has implications for the durability of franchise agreements. The regulator will prefer dealing long term with a single supplier rather than periodically shifting between suppliers. This is because investment incentives are greatest for long-lived suppliers.

Settings may also occur where supply costs rise with previous production. For instance, future costs of supplying electricity may increase when inexpensive and environmentally benign fuel inputs are used up from previous production. In Section 4 we consider this setting and find that the observations reported for the declining-service-cost case are reversed here. Specifically, we find that the regulator and monopolist become "tougher" negotiators, with current service levels decreasing in anticipation of higher future supply costs. Further, the regulator prefers less-durable franchises, where service suppliers are replaced with great frequency.

Section 5 summarizes our findings and discusses some procurement and regulatory issues relating to the insights developed in the article. Proofs of all formal results appear in the Appendix. Our findings pertain to several previous articles on dynamic regulation, price-cap regulation, learning by doing, and the durability of bilateral relationships. We will relate our findings to these studies in the process of discussing our results.

2. A model of dynamic regulation

■ Our model is a straightforward extension of Baron and Myerson (1982) to allow for cost-reducing innovation.[9] The parties consist of a risk-neutral utility and a regulator representing risk-neutral consumers. Each period the monopolist provides service, x, yielding a flow of utility $v(x)$ to consumers, where $v(\cdot)$ is strictly increasing and concave with $v(0) = 0$. The firm incurs a unit supply cost, $D(c, T) = d(T)+c$ consisting of two parts. The first component, $d(T)$, is the intrinsic cost depending on T, the current technology or resources available to the firm. The state variable, T, assumes positive integer values, and a Poisson process, described below, governs its evolution from one state to another. In settings where the firm learns from previous production, $d(T)$ is decreasing as the utility employs better production techniques acquired through experience. Alternatively, $d(T)$ is increasing if T measures the degree of resource depletion resulting from previous production. The second cost component, c, is a transitory cost. The firm knows it privately, and it depends on the monopolist's current operating conditions and access to inputs. Transitory cost, c, is independently and identically distributed each period by the density $f(c) > 0$ for $c \in [c_L, c_H]$ with $h'(c) > 0$, where $h(c) = c + F(c)/f(c)$.[10] A noteworthy feature of our model is the recurrence of private information. Since there is no temporal correlation between different realizations of private costs, c, and the current state T is public knowledge, the regulator does

[8] Numerous studies including Kolbe and Tye (1991), Lyon (1991, 1992, 1995), Mayo and Flynn (1988), and Teisberg (1993) suggest that utilities will be reluctant to invest if they anticipate regulators will disallow these expenditures from the utility's rate base. In contrast, we show that investments in learning generate a sufficiently high return in equilibrium to induce innovation. However, the rate of innovation induced is slower than the socially optimal rate.

[9] We obtain the same qualitative results if our analysis is cast in terms of the Laffont and Tirole (1986) model of cost reimbursement. Details of our analysis for that model are available upon request.

[10] The expression $h(c)$ is called the virtual cost of supply by Baron and Myerson (1982) as it includes the cost of information rents earned by the privately informed firm. The requirement, $h'(c) > 0$, is a standard condition employed in hidden-information problems to ensure satisfaction of second-order conditions and the existence of separating equilibria.

not learn about the efficiency of the firm from observing its past behavior.[11] Strategic learning and signalling are significant aspects of most previous analyses of dynamic regulation. Here, we abstract from these issues to focus on the role of learning by doing and declining resources in regulation.

A simple Poisson process governs the evolution of T,

$$\lambda(T+1; x, T) = ax, \qquad a > 0, \tag{1}$$

where $\lambda(\cdot)$ is the probability the state moves from T to $T+1$ next period, given that the current output level is $x \geq 0$.[12] When learning occurs, equation (1) implies that the firm is more likely to inherit a superior technology next period, the more it produces currently.[13] We do not analyze the possibility of the monopolist reducing cost through direct investment, though we discuss it briefly in Section 5.

The dynamic relationship between the regulator and the utility is a series of short-term contracts. In practice, legal and administrative constraints prohibit a regulator from negotiating long-term service agreements with utilities. Firms are unable to credibly commit to an agreement for the future supply of service without knowing their costs of production. Negotiations between the firm and regulator begin each period with both parties observing the current state T. Only the firm observes its private cost c. Next, the regulator offers the firm a single-period contract $\{P(c, T), x(c, T)\}$. $P(\cdot)$ is the firm's payment, and $x(\cdot)$ is the firm's required supply of service. Both quantities are conditioned on the firm's report of its cost, c, and the state, T. The firm follows by either accepting or rejecting the contract. If the firm accepts the contract, it delivers $x(\cdot)$ and receives $P(\cdot)$. If the contract is rejected, the parties suspend negotiations until the next period. This is an ongoing process, beginning again next period with realizations of the state T and private costs c and the offering of a new contract by the regulator.

We model the ongoing relationship between the regulator and firm as a dynamic game. In each period the regulator selects a contract to maximize the expected present value of consumer surplus. The utility selects a level of service to maximize its expected present value of profits. We focus on Markov strategies in which the parties condition their actions solely on the current state T and on their private information (in the case of the utility). The focus on Markov behavior has intuitive appeal. In settings like ours where there is no long-term legal institution governing the franchise, it seems reasonable for the parties to predicate their behavior on the current state as it directly affects their payoffs. Our approach to modelling strategic behavior differs from previous analyses by Gilbert and Newbery (1994) and Salant and Woroch (1991). These analyses investigate reputation equilibrium, whereby the regulator compensates the utility for its investment to maintain a reputation for honoring the regulatory compact. Although reputation concerns do not enter into our analysis, we find that investment behavior is nonetheless supported in equilibrium.

□ **Characterizing equilibrium.** One can simplify the characterization of this complicated dynamic interaction between the regulator and utility by using dynamic programming arguments. Denote by $V(T)$ and $W(T)$ the expected value of beginning the current period in state T for the regulator and firm respectively. Since the horizon is infinite and we restrict attention to

[11] This is in contrast to several earlier articles that examine repeated contracting and regulation in settings where the value of exchange or the cost of providing service remains constant and the contracting parties learn about each other's private information over time. See for example, Baron and Besanko (1984, 1987), Hart and Tirole (1988), Laffont and Tirole (1987, 1988, 1990), Lewis and Sappington (1997), and Meyer (1991).

[12] We bound the constant, a, from above to ensure that the probability of a transition from technology T to $T+1$ does not exceed one. In practice the rate of innovation might also depend on the current state of technology and on the cumulative production to date. We abstract from these features for simplicity.

[13] Our model relates to a large literature on learning by doing and industrial structure. Two articles most closely related to our formal analysis are by Cabral and Riordan (1994) and Habermeier (1992). These articles investigate the impact of learning by doing on oligopoly competition. In contrast, our article focuses on how regulated monopolies are induced to exploit learning economies in the absence of market competition.

Markov strategies, the value functions are independent of calendar time. The change arising in the regulator's and firm's value functions as the state moves from T to $T+1$ is, respectively, $\Delta V(T) \equiv V(T+1) - V(T)$ and $\Delta W(T) \equiv W(T+1) - W(T)$.

The optimal strategy for the firm with private cost c in state T is to select a cost report c' to

$$\max_{c'} \{P(c', T) - x(c', T)[d(T) + c] + \delta[W(T) + \lambda(T+1; x(c', T), T)\Delta W(T)]\} \tag{2}$$

when the regulator offers the menu of contracts $\{P(c', T), x(c', T)\}$. The regulated firm's expected profit in state T is

$$W(T) \equiv E_c W(T, c), \tag{3}$$

where $W(T, c)$ is the maximized value of firm profit in (2) and E_c is the expectation with respect to c. Notice that $W(T, c)$ consists of current-period payments minus production costs, plus the discounted (by $\delta \in (0, 1)$) stream of future profits. Future expected profits consist of the returns from beginning next period in the same state, $W(T)$, plus the probability the state increases next period to $T+1$ multiplied by the corresponding increase in profits $\Delta W(T)$.

The regulator's problem, designated by [R], is to offer a menu of contracts $\{P(c, T), x(c, T)\}$ to maximize $V(T)$ defined by

$$V(T) = E_c\{v(x(c, T)) - P(c, T) + \delta\{V(T) + \lambda(T+1, x(c, T), T)\Delta V(T)\}\} \tag{4}$$

subject to (2) and

$$W(T, c) \geq \delta W(T) \qquad \text{for all } c \in [c_L, c_H]. \tag{5}$$

According to [R] the regulator maximizes the sum of expected current-period surplus and expected discounted (by $\delta \in (0, 1)$) future surplus. Future surplus equals $V(T)$ plus the probability of transitioning to state $T+1$ multiplied by the corresponding increase in continuation value $\Delta V(T)$. This maximization is subject to (2), indicating how the firm optimally reacts to the regulator's contract menu. The maximization is also subject to the individual-rationality constraint, (5), indicating the minimum surplus the firm expects from contracting with the regulator. The firm can guarantee itself $\delta W(T)$, the discounted value of beginning next period in state T, by refusing to contract in the current period.

Combining the firm's optimal reporting strategy embodied in (2) with the regulator's optimal contracting strategy characterized by the solution to [R] enables us to establish necessary and sufficient conditions for a Markov-perfect equilibrium (MPE). Informally, a MPE consists of a pair of strategies for the firm and regulator constituting a perfect equilibrium for all payoff-relevant histories described by the state variable T. For technical reasons, we assume there exists some state $T^H > 0$ such that $d(T)$ is constant for all $T \geq T^H$.[14] In cases where learning reduces future supply costs, this assumption implies that cost converges to its minimum value after a finite number, T^H, of innovations. Given this assumption we can establish the following:[15]

Proposition 1. There exists a unique MPE to the dynamic regulation game. The optimal contract $\{P(c, T), x(c, T)\}$ supporting the MPE satisfies the following: $x(c, T)$ is strictly decreasing in c for $x(c, T) > 0$, and

(i) $v'(x(c, T)) - [d(T) + h(c)] + a\delta[\Delta W(T) + \Delta V(T)] \leq 0$ (= 0 if $x(c, T) > 0$)

(ii) $P(c, T) = [d(T) + c]x(c, T) + \int_c^{c^H} x(c', T)dc' - ax(c, T)\delta\Delta W(T)$

[14] Restricting $d(T)$ to be constant for T sufficiently large significantly simplifies our formal analysis. It permits us to solve for the equilibrium by backward induction. We define T^H to be the smallest T for which $d(T')$ is constant when $T' \geq T^H$.

[15] The equilibrium reported in Proposition 1 is for the case where some subset of the higher-cost types are shut down each period, so $x(c, T) = 0$ for c sufficiently large. This arises whenever the range of possible cost types is sufficiently large. For consistency and simplicity we focus on this case throughout.

(iii) $W(T) = E_c \left\{ \dfrac{x(c, T)[F(c)/f(c)]}{1-\delta} \right\}$

(iv) $V(T) = E_c \left\{ \dfrac{x(c, T)[F(c)/f(c)]h'(c)}{1-\delta} \right\}$.

The proof of this proposition and all formal results to follow are contained in the Appendix. According to part (i) of Proposition 1, in equilibrium the output assigned to a firm of type $\{c, T\}$ maximizes the net benefit from service by setting marginal net benefit to zero when output is strictly positive. Net marginal benefit includes the marginal benefit from current consumption, $v'(x)$, minus the marginal cost of production, $(d(T)+c)$, and the firm's information rents, $F(c)/f(c)$, plus the discounted expected change in future surplus from an increase in output, given by $a\delta[\Delta W(T)+\Delta V(T)]$. Part (ii) indicates that the firm receives a payment equal to its direct cost of production, $[d(T)+c]x(c, T)$, plus the rent accruing from its private information, minus the expected increase in future revenue resulting from an improvement in technology, $ax(c, T)\delta\Delta W(T)$. Notice that the regulator taxes away the firm's additional expected surplus from a technology improvement, $ax(c, T)\delta\Delta W(T)$, by lowering the firm's payment by that amount. Parts (iii) and (iv) provide a convenient closed-form expression for the expected surplus earned by the firm and regulator respectively.

3. Dynamic regulation: learning by doing

■ This section characterizes optimal regulation when the monopolist learns to reduce service cost with experience. To capture the possibility of service costs declining with previous production, we introduce the following:

Assumption 1. $d(T)$ is weakly decreasing in T for $T \leq T^H$ and $d(T^H - 1) > d(T^H)$.

Assumption 1 implies that intrinsic cost, $d(T)$, is weakly decreasing and that $d(T^H)$ is the minimal intrinsic cost the firm can achieve. Since $d(T)$ is only weakly decreasing, service costs may strictly decline only after several improvements in technology.

In settings where supply costs decrease with experience, it seems likely that both parties benefit as the franchise matures.[16] This conjecture is confirmed in the next proposition.

Proposition 2. If Assumption 1 is satisfied, the equilibrium value functions for the firm and the regulator, $W(T)$ and $V(T)$, are strictly increasing in T for $T < T^H$.

Proposition 2 indicates that transitioning to a higher technology strictly increases both the firm's flow of future profits and the future flow of consumer surplus even when the new technology does not strictly reduce service costs. Apparently, each technology transition moves the firm closer to an eventual cost-reducing state, thus increasing the future flow of profits and consumer surplus. There are two noteworthy implications of this result, which we shall explore further in the next two subsections. First, regulation must be tailored to encourage learning and cost-reducing innovation. Second, the regulator must somehow guarantee the firm an adequate return on its investment in learning to facilitate innovation.

□ **Regulation to exploit learning economies.** How is regulation tailored to exploit learning economies? To answer this question, it is instructive to review the properties of the single period or static regulatory equilibrium as first analyzed by Baron and Myerson (1982). In a static environment without learning, technology remains at its initial level, T, throughout time. In this case the optimal regulated service schedule, denoted by $x^0(T, c)$, satisfies

$$v'(x^0(c, T)) - [d(T) + h(c)] \leq 0 \qquad (= 0 \text{ if } x^0(c, T) > 0). \tag{6}$$

[16] This requires stationary demand. If demand were to decrease over time, or with previous consumption, consumers might not benefit with improvements in technology over time.

According to (6), the regulator selects service to maximize only current net benefits. Current service does not affect future benefits, in contrast to settings in which learning arises due to the experience gained from providing current service. A comparison of the service levels induced in settings where learning does and does not occur and the impact of learning on induced service is summarized in the next proposition.

Proposition 3. If Assumption 1 holds, then for $T \leq T^H$,

(i) $x(c, T) \geq x^0(c, T)$, with (>) for $x(c, T) > 0$.
(ii) $x(c, T)$ is strictly increasing in T, for $x(c, T) > 0$.

Part (i) of Proposition 3 indicates that the regulator optimally induces greater service from the firm when learning economies exist. The regulator induces the firm to provide greater service to expedite the adoption of new cost-reducing technology. The arrival of advanced technologies benefits both the firm and consumers. These benefits are manifested in two ways, both leading to the firm's increasing its service level. First, the marginal cost of inducing the firm to supply more service is reduced by the amount $a\delta\Delta W(T) > 0$ when learning is possible. This amount is the expected increase in the firm's future profits resulting from an increase in present service. The firm supplies service at a lower price expecting to earn greater profits in the future, and since service costs are reduced, the regulator optimally induces more output from the firm.

The second factor leading to greater service is that marginal benefit to consumers from service increases by the amount $a\delta\Delta V(T) > 0$ when learning is possible. This amount measures the additional future expected consumer surplus from a marginal increase in current service. As a consequence of this added marginal benefit, the regulator induces the firm to provide greater service compared to the static, no-learning case.

The regulator induces greater service, anticipating returns from learning in the future. This anticipatory behavior may also improve current regulatory performance. In a static setting the regulator induces too little service to limit the monopolist's information rents. When the regulator induces greater service to encourage innovation, it may bring current production closer to static efficiency levels, thus improving current performance.

Part (ii) of Proposition 3 implies that the firm supplies greater service as operating costs decrease. This result may seem surprising to some readers. After all, as technology improves, the incentives to increase service to learn decrease as the returns from learning are eventually exhausted. Although the learning benefits from service decline, the cost of supplying service decreases when technology improves. This cost reduction causes the regulator to induce a greater level of service overall.[17]

□ **Incentives to innovate and the distribution of gains from learning.** Proposition 2 indicates that learning economies resulting in an improved technology strictly benefit the firm and consumers in the future.[18] To examine the distribution of learning gains between the firm and consumers, we compute $\Delta W(T)/[\Delta W(T) + \Delta V(T)]$ to measure the percentage of technology gains accruing to the firm. From parts (iii) and (iv) of Proposition 1, we compute this ratio as

$$\frac{\Delta W(T)}{\Delta W(T) + \Delta V(T)} = \frac{E_c\{[x(c, T+1) - x(c, T)]F(c)/f(c)\}}{E_c\{[x(c, T+1) - x(c, T)]F(c)/f(c)[1 + h'(c)]\}}. \tag{7}$$

An easy interpretation of (7) arises for the case where $F(c) = [(c - c_L)/(c_H - c_L)]^\eta$ with $\eta > 0$. This is an isoelastic generalization of the uniform distribution with $\eta = 1$ corresponding

[17] For a technical explanation, recall from Proposition 1 that the $V(T)$ is an increasing function of the service levels $x(T, c)$ and from Proposition 2 that $V(T)$ is increasing in T. Therefore as T increases it must be that the service levels are increasing in order for $V(T)$ to increase.

[18] This result relies on the assumption of stationary demand. If demand were to be contracting over time, consumers might not benefit as the franchise matures.

to the uniform density. For this case, $h'(c) = 1 + 1/\eta$, and (7) simplifies to

$$\frac{\Delta W(T)}{\Delta W(T) + \Delta V(T)} = \frac{1}{2 + \frac{1}{\eta}}. \tag{8}$$

Inspecting (8), it is clear that when η is small, consumers capture most of the additional surplus from a technology advance. When η is small, most of the probability mass is concentrated on small values of c. Knowing that the monopolist's costs are likely to be small, the regulator can safely offer the firm a demanding contract requiring it to supply significant service with small compensation. Conversely, when η is large, there is a substantial probability that the firm's private cost of service is high. So the regulator must offer the firm more generous compensation to supply service, thus enabling the firm to capture a greater share of the surplus generated from the technology improvement. In the limiting case where η becomes large, the firm's ability to command information rents grows to such an extent that it and consumers share equally in the gains from learning.

Although the firm shares in the future surplus gain from a cost-reducing innovation, the regulator taxes away the firm's increase in future surplus by offering lower payment for current service. Recall from part (ii) of Proposition 1 that the monopolist's payment is given by

$$P(c, T) = [d(T) + c]x(c, T) + \int_c^{c^H} x(c', T)dc' - ax(c, T)\delta\Delta W(T).$$

This formula indicates that payment is reduced by $[ax(c, T)\delta\Delta W(T)]$, the monopolist's expected increase in future surplus. This reduction in payment is similar to the productivity offset employed to adjust service rates under price-cap regulation. Accepting lower payment for service constitutes a relationship-specific investment the firm makes to increase the future surplus generated by the franchise. Although the monopolist is not guaranteed a return on his investment absent a long-term regulatory agreement, having a persistent source of private information that does not erode with experience permits the monopolist to earn a sufficient return to warrant his investment in learning. However, the level of investment is not efficient. This is because the firm does not capture the full share of future surplus created by the cost-reducing innovation.[19]

Finally, notice that investment arises in our setting without an implicit "regulatory compact" supported by reputation concerns as modelled in Gilbert and Newbery (1994) and Salant and Woroch (1991). Our findings suggest that earlier analyses of multiperiod regulation presuming that the monopolist's private knowledge is eventually revealed may overstate the difficulties arising from limited regulatory commitment.

□ **Implementation of dynamic regulation.** A type of price-cap regulation could implement the dynamic regulatory scheme that we have outlined above.[20] Assume the regulator offers the firm a choice of two-part tariffs $\{P(c, T), p(c, T)\}$ based on the firm's transitory cost of service, c, and its current technology, T. $P(c, T)$ is a lump-sum payment or tax the firm receives or pays, and $p(c, T) = v'(x(c, T))$ is the price for which consumers would demand $x(c, T)$ units of service, assuming $v(x)$ measures consumers' utility of service. The offering of two-part tariffs is standard in incentive-regulation analysis, but it is sometimes not offered in practice. In principle, though, regulators could assess consumer access fees to finance lump-sum payments to firms. Think of the price schedule $\{p(c, T)\}$ as a price-cap menu that permits the firm to choose a service price

[19] Laffont and Tirole (1993) similarly find investment is suboptimal when a regulated firm invests in cost-reducing technology that is not generated by learning by doing.

[20] See the *RAND Journal Symposium on Price-Cap Regulation* (1989) and Sappington and Weisman (1996) for a summary of price-cap regulation.

based on its current cost of service and technology. And notice, like price-cap regulation, that whenever the firm implements a more advanced technology (as T increases) and the expected cost of service declines, the price-cap menu would be adjusted down. This is implied by part (ii) of Proposition 3, which reports that service levels are increasing (and thus service prices must be decreasing) as technology improves.

Although our regulatory scheme would resemble price-cap regulation, it would differ from it in some important respects. With price-cap regulation, real prices would typically be reduced annually by the forecasted rate of technology improvement. Under our scheme, it would be the firm that triggers a reduction in prices by implementing the improved technology.[21] With price-cap regulation the firm would be either under- or overcompensated when actual technology growth was less (or greater) than the forecasted growth rate. Price-cap regulation would require the regulator to commit to a price revision plan that did not permit the regulator to adjust prices to tax away the extra profit firms would sometimes earn. Under our scheme, the regulator would have no incentive to renegotiate prices. The regulator would set prices each period to maximize current plus future expected surplus flowing to consumers. With price caps, the firm and consumers would share the extra surplus derived from a technology improvement. Under our scheme, the regulator would tax away the entire expected gain in surplus from a technology improvement. Nonetheless, the firm would invest to discover and implement cost-reducing technologies, because it would earn additional rents once the price-cap schedule was revised.

□ **Durability of the franchise relationship.** Until now we have assumed that the same firm continually serves consumers. However, conceivably the firm may go out of business or leave to service other customers. This subsection analyzes the regulator's preference for dealing with short-lived and long-lived firms. Suppose there is some exogenous survival probability $\mu \in [0, 1]$ the firm remains to serve consumers for another period. This probability depends on factors not explicitly modelled here that include the firm's outside opportunities and consumers' inclination to switch suppliers. Assume with probability $(1 - \mu)$ the firm leaves the franchise, whereupon it is immediately replaced by another supplier. It is costless for consumers to switch suppliers, and the new supplier is able to adopt the incumbent's existing technology. This would arise, for instance, if consumers own the equipment that firms utilize to provide service, as often occurs with municipal utilities. Assuming that the firm is costlessly replaced without loss of technological knowledge is unrealistic, but it serves to reinforce the findings reported in the next proposition.

Proposition 4. Given Assumption 1, the regulator prefers the most durable franchise with $\mu = 1$.

The intuition for Proposition 4 follows from our earlier discussion of how one optimally regulates to exploit learning economies. Learning is best cultivated in a durable relationship. A long-lived firm willingly provides service at reduced compensation in anticipation of increased future profits from learning. The value of learning is reduced when the firm's tenure is limited. Consequently, the firm requires larger payment for current service if it does not expect to share in the returns from learning. The regulator reacts by decreasing the level of service demanded in current periods, thus retarding the rate of innovation. All of this conspires to reduce the future surplus from learning generated under the franchise. This further suggests that the turnover of regulated firms should be small in settings where learning economies are important and that the rate of innovation is likely to be greater in durable relationships.[22]

4. Dynamic regulation with increasing costs

■ In some settings, supply costs may rise with previous production. For instance, the cost of electricity may increase over previous production if the utility exhausts the supply of inexpensive

[21] Our mechanism is similar to firm-triggered rate reviews as in Joskow (1974).

[22] This prediction is consistent with McCabe (1996), who reports that suppliers learned to reduce design and construction costs of electric power plants more when they worked for one rather than several customers over time.

fuels.[23] We formally describe the setting where supply costs rise with previous production by the following assumption:

Assumption 2. $d(T)$ is weakly increasing in T for $T \leq T^H$ and $d(T^H - 1) < d(T^H)$.

According to the assumption, production costs are weakly increasing until they reach an upper bound level of $d(T^H)$.

Under Assumption 2, the beneficial effects on regulation arising from the possibility of future cost reduction are no longer present. In fact, there is an adverse side to dynamic regulation. Current service is reduced below the level that would prevail in a static setting, and expected profits and consumer surplus fall as the regulatory relationship matures. We record these findings in the next proposition.

Proposition 5. If Assumption 2 is satisfied,

(i) the equilibrium expected firm profits $W(T)$ and expected consumer surplus $V(T)$ are strictly decreasing in T, for $T < T^H$;
(ii) service, $x(c, T)$, is strictly decreasing in T for $x(c, T) > 0$;
(iii) $x(c, T) < x^0(c, T)$, with $(<)$ for $x^0(c, T) > 0$;
(iv) the regulator prefers short-lived franchises, with μ as small as possible.

When production costs are increasing, both parties realize that an increase in current service will cause expected costs to rise in the future. This increase in costs reduces the expected surplus both parties expect as reported in part (i) of Proposition 5. Greater future costs cause the regulator to induce smaller service levels as access to inputs deteriorates as reported in part (ii). The firm requires greater compensation in current periods to supply service as compensation for the reduction in profits arising in the future. Similarly, the regulator receives smaller benefits from current production service, since future expected surplus decreases as current service increases. These two effects lead to the finding in part (iii) that the regulator reduces service below the level occurring in a static setting.

Part (iv) of Proposition 5 examines the regulator's preference for franchise durability in this setting. When parties expect their relationship surplus to decline with experience, they will seek less durable relationships. The advantage of a short-term franchise is that the firm is willing to supply current service at a lower cost, when its future stake in the franchise is reduced. An increase in current service does not diminish the firm's future profits if it is unlikely to be serving the same consumers again. The regulator prefers to engage firms with a short time horizon because they are "softer" bargainers, willing to accept smaller payment to provide current service.

Combining part (iv) of Proposition 5 with Proposition 4 suggests that the regulator's preference for durable franchises depends on the potential for the relationship to grow. In growing environments where technological advance is likely to reduce future service costs, consumers will prefer maintaining a stable relationship by retaining a single supplier throughout the lifetime of the franchise. This naturally assumes that only a single firm may supply consumers at one time. (Below we briefly discuss the possibility of several suppliers serving customers simultaneously.) Conversely, when exchange surplus decreases with previous production, regulators prefer short-term franchises with frequent turnover of service suppliers.

5. Conclusion

■ Technological progress resulting in less costly service is important in regulated industries, especially telecommunications and electricity. This article extends the incentive-regulation literature by characterizing the optimal regulation of an innovating monopolist with private and changing supply costs. Our principal findings are as follows: (1) the regulator induces learning

[23] The cost of fuel might increase because it is more difficult to obtain, or because it is dirtier and requires more cleanup to meet environmental emission standards.

and innovation through light-handed regulation that allows the monopolist to earn greater information rents while providing greater service, (2) both the monopolist and consumers strictly benefit from cost-reducing innovation, (3) innovation occurs in the absence of long-term agreements when private information is renewed each period, and (4) innovation is more rapid in a durable franchise, and the regulator prefers durable franchises for exploiting learning economies.

This article has focused on cost-reducing innovation. It seems clear that the results reported here would also apply when experience permits the monopolist to improve the quality of customer service. Besides learning by doing, other vehicles like R&D may exist for discovering new technologies. In these instances it would be interesting to analyze how the regulator induces the appropriate mixture of innovation activities.

In electricity and telecommunications markets, consumers are increasingly able to purchase services from nonregulated suppliers. Over time these suppliers may improve their service offerings and reduce their costs of supply to become more competitive with the regulated firm. An interesting extension to the current analysis would be to consider the regulator's optimal policy toward outside suppliers who, like the regulated firm, may reduce their costs through learning by doing. The regulator may encourage consumers to purchase from nonregulated suppliers to increase competition and provide ratepayers with alternative sources of supply. This might also allow the regulator to reduce the regulated firm's rents by comparing its performance to the performance of other suppliers in the market. The regulator might also encourage rival service suppliers to share technological information, to increase the rate of technology diffusion, and increase the rate of reduction in service costs.

Finally, the techniques developed here might also be applied to the study of optimal procurement policy. Cost reductions from learning are important in repeated procurements of factories, ships, aircraft, and weapons.[24] The optimal procurement procedure would trade off the advantages of purchasing from a single supplier to exploit learning economies against the benefits of dealing with several suppliers to maintain competition.

Appendix

■ Proofs of Propositions 1–5 follow.

Proofs of Propositions 1–3. For convenience we presume Assumption 1 holds, although the proof of Proposition 1 does not require this. In the text, we establish that any MPE is characterized by a menu of contracts $\{P(c, T), x(c, T)\}$ that maximize

$$V(T) = \max E_c\{v(x(c, T) - P(c, T) + \delta[V(T) + \lambda(T + 1; x(c, T), T)\Delta V(T)]\} \qquad \text{[R]}$$

subject to

$$W(T) = E_c \max_{c'}\{P(c', T) - [d(T) + c]x(c', T) + \delta[W(T) + \lambda(T + 1; x(c, T), T)\Delta W(T)]\} \equiv E_c W(T, c) \qquad \text{[IC]}$$

with

$$W(T, c) \geq \delta W(T), \qquad \text{for all } c \in [c_L, c_H]. \qquad \text{[IR]}$$

Without loss of generality, we require $c'(c) = c$ for all c by the revelation principle. By employing usual arguments for characterizing mechanisms satisfying [IR] and [IC] (see Fudenberg and Tirole, 1991), we require that

$$W(T, c) = \delta W(T) + \int_c^{c_H} x(c', T)dc' \qquad \text{(A1)}$$

$$x(c, T) \text{ is nonincreasing in } c. \qquad \text{(A2)}$$

Substituting for (A1) into the expression for $W(T, c)$ in [IC] establishes part (ii) of Proposition 1.

[24] The importance of learning economies is documented in Fox (1988) and Gansler (1989). Lewis and Yildirim (2000) apply some techniques developed here to study optimal procurement.

Substituting the expression for $P(c'(c), T)$ into [R], where $c'(c) = c$, and integrating by parts, one obtains

$$V(T) = \max_{x(c,T)\geq 0} \frac{1}{1-\delta} E_c \left\{ v(x(c, T) - [d(T) + h(c)]x(c, T) + ax(c, T)\delta[\Delta V(T) + \Delta W(T)] \right\}. \tag{A3}$$

The maximization in (A3) requires that part (i) of Proposition 1 be satisfied. Further, totally differentiating the expression in part (i) of Proposition 1 with respect to c confirms that $x(c, T)$ is strictly decreasing in c for $x(c, T) > 0$, as stated in the proposition.

To obtain part (iii) of Proposition 1, substitute from (A1) for $W(T, c)$ to obtain

$$W(T) = E_c[\delta W(T) + \int_c^{c_H} x(c', T)dc'] = E_c \left[\frac{x(c, T)F(c)/f(c)}{1-\delta} \right], \tag{A4}$$

where the second part of (A4) follows from the first by integrating by parts.

Part (iv) of Proposition 1 is obtained from (A3) by integrating by parts and employing part (i) of Proposition 1.

The proof of Proposition 1 is completed by showing that the value functions $V(T)$ and $W(T)$ exist and are unique. The proof is by induction, and in the course of this proof we also establish Propositions 2 and 3.

$\boldsymbol{T \geq T^H}$. For $T \geq T^H$, $d(T)$ is constant. Therefore, since the instantaneous payoff functions for both players are invariant with T for $T \geq T^H$, all states are payoff equivalent, implying $V(T) = V(T^H)$ and $W(T) = W(T^H)$ for $T \geq T^H$. In this case, part (i) combined with the fact $\Delta W(T) = \Delta V(T) = 0$ uniquely defines $x(c, T^H) = x(c, T)$ for all $T \geq T^H$ implicitly by

$$v'(x(c, T)) - [d(T) + h(c)] \leq 0 \qquad (= 0 \text{ if } x(c, T) > 0). \tag{A5}$$

Combining (A5) with parts (iii) and (iv), we have

$$W(T^H) = E_c \left[\frac{x(c, T^H)F(c)/f(c)}{1-\delta} \right] \tag{A6}$$

$$V(T^H) = E_c \left[\frac{x(c, T^H)[F(c)/f(c)]h'(c)}{1-\delta} \right]. \tag{A7}$$

$\boldsymbol{T = T^H - 1}$. Define $Z(T) = W(T) + V(T)$. By parts (iii) and (iv) of Proposition 1,

$$Z(T) = E_c[x(c, T)(1 + h'(c))F(c)/f(c)] \tag{A8}$$

$$\Delta Z(T^H - 1) = E_c[(x(c, T^H) - x(c, T^H - 1))(1 + h'(c))F(c)/f(c)]. \tag{A9}$$

Also, part (i) implies that $x(c, T^H - 1)$ is defined by

$$v'(x(c, T^H - 1) - [d(T^H - 1) + h(c)] + a\delta\Delta Z(T^H - 1) \leq 0 \qquad (= 0 \text{ if } x(\cdot) > 0). \tag{A10}$$

Equations (A9) and (A10) together define a mapping $G(\cdot)$ that maps values of $\Delta Z(T^H - 1)$ into $\Delta Z(T^H - 1)$. A fixed point of that mapping exists if

$$\Delta\tilde{Z}(T^H - 1) = G(\Delta\tilde{Z}(T^H - 1)) = E_c \left\{ [x(c, T^H) - x(c, T^H - 1; \Delta\tilde{Z}(T^H - 1))][1 + h'(c)]\frac{F(c)}{f(c)} \right\}, \tag{A11}$$

where $x(c, T^H - 1; \Delta\tilde{Z}(T^H - 1))$ is given by (A9), where $\Delta Z(T^H - 1) = \Delta\tilde{Z}(T^H - 1)$.

Note that $G(\Delta Z(T^H - 1))$ is continuously decreasing in $\Delta Z(T^H - 1)$, $\Delta Z(T^H - 1) = 0 < G(0)$, and that

$$\Delta Z(T^H - 1) = \frac{d(T^H - 1) - d(T^H)}{a\delta} > G\left(\frac{d(T^H - 1) - d(T^H)}{a\delta} \right) = 0,$$

implying that there exists a unique fixed point

$$\Delta\tilde{Z}(T^H - 1) \in \left(0, \frac{d(T^H - 1) - d(T^H)}{a\delta} \right). \tag{A12}$$

This fixed point uniquely determines $V(T^H - 1)$ and $W(T^H - 1)$, as $Z(T^H) = W(T^H) + V(T^H)$ is known and

$$Z(T^H - 1) = Z(T^H) + \Delta\widetilde{Z}(T^H - 1) \tag{A13}$$

$$W(T^H - 1) = E_c\left\{\frac{1}{1 + h'(c)}\right\} Z(T^H - 1) \tag{A14}$$

$$V(T^H - 1) = E_c\left\{\frac{h'(c)}{1 + h'(c)}\right\} Z(T^H - 1). \tag{A15}$$

Note also that (A12)–(A15) imply $\Delta W(T^H - 1)$ and $\Delta V(T^H - 1)$ are strictly positive. And part (iii) of Proposition 1 therefore implies $x(c, T^H) \geq x(c, T^H - 1)$, (with $>$ for $x(c, T^H) > 0$), thus establishing Proposition 2 and 3 for $T = T^H - 1$.

$\boldsymbol{T < T^H - 1}$. To complete the induction argument, suppose $W(T)$ and $V(T)$ exist and are unique for all $T' \geq T$ and $\Delta Z(T) > 0$ for all $T \leq T' \leq T^H - 1$. Then to show the existence and uniqueness of $W(T - 1)$ and $V(T - 1)$, we search for a fixed point satisfying

$$\Delta\widetilde{Z}(T - 1) = G(\Delta\widetilde{Z}(T - 1)) = E_c\left\{[x(c, T) - x(c, T - 1; \Delta\widetilde{Z}(T - 1))][1 + h'(c)]\frac{F(c)}{f(c)}\right\}, \tag{A16}$$

where $x(c, T - 1; \Delta\widetilde{Z}(T - 1))$ is determined by

$$v'(x(c, T - 1; \Delta\widetilde{Z}(T - 1)) - [d(T - 1) + h(c)] + a\delta\Delta\widetilde{Z}(T - 1) \leq 0 \quad (= 0 \text{ if } x(c, T - 1; \Delta\widetilde{Z}(T - 1) > 0). \tag{A17}$$

Note that $G(\Delta Z(T - 1))$ is continuously decreasing in $\Delta Z(T - 1)$, $\Delta\widetilde{Z}(T - 1) = 0 < G(0)$, and

$$\Delta\widetilde{Z}(T - 1) = \Delta Z(T) + \frac{d(T - 1) - d(T)}{a\delta} > G\left(\Delta Z(T) + \frac{d(T - 1) - d(T)}{a\delta}\right) = 0,$$

implying that there exists a unique fixed point satisfying

$$\Delta\widetilde{Z}(T - 1) \in \left(0, \Delta Z(T) + \frac{d(T - 1) - d(T)}{a\delta}\right). \tag{A18}$$

This fixed point uniquely determines $V(T - 1)$ and $W(T - 1)$, as $Z(T) = W(T) + V(T)$ is known and

$$Z(T - 1) = Z(T) + \Delta\widetilde{Z}(T - 1) \tag{A19}$$

$$W(T - 1) = E_c\left\{\frac{1}{1 + h'(c)}\right\} Z(T - 1) \tag{A20}$$

$$V(T - 1) = E_c\left\{\frac{h'(c)}{1 + h'(c)}\right\} Z(T - 1). \tag{A21}$$

Note also that (A18)–(A21) imply $\Delta W(T - 1)$ and $\Delta V(T - 1)$ are strictly positive. And part (i) of Proposition 1 therefore reveals $x(c, T) \geq x(c, T - 1)$, (with $>$ for $x(c, T) > 0$), thus establishing Propositions 2 and 3 for $T < T^H - 1$. *Q.E.D.*

Proof of Proposition 4. We let $\rho = \mu\delta$ denote the firm's effective discount factor and use the subscript ρ_i to indicate the dependence of the equilibrium strategies and payoffs on ρ_i. Arguing as in the proof of Proposition 1, MPE is characterized by the solution to the following problem:

$$V_\rho(T) = \max_{x_\rho(c,T)\geq 0} \frac{1}{1 - \delta} E_c\left\{v(x_\rho(c, T) - [d(T) + h(c)]x_\rho(c, T) + ax_\rho(c, T)[\delta\Delta V_\rho(T) + \rho\Delta W_\rho(T)]\right\}. \tag{A22}$$

The maximization in (A22) implies

$$v'(x_\rho(c, T^H - 1) - [d(T^H - 1) + h(c)] + a\Delta Z_\rho(T^H - 1) \leq 0 \qquad (= 0 \text{ if } x_\rho(\cdot) > 0), \tag{A23}$$

where $\Delta Z_\rho(T) = \delta \Delta V_\rho(T) + \rho \Delta W_\rho(T)$. The corresponding value function for the firm is given by

$$W_\rho(T) = E_c[\rho W_\rho(T) + (\delta - \rho)\overline{W} + \int_c^{c_H} x_\rho(c', T)dc'], \tag{A24}$$

where $\overline{W}$ is the firm's expected continuation value if it leaves the franchise for another market. The expressions in (A22) and (A24) can be integrated and rewritten to yield

$$V_\rho(T) = E_c\left[\frac{x_\rho(c, T)[F(c)/f(c)]h'(c)}{1-\delta}\right] \tag{A25}$$

$$W_\rho(T) = E_c\left[\frac{x_\rho(c, T)F(c)/f(c)}{1-\rho}\right] + \frac{\delta-\rho}{1-\rho}\overline{W}. \tag{A26}$$

Employing arguments used to prove Propositions 1–3, we know that a unique MPE exists for each value of ρ and that $\Delta W_\rho(T)$ and $\Delta V_\rho(T)$ are strictly increasing for $T < T^H$ under Assumption 1.

Consider different discounted survival probabilities $\rho_1 > \rho_2$. We wish to show that $V_{\rho_1}(T) > V_{\rho_2}(T)$ for all $T < T^H$. We argue by induction. Beginning with $T \geq T^H$, it is clear from (A25) that $V_{\rho_1}(T) = V_{\rho_2}(T)$, since $\Delta V_\rho(T) = \Delta W_\rho(T) = 0$ and therefore $x_\rho(c, T)$ is independent of ρ.

Consider $T = T^H - 1$. Suppose $\Delta Z_{\rho_1}(T) \leq \Delta Z_{\rho_2}(T)$. By (A23), that implies $x_{\rho_1}(c, T) \leq x_{\rho_2}(c, T)$. Since (A25) and (A26) imply

$$\Delta V_\rho(T) = E_c\left[\frac{(x_\rho(c, T+1) - x_\rho(c, T))[F(c)/f(c)]h'(c)}{1-\delta}\right], \tag{A27}$$

$$\Delta W_\rho(T) = E_c\left[\frac{(x_\rho(c, T+1) - x_\rho(c, T))[F(c)/f(c)]}{1-\rho}\right], \tag{A28}$$

and $x_{\rho_1}(c, T+1) = x_{\rho_2}(c, T+1)$, it follows that $\Delta V_{\rho_1}(T) \geq \Delta V_{\rho_2}(T)$ and $\Delta W_{\rho_1}(T) > \Delta W_{\rho_2}(T)$, thus contradicting our original supposition. Consequently,

$$\Delta Z_{\rho_1}(T) > \Delta Z_{\rho_2}(T). \tag{A29}$$

Then, (A23) and (A29) imply that

$$x_{\rho_1}(T) > x_{\rho_2}(T). \tag{A30}$$

From (A25) and (A30), it follows that $V_{\rho_1}(T) > V_{\rho_2}(T)$.

To complete our proof, suppose $V_{\rho_1}(T) > V_{\rho_2}(T)$ for all $T \leq T^H - 1$. If we assume $\Delta Z_{\rho_1}(T-1) \leq \Delta Z_{\rho_2}(T-1)$, we can employ the same argument by contradiction used above for the $T^H - 1$ case together with part (ii) of Proposition 3 to show that $\Delta Z_{\rho_1}(T-1) > \Delta Z_{\rho_2}(T-1)$, which implies $x_{\rho_1}(T-1) > x_{\rho_2}(T-1)$ from (A23). Then, from (A25), it follows that $V_{\rho_1}(T) > V_{\rho_2}(T)$. This completes our proof. *Q.E.D.*

Proof of Proposition 5. Proposition 5 is proved with the exact arguments employed in the proofs of Propositions 1–4, only under the conditions set out in Assumption 2 rather than Assumption 1. *Q.E.D.*

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