Endogenous Regulatory Delay and the Timing of Product Innovation

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Abstract

This paper endogenizes the interplay between innovation by a regulated firm and regulatory delay. When product innovation costs fall over time, an extra day of regulatory delay increases time to introduction by more than a day. In the signaling model, the firm therefore times its innovation to communicate its private information about the marginal cost of delay to the regulator. Successful signaling leads the regulator to reduce regulatory delay. The model places testable restrictions on the empirical relationship between innovation delay and regulatory delay. The model is consistent with data gathered from a large U.S. telecommunications provider.

JEL Codes: L51, L96

1 Introduction

The potential for economic regulation to distort the incentives of the firm to innovate is well known (e.g., Sweeney, 1981; Cabral and Riordan, 1989). Most of the literature examining regulation and innovation focuses on the impact of the type of regulatory regime (rate of return vs. incentive regulation, for example) or on the frequency of policy revision (the so-called "regulatory lag"). A little-explored avenue is the effect of regulatory delay on innovation.[1] Regulatory delay exists when the regulator does not allow the introduction of new products without regulatory review and approval. Regulated firms—for example, in the telecommunications, pharmaceutical, and banking industries[2]—often claim that regulatory delays are long, costly, and distort the incentives to introduce new products. The impacts may also run in the other direction: the firm's innovation decisions may reveal information to the regulator, which might adjust regulatory delay in response. This direction of causality—from firm's innovation to regulator's policy— is neglected in the literature to my knowledge. This paper explores the relationship between regulatory delay and the timing of the firm's innovation. The regulator adjusts delay as the firm, through its timing of innovation, reveals information about the cost of delay. The model I develop places testable restrictions on the empirical relationship between innovation delay and regulatory delay, and is consistent with data from an incumbent local exchange telephone company in the Midwest.

There are regulator-side and firm-side components to the delay between technological feasibility of a product and its introduction to consumers. The regulator-side component is the time between the firm's submission of a new product to the regulator for approval and the granting of approval. I term this component *regulatory delay* (the term is not intended to be pejorative; delay may have social benefits). The firm-side component is the time between the first technologically feasible

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[1] Note that "regulatory delay" is a different concept than "regulatory lag". The former refers to delayed introduction of a new product, whereas the latter refers to the term of regulatory commitment.

[2] Examples of regulatory delay in telecommunications are presented in this article. In the pharmaceutical industry, regulatory delay comes from required FDA approval of new drugs. Regulatory delay in the banking industry came from line-of-business restrictions before deregulation.

introduction date[3] and the submission of the product to the regulator. I term the firm's component *innovation delay.* Recent history in the telecommunications industry shows that innovation and regulatory delay tend to move in the same direction. In the data from the beginning of the 1990's from four Midwestern states examined here, a given new product tended to be introduced in different areas at very different times. For example, products were typically introduced in Ohio more than a year after availability in other states. By the end of the decade, product launches were more likely to be closer together among the states, and in some cases were simultaneous. On the other side, many state regulatory commissions have modified their policies over time to allow products to reach the market sooner. This pattern also shows up in these data. Furthermore, not only do innovation and regulatory delay both trend down over time, but my empirical analysis shows that regulatory innovation delay is positively correlated with innovation delay at the level of the individual product as well.

There are two non-exclusive explanations for the observed correlation between the firms' and the regulators' behavior that I explore. It may be that state regulatory commissions exogenously streamlined their procedures for product introductions by regulated firms, leading to shorter regulatory delay. In that case, I show that the profit-maximizing response of the firm is to reduce innovation delay. Regulatory delay reduces the opportunity cost of innovation delay for the firm by pushing the forgone profits from the new product farther into the future. When innovation costs fall over time, regulatory delay thereby induces the firm to postpone innovation. This explanation applies to the general trends noted, but does not address the product-specific correlation between regulatory and innovation delay. A second explanation that does is that regulators endogenously choose regulatory delay for an individual service based on the cost of delaying that service. I explore the latter explanation under full and asymmetric information and find that in both cases there is a positive correlation between regulatory and innovation delay in equilibrium. In the asymmetric information model, the firms hold private information about the cost of delay, and signal to the

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[3] I.e., the first date at which the introduction costs are less than infinite.

regulator through their innovation delay.

In the model with endogenous regulatory delay, the regulator trades off the benefit of reducing delay (quicker return on investment for the firm and earlier accrual of benefits for consumers) and the costs (loss of regulatory control, potentially lower quality of service, harm to competing firms, and the like). These costs stem from the regulator's "taste for delay". A few papers in political economy attempt to peer inside the black box of regulatory delay in other contexts (Ando, 1999; Dwyer, Brooks and Marco, 1999). Here, I take the regulator's preferences as exogenous and merely note that given the lengthy regulatory delay exhibited in the data analyzed here, there must be a strong taste for delay.

The trade-off between the costs and benefits of regulatory delay depends in part on the cost that regulatory delay imposes on the firm. The cost of delay to the firm is likely to be better known by the firm than the regulator. Unless the firm has the lowest possible delay cost, it would like to communicate its private information to the regulator. The firm can signal its cost of delay with an action that cannot be profitably mimicked by a firm with different cost. A costly action available to the firm is innovation delay. In particular, innovating sooner than the full-information optimal delay serves as a signal to the regulator.

The regulator must observe innovation delay for it to function as a signal. The regulator is not likely to know when products are technologically feasible. If the firm operates in several jurisdictions (e.g., a Bell Operating Company spanning several states), and the firm chooses to introduce new products at differing times in the various jurisdictions, each regulator learns from observing the firm's actions in the other jurisdictions. Once the product is introduced in one area, the regulator in another jurisdiction knows that introduction is technologically feasible.[4] The firm can then use

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[4] As long as the existing infrastructure among the jurisdictions is not too dissimilar. When looking at a single Bell Operating Company, as in my empirical application, this is not likely to be a problem. There evidence that regulators also use product introductions by out-of-area companies the reveal information about technoligical feasiblility. For example, around 2000 regulators in the Ameritech states pressured the firm to speed up introduction of digital subscriber line (DSL) service, based on observation that deployment by all the other major former Bell companies was ahead of Ameritech.

the time until subsequent submission for approval in the other jurisdictions as a signal.

It is important to understand the determinants of innovation delay. For example, regulators may delay approval of a new product because of concerns about the price at which it will be offered to consumers. However, welfare gains from introducing a new product (the so-called Dupuit triangle) are typically an order of magnitude higher than any deadweight loss from a supra-competitive price (the Harberger triangle).[5] By jointly modeling the determination of regulatory and innovation delay, this article breaks new ground on this important issue. The earliest literature on regulation and the timing of innovation looked at a monopolist's incentive to innovate given a fixed regulatory regime (Braeutigam, 1979). More recent work focuses on adoption timing as entry deterrence or accommodation under different regulatory regimes (Riordan, 1992; Lyon and Huang, 1995), but does not explicitly consider regulatory delay. This paper leaves aside rivalry considerations to focus on the relationship between the regulator and the firm. There are a few empirical studies of the impacts of regulatory delay on innovation and product introduction. Prager (1989) finds that regulatory delay by public utility commissions raises the cost of capital for electricity firms considering constructing new plants. Gruber and Verboven (2001) show that regulatory delay in the granting of operating licenses to providers had a persistent effect on the evolution of the mobile telecommunications industry in Europe. Prieger (2001, 2002a, 2002b) finds that increased regulatory delay is associated with fewer new telecommunications products introduced in several different contexts. Hazlett and Ford (2001) highlight the potential for firms to use regulatory delay to raise rivals' entry costs. These studies all focus on aspects other than asymmetric information and signaling.[6] Spiegel and Wilkie (1996) consider a model in which investment in a new technology has signaling value in a regulated environment, although the receiver of the signal in their model is the capital market, not the regulator.

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[5] Hausman (1997) quantifies of the high welfare cost of regulatory delay in telecommunications.

[6] In the only other empirical study of regulatory delay I found, Sanyal (2003) asserts that patent approval delays detrimentally affect the incentive of firms to innovate. However, the dependent variable in the estimations performed is patent approvals and not applications. Approvals would decline as patent delays increase merely due to queuing, even if the application rate were unchanged.

The outline of the paper is as follows. In the next section, I introduce a basic model of a firm's decision of when to introduce a new product. In Section 2.1 the regulatory environment is taken to be exogenous, and then in Section 2.2 regulatory delay is endogenized as the second period in a two-period game. Section 2.2 discusses both the complete information game and its asymmetric information extension. Section 3 presents the testable implications derived from the signaling model and introduces the data from a large incumbent local exchange telephone company that are used to perform the tests. Testing of the predictions is carried out in Section 4. The results show that the signaling model is consistent with the observed patterns of innovation delay and regulatory delay in all states tested.

2 The Theoretical Model

2.1 A basic model with fixed regulatory delay

I now introduce a simple model of regulated product introduction. Let time $t = 0$ represent the point at which a firm can first feasibly introduce a given product. The firm chooses to submit the product to the regulator for approval at time $s \geq 0$, at which time it incurs fixed cost $F(s)$. F may include the cost of development, adoption, or regulatory filing. The length of innovation delay s will be referred to as the innovation date.[7] Following Riordan (1992), fixed costs are assumed to be falling over time as exogenous technological advances lower the cost of adopting the new service. In dynamic industries such as telecommunications, it is realistic to assume that the fixed costs of innovation fall over time. I assume $F'(t) < 0$ and $F''(t) > 0$, and all functions in the model are assumed to be continuous and twice differentiable. Falling fixed costs give the firm an incentive to delay innovation. The regulator approves the service after an examination period (i.e., regulatory delay) of length b. Firms cannot sell and consumers cannot purchase the good until time $s + b$, the introduction date. After introduction, the firm earns constant flow profit of $\pi(\theta)$ per unit time,

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[7] Whether s represents true innovation or merely adoption of existing technology (diffusion), the structure of the resulting game is the same (although the interpretation of the results changes).

where θ is a parameter known to the firm but not the regulator.[8] There is a continuum of possible types, drawn from a compact set: $\theta \in [\theta^-, \theta^+] \subset \mathbb{R}$. I assume that $\pi'(\theta) > 0$, so larger θ might correspond to higher demand or to lower marginal costs. Note that π is not an explicit function of price; to focus on the strategic variable s I assume that the firm is allowed by the regulator to charge the profit-maximizing price,[9] which will be a function of θ. The firm's discount rate is r, so that its net present value of introduction at time s is:

$$\Pi(\theta, s, b) = -e^{-rs}F(s) + \int_{s+b}^{\infty} e^{-rt}\pi(\theta)dt = e^{-rs}\left(-F(s) + e^{-rb}\frac{\pi(\theta)}{r}\right) \tag{1}$$

The firm chooses optimal innovation date $s^* = \operatorname{argmax}_s \Pi$, which is defined by the first order condition:[10]

$$\frac{\partial \Pi(\theta, s, b)}{\partial s} = 0 \Rightarrow rF(s^*) - F'(s^*) = e^{-rb}\pi(\theta) \tag{2}$$

The left side of equation (2) is the marginal benefit from postponing innovation (the reduction in fixed costs), and right side is the marginal cost from postponing innovation (the forgone profit). Thus the firm's private information about θ can be interpreted as information about the firm's opportunity cost of delay.

Given the assumptions of the model, regulatory delay is unambiguously bad for the firm.

Proposition 1 $\partial \Pi / \partial b < 0$. *Longer regulatory delay lowers the firm's profit.*

From (1), $\partial \Pi / \partial b = -e^{-r(s+b)}\pi(\theta) < 0$. There is no provision in this model for beneficial regulatory delay. An example of positive delay is for the regulator to delay introduction until technical standards or coordination issues are resolved, which may reduce the firm's cost or increase demand for the service.[11]

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[8] The timing of the model is similar to that of Braeutigam (1979).

[9] Many of the new telecommunications services introduced in the data are classed as "competitive" services and are allowed to be freely priced by the firm.

[10] To guarantee $s^* > 0$, assume $rF(0) - F'(0) > e^{-ra}\pi(\theta)\forall\theta$. To guarantee finite s^*, assume that $\lim_{t\to\infty} rF(t) - F'(t) \leq 0$.

[11] The Federal Communications Commission, for example, delayed approval of high-definition television broadcasts for many years during the late 1980's and 1990's while it tested various technologies and chose a standard. The FCC apparently believed that consumers would ultimately benefit more from a high-quality product offered under a single standard, even if they had to wait an extra decade. If so, then increased demand may raise firms' profits.

Proposition 2 $\partial s^*/\partial b > 0$. *Longer regulatory delay induces the firm to innovate later.*

The proof is in the appendix. As regulatory delay increases (e.g., from b_L to b_H in Figure 1), the forgone profit is pushed farther into the future and its present value, which is the marginal cost of delay, falls. Since marginal benefit is decreasing, to re-equate marginal cost and marginal benefit later innovation dates are chosen by the firm. Thus there is a multiplier associated with regulatory delay: adding a day of regulatory delay increases the time until introduction by more than a day.

Proposition 3 $\partial s^*/\partial \theta < 0$. *A higher opportunity cost of delay induces the firm to innovate earlier.*

The proof is in the appendix. The relevant picture is the same as Figure 1, where now the top marginal cost curve corresponds to a higher θ and the bottom marginal cost curve corresponds to a lower θ. At first this result might appear counterintuitive; if regulation is "bad for the firm" why would higher marginal costs of regulatory delay lead to *earlier* innovation? The answer requires distinguishing between the direct and opportunity costs of regulation. It is the opportunity costs of regulation that θ measures; as the forgone profit from delay increases, the firm innovates earlier to speed accrual of those profits. If the direct cost of the regulatory process is included as a constant in F, then an increase in direct cost would postpone innovation. This can be seen from Figure 1 by shifting the marginal benefit of delay curve up.

2.2 A signaling model

In this section I present a signaling model of innovation and regulation that allows regulatory delay to be chosen after the firm chooses its innovation date. Here, regulatory delay is split into an exogenous component, $\bar{a} \geq 0$, and an endogenous component $a \geq -\bar{a}$. Structural delay $\bar{a}$ is taken as fixed before the game begins, and represents the delay that any service expects to go through. Structural delay may include time spent getting on the regulator's docket, waiting for a monthly review meeting, and mandatory examination periods. In the empirical models to follow, structural delay is taken to be exogenous when considering any single innovation. The part of regulatory delay specific to the service in question is a. I do not rule out the possibility that the regulator sets $a < 0$ and chooses to expedite approval. Thus the regulator can choose total regulatory delay $b = \bar{a} + a$ to be any positive length The role of $\bar{a}$ in the model is to provide a link to the empirical application, in which structural, service-inspecific delay clearly is a salient feature of the regulatory regimes examined.

The firm is the first mover in the game, and chooses s as in the basic model above, taking $\bar{a}$ as predetermined. The regulator subsequently observes the firm's action s, updates its beliefs about the firm's type θ, and chooses delay a.[12] Because the regulator makes its decision after the firm's, the firm can signal its type to influence regulatory delay.

The regulator's objective function may represent either social welfare (the "benevolent dictator" framework) or the utility function of the regulator (the "economic theory of regulation" approach to regulation (Peltzman, 1976)). Take utility at time s when the regulator believes the firm to be of type $\hat{\theta}$ to be

$$U(\hat{\theta}, a) = W(b, \hat{\theta}) + V(a) \tag{3}$$

The first part of the utility function, W, comes from the profit of the firm and the consumers' surplus. In the simplest case, W is the sum of the present discounted value of total welfare. Other transformations of profit and consumers' surplus are allowed, but it is assumed that $\partial W/\partial b < 0$, $\partial W/\partial\hat{\theta} > 0$, $\partial^2 W/\partial b^2 > 0$, and $\partial^2 W/\partial b\partial\hat{\theta} < 0$. These assumptions are consistent with $W = \Pi + CS$, where CS is the present discounted value of a constant surplus flow $\alpha(\theta)$ with $\alpha'(\theta) > 0$. The firm's type affects CS at least indirectly because the monopoly prices charged are a function of θ. If θ represents a demand parameter, then θ will also have a direct impact on CS.

Crucial to the model is V, the benefit to the regulator from regulatory delay, with $V' > 0$ and

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[12] The game assumes that the regulator cannot commit to a policy a before the firm moves. Lack of commitment is a common assumption in regulatory games (outside of the mechanism design literature). See Spiegel and Spulber (1997) for a discussion of why regulatory commitment is not a realistic assumption.

$V'' < 0$. The interpretation of V varies with the interpretation of the regulator's objective. In a benevolent dictator setting, V may represent benefits not reflected in CS as defined above from higher quality or lower level of externalities that may result from regulatory delay.[13] In a political economy setting, V might represent a preference for exercising authority or direct or indirect payoffs to the regulator from the firm's rivals (although any such rivals are not modeled explicitly here). This "taste for delay" in the model, although *ad hoc*, is clearly realistic. Examination of the data below shows that regulatory delay is often quite lengthy in the real world, and therefore regulators must perceive there to be benefits of some sort to delay.

Finally, it is required that the concavity of V be great enough in magnitude, so that $\partial^2 U(a)/\partial a^2 < 0$. This assumption, for technical convenience, assures that the relevant single-crossing condition holds. Note finally that U is forward looking or "memoryless" in the sense that s does not affect U. This assumption means the regulator treats innovation delay as a bygone by the time its decision is to be made, and simplifies some of the results but is not intrinsic to the argument.

Solution concept I restrict focus in this Spence-type signaling game to cases of successful signaling: sequential separating equilibria. As will be shown, equilibrium in the model is unique and consists of pure strategies, and so I do not discuss mixed strategies here. Equilibrium consists of the firm's one-to-one strategy $\sigma(\theta)$ for s, and the regulator's strategy $\alpha(\hat{\theta}, s)$ for a, and the regulator's posterior beliefs $\hat{\theta}$ about θ such that

- $\sigma(\theta)$ maximizes $\Pi(\theta, s, \bar{a} + a)$ given the firm's correct expectation that $a = \alpha(\theta, s)$,
- $\alpha(\hat{\theta})$ maximizes $U(\hat{\theta}, a)$ given the posterior beliefs and the regulator's correct expectation that $s = \sigma(\hat{\theta})$, and

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[13] If delay represents the time taken by the firm to bring the product up to a regulatory quality standard, then longer delays may increase product quality. If delay represents time taken by the regulator to investigate safety or privacy concerns (e.g., caller ID or caller ID blocking), then longer delays may decrease externalities. In these cases, CS is read as surplus conditional on a fixed level of quality or externalities, and all benefits of delay are subsumed in V.

- $\hat{\theta} = \theta$ on the equilibrium path.[14]

With continuous types Mailath (1987) shows that a unique separating equilibrium exists if certain technical conditions are met, which are discussed below and in the appendix.

The regulator's strategy Because equilibrium is sequentially rational, we may use backward induction to solve the game. The regulator will choose a as

$$\alpha(\hat{\theta}) = \underset{a}{\mathrm{argmax}} U(\hat{\theta}, a) \tag{4}$$

when it believes the firm is type $\hat{\theta}$. Assuming an interior solution ($\alpha > -\bar{a}$), the optimal choice of regulatory delay α thus satisfies $\partial U/\partial a = 0$, or

$$V'(\alpha) = -\left.\frac{\partial W}{\partial b}\right|_{b=\bar{a}+\alpha} \tag{5}$$

The expression shows that α ensures that the marginal benefit of delay for the regulator (on the left) equals the regulator's marginal cost of delay (on the right). Of central interest for characterizing the separating equilibrium is how α changes with $\hat{\theta}$. Applying the implicit function theorem to 5 implies that

$$\frac{d\alpha}{d\hat{\theta}} = -\left.\frac{\partial^2 W}{\partial \hat{\theta} \partial b}\right/ \frac{\partial^2 U}{\partial b^2} \tag{6}$$

which, by the assumptions above, is negative. Figure 2 shows a typical case. The implication is that the firm knows it will receive lower regulatory delay the higher the regulator thinks θ is. Thus the worst belief the regulator can hold, from the firm's point of view, is that $\theta = \theta^-$. All firm types other than θ^- therefore wish to signal to the regulator to avoid the worst outcome, $\alpha(\theta^-)$.

The firm's strategy Following Mailath (1987), define the firm's concentrated profit function as

$$\tilde{\Pi}(\theta, \hat{\theta}, s) = \Pi(\theta, s, \bar{a} + \alpha(\hat{\theta})) \tag{7}$$

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[14] More formally, strategies and beliefs are *sequentially rational* and *consistent* in the sense of Kreps and Wilson (1982). Sequential equilibrium in this game may impose more restrictions on play off the equilibrium path than does the more familiar perfect Bayesian equilibrium, because there are more than two types (see Thm. 8.2 of Fudenberg and Tirole (1991)).

The function is concentrated in the sense that the optimal action of the regulator is incorporated into $\tilde{\Pi}$. It is useful to note that in this model $\tilde{\Pi}$ satisfies a single crossing condition for θ:

$$\frac{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial s}{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial\hat{\theta}} \text{ is strictly monotonically decreasing in } \theta. \tag{8}$$

The single crossing condition for θ, proved in the appendix, means that strengthening the signal is costlier for firms with higher costs of delay. The condition implies that the firm's strategy will be monotone in θ. Condition (8) holds without any additional assumptions needed.

If the firm's type were observable to the regulator, then the firm would choose its optimal innovation delay as

$$s^* = \tau(\theta) = \underset{s}{\operatorname{argmax}}\ \tilde{\Pi}(\theta,\theta,s) \tag{9}$$

The function τ is the full-information benchmark strategy for innovation delay.

Looking ahead to the regulator's policy $\alpha(\hat{\theta})$, the firm wishes to signal its type when doing so will cause the regulator to reduce regulatory delay from $\alpha(\theta^-)$. Thus $\tau(\theta) = \sigma(\theta)$, where σ is the firm's signaling strategy for s, only at $\theta = \theta^-$. The type with the lowest cost of delay has no incentive to signal, which provides an initial value condition needed to solve for the equilibrium strategy below.

If $\sigma(\theta)$ is part of a separating equilibrium, it must be one-to-one and be incentive compatible. Incentive compatibility requires that the firm maximize $\tilde{\Pi}$ recognizing that the regulator will (in equilibrium) correctly infer its type: if the firm chooses delay s, the regulator will correctly believe that the firm's type is $\sigma^{-1}(s)$. Mathematically, incentive compatibility requires that

$$\sigma(\theta) = \operatorname{argmax}_{s\in\sigma([\theta^-,\theta^+])}\tilde{\Pi}(\theta,\sigma^{-1}(s),s) \tag{10}$$

Mailath (1987) shows that under condition (8) and other regularity conditions (see the appendix) a unique, continuous, strictly monotonic pure strategy $\sigma(\theta)$ exists. The firm's strategy may be found as the solution to an ordinary differential equation:

$$\begin{aligned} \frac{d\sigma}{d\theta} &= -\left.\frac{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial\hat{\theta}}{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial s}\right|_{\hat{\theta}=\theta,s=\sigma} && (11) \\ \sigma(\theta^-) &= \tau(\theta^-) && (12) \end{aligned}$$

Given the assumptions of the model, $d\sigma/d\theta < 0$. The derivative of σ at θ^- approaches infinity, because the denominator of (11) vanishes at θ^- since $s = \tau(\theta^-)$ by equation (12) and τ maximizes $\tilde{\Pi}$ from (9). Thus, since τ has finite derivative at that point, σ is below τ to the right of θ^- (this is formalized as Proposition 7 in the appendix). In Figure 3, which shows a typical case, the firm's full information strategy is the heavy line and the signaling strategy is the lighter line below. The economic interpretation of the firm's behavior at θ^- is that types marginally higher than θ^- must decrease innovation delay a lot to differentiate themselves from the worst type, θ^-. The derivative of σ, although still negative, is not as large for higher types. Thus the additional decrease in the firm's innovation delay needed to signal its type decreases as θ increases. In all cases, however, the innovation delay chosen by the firm is less than that chosen in the full information case. This is the cost of signaling for the firm. As one expects in a signaling model, the firm earns less profit compared to the full information case. Note, however, that consumers benefit from the firm's private information. Because the firm signals by reducing its innovation delay, consumers receive the new service earlier than in the full information case.

Before concluding the theoretical exposition, I highlight three empirically testable predictions of the model. The first, that longer structural regulatory delay induces the firm to innovate later, requires an additional assumption. Given θ, define the single-crossing condition for $\bar{a}$ to be:

$$\frac{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial s}{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial\hat{\theta}} \text{ is strictly monotonically decreasing in } \bar{a}. \qquad (13)$$

Condition (13) means that in the family of signaling games parameterized by $\bar{a}$, for a given type the isoprofit curves of the firm in $(\hat{\theta}, s)$-space for two different values of structural regulatory delay $\bar{a}$ cross no more than once. The following proposition states that when the single-crossing condition for $\bar{a}$ is satisfied, we have a result in the signaling game similar to Proposition 2 for exogenous regulatory delay. This single-crossing condition is not implied by the assumptions made so far, because it places restrictions on third-order derivatives of U.[15]

Proposition 4 *If the single-crossing condition for* $\bar{a}$ *(13) is satisfied, then* $\partial\sigma(\theta)/\partial\bar{a} > 0$*. Longer structural regulatory delay induces the firm to innovate later.*

Condition (13) ensures that the single crossing condition of Milgrom and Shannon (1994) is satisfied (see their Theorem 3). Since s is scalar, $\tilde{\Pi}$ is supermodular in s.[16] Then Theorem 4 of Milgrom and Shannon (1994) proves the proposition.

The second empirically testable result is that innovation delay and discretionary regulatory delay will be correlated, in the following sense:

Proposition 5 $da/ds > 0$ *in equilibrium. Regulatory delay is positively associated with innovation delay in the equilibrium of the signaling model.*

Note that, in anticipation of the empirical specification below, regulatory delay is described as a function of innovation delay. The proposition follows formally from the theory of supermodular games.[17] However, in the present context the proposition may be seen to follow directly from the fact that s and a are both decreasing in the firm's type. Thus, in equilibrium, low types lead to high regulatory and innovation delay, and high types lead to low innovative and regulatory delay, so that (ceteris paribus) s and a would appear to move together in a sample of observations on the outcome of this one-shot game.

The third empirically testable result is a refinement of the second. In addition to positive association between innovation delay and regulatory delay, the model also predicts that the functional relationship is concave:

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[15] To see this, note that from (25), $(\partial\tilde{\Pi}/\partial s)/(\partial\tilde{\Pi}/\partial\hat{\theta})$ involves second order derivatives of U.

[16] See Topkis (1998), example 2.6.2.a.

[17] See, e.g., Topkis (1998), Lemma 4.2.2.

Proposition 6 *da/ds is decreasing in a neighborhood to the left of $\alpha(\theta^-)$ in equilibrium. Regulatory delay is concave in innovation delay in the equilibrium of the signaling model, at least in that region.*

The proof is in the appendix. The proposition states that marginal increases in innovation delay prompt diminishing marginal increases in regulatory delay, as can be readily seen in Figure 4. Concavity of regulatory delay is thus a necessary implication of signaling, and may be used to distinguish signaling from full-information behavior, since concavity need not hold in the full-information case.

2.3 An example

Before turning to the empirical tests, consider the following example to illustrate the results of the signaling model. Assume these functional forms

$$W(b,\hat{\theta}) = \hat{\theta}\exp(-r(b)) \tag{14}$$

$$V(a) = -\exp(-2ra)/2 \tag{15}$$

$$\pi(\theta) = r\theta \tag{16}$$

$$F(s) = e^{-s} \tag{17}$$

which satisfy the needed conditions given above, including the single crossing condition (13). The regulator's best response regulatory delay is found from (5) as

$$\alpha(\hat{\theta}) = \bar{a} - \frac{\ln\hat{\theta}}{r} \tag{18}$$

and the firm's best response innovation delay under full information is found from (9) as

$$\tau(\theta) = 2r\bar{a} + \ln\frac{r+1}{r\theta^2} \tag{19}$$

When signaling is necessary in the separating equilibrium, the firm's strategy is defined by (11)–(12):

$$\begin{aligned} \frac{d\sigma}{d\theta} &= -\frac{\theta \exp\left(-2r\bar{a}\right)}{(1+r)e^{-s} - r\theta^2 \exp\left(-2r\bar{a}\right)} && (20) \\ \sigma(\theta^-) &= \tau(\theta^-) && (21) \end{aligned}$$

This initial value problem does not have an analytic solution, but is readily solved by numerical methods. For example, set $\theta^- = 0.1$, $\theta^+ = 1$, $\bar{a} = 20$, and $r = 0.1$. The regulator's strategy for this case is the one depicted in Figure 2, the firm's full information (the heavy line) and signaling strategies are the ones depicted in Figure 3, and the equilibrium relationship between regulatory and innovation delay is the one shown in Figure 4. The relationship between a and s for the full information case is linear in this example:

$$\alpha(\tau^{-1}(s)) = \frac{s + \ln r - \ln\left(r+1\right)}{2r} \qquad (22)$$

For the signaling case, in the function $\alpha(\sigma^{-1}(s))$ a given regulatory delay results in longer regulatory delay, compared with the full information case. This follows directly from Figure 3, because regulatory delay depends only on the type of the firm, and a given type signals with an s shorter than it would like to absent signaling. Note that the sign of the relationship between regulatory and innovation delay is positive in both the full information and signaling cases. However, Proposition 6 applies only to the signaling model: $\alpha(\sigma^{-1}(s))$ is concave but $\alpha(\tau^{-1}(s))$ is not. Therefore, the sign of correlation between regulatory and innovation delay may be used to distinguish strategic from non-strategic or random behavior, but concavity must be tested to distinguish between the full information and signaling cases.

3 Data and Discussion of the Tests

The theoretical model places restrictions on the relationship between regulatory and innovation delay. First, from Proposition 2 or 4, the firm's innovation delay rises as structural regulatory delay rises. This prediction applies to average behavior within a regulatory regime, and implies that innovation delay is longer in regimes with longer structural delay. Second, from Proposition (5) endogenous, discretionary regulatory delay rises with innovation delay. Proposition 6 further asserts that regulatory delay is concave in innovation delay. The latter two predictions pertain to the behavior of the regulator and the firm concerning a specific new product introduction. Note that tests of these three predictions are non-parametric, in the sense that the tests depend only on the sign or shape of the correlation between the observed regulatory and innovation delay, and no specific functional forms need be assumed for π, W, or V.

Data were collected on innovation and introduction dates for telecommunications services introduced in the 1990's by Ameritech in Illinois, Indiana, Ohio, and Wisconsin.[18] Ameritech, one of the Bell regional holding companies and later acquired by SBC, is the dominant local exchange company in each of these states, and its intrastate activities are regulated by the state commissions. Introduction of a new service required petitioning the public utility commission in each state; the service could not be offered to subscribers until regulatory approval was granted. Examples of the residential and business services in the data are new voice mail features, virtual networking services, and high-speed transmission services. The data cover the span 1991 through 1999, which comprises three regulatory periods.[19] In the first period, 1991 through mid 1994, Ameritech was under some form of rate of return regulation in each state. Following this first period, each state switched to some form of incentive regulation. After three years of the new regulation, in 1997 the regimes were reviewed in at least some of these states.[20] Thus the regulators (or state legislatures) had three opportunities to set their policy concerning structural regulatory delay (i.e., to choose $\bar{a}$). Preliminary statistical work revealed that the latter two periods were indistinguishable in terms of average innovation and regulatory delay, and so I collapse the years 1994–1999 into a single period

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[18] The data are from the tariff filing logs of the company and the state commissions. Supplemental information was culled from the actual state tariffs where needed.

[19] The data for Ohio are complete only for years 1994-1999.

[20] See Roycroft (1999) for more information on the regulatory regimes.

of incentive regulation in the empirical models and refer to it as Period 2 in the tables.

The first difficulty for the empirical investigation is measuring s, time between potential and actual innovation ("innovation delay"). I take the date at which a service is first introduced in any of these states or in the FCC's access tariff to be $t = 0$, and then measure s for the other states relative to the first state's innovation date. This effectively underestimates true innovation delay: the true time 0 must be weakly before the observed first "innovation" under this definition. However, time elapsed before the first tariffing is not observed by the regulator and cannot serve as a signal. Thus my measurement of s corresponds to the useful part (for signaling) of innovation delay, and therefore corresponds to s as used in the model.[21] Applying the single-firm, single-regulator theoretical model requires the assumption that there are no strategic interactions among jurisdictions. To be included in the data set, a new service had to be introduced in at least two states. One hundred fourteen services were introduced in at least two states, generating 349 observations. Summary statistics for the observations on innovation delay are in Table 1. Regulatory delay, a, is measured as the time from the first tariff filing submission date to the approval date of the last tariff filing for the service.[22] Regulatory delay data is not available for Ohio. Summary statistics for regulatory delay are in Table 2.

What is the power of tests based on these predictions to distinguish between the signaling model and alternative explanations? If the firm and the regulator choose delay to maximize objectives other than those described above, then there is no particular reason to expect innovation and regulatory delay to be positively correlated. Similarly, if innovation and regulatory delay vary across regulatory regimes or individual products only in response to factors orthogonal to the variables in the model, there will be no statistically significant relationship between s and $\bar{a}$ (or a). However, unobserved heterogeneity among regimes or products may induce correlation between innovation

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[21] The one caveat is that Ameritech also operates in Michigan. New services were effectively deregulated in Michigan and were not tariffed. It is thus unclear how observable introductions in Michigan were to regulators in the other states.

[22] Some services had multiple tariff filings and withdrawals before approval was granted.

and regulatory delay in other cases. For example, if profit opportunities are systematically higher in one regime than another, and the first regime also happens to have lower structural regulatory delay, then we may observe spurious positive correlation between s and $\bar{a}$. In the empirical application, therefore, I control for variables that affect average profit, cost, and consumers' surplus (size, density, and wealth of the market, etc.) in the regulatory regime. Controlling for differences in profit, cost, and consumers' surplus isolates the impact of regulatory delay on innovation.

At the product-specific level, we may observe spurious positive correlation between innovation delay and discretionary regulatory delay if services differ in the complexity of implementation. If so, the firm may delay filing for approval as it works out technical issues, and the regulator may delay approval as it reviews the complex issues raised. Correlation between s and a would be positive, but not for any reason coming from the theoretical model. Controlling for the complexity of a new service offering in the empirical work is difficult. In related work, Prieger (2002*b*) uses the number of pages in the tariff filing to proxy complexity, but this variable is not available in the present data. Instead, I proxy complexity with the rank of the introduction of a service among the various states. The idea behind using the order of introduction to reveal complexity of product implementation is based on learning by doing. Ameritech gains experience each time a particular service is introduced in another state. Thus (on average) the first introduction may be the most complex. Similarly, regulators in subsequent states can learn from the experience of regulators in previous states, as the examine the issues that were raised and their resolution during previous approval processes. Thus the complexity of the regulatory approval process should also decrease in subsequent states. Of course, the rank of a state in the order of introduction is not unrelated to innovation delay: longer delay in a state increases the likelihood that introduction is later than in other states. However, in estimations including the rank of introduction as a control, I already control directly for innovation delay. The rank therefore communicates extra information about complexity not captured by innovation delay. The idea: given two distinct services with equal innovation delay, regulatory approval is more complex on average for a novel service than for a service already introduced elsewhere in neighboring jurisdictions.

Finally, note that the first two predictions hold in the model for both the full-information and signaling cases, and cannot be used to distinguish between these alternatives. However, the condition of concavity implied by Proposition 6 is necessary for the signaling model but not the full information model (as may be seen from Figure 4). Thus rejecting concavity of regulatory delay in innovation delay would reject the signaling model but not the full information model.

4 Results of the Empirical Tests

The goal of the empirical work is to test the predictions from the signaling model. To this end, I first examine the relationship between innovation delay and structural regulatory delay and then look at the relationship between discretionary regulatory delay and innovation delay.

Estimating how innovation delay varies with structural regulatory delay. Structural regulatory delay varies greatly over time in the data. The institutional changes that took place in 1994 in each state expedited approval for new services. Streamlining the regulatory approval process received special attention in the new incentive regulation plans. In Illinois, the legislature mandated that the regulatory commission evaluate whether an alternative regulatory plan would "reduce regulatory delay and costs over time".[23] Under the new regulation, termed Advantage Illinois, new services deemed competitive were allowed to be introduced on one day's notice, and many more services were classified as competitive after the regulatory change. In Indiana, all new services were allowed to be introduced on one day's notice under the "Opportunity Indiana" alternative regulatory plan, down from at least a month of regulatory delay before the new plan. In Ohio, the legislature explicitly noted that "Alternative methods [of regulation] may include, but are not limited to, methods that...minimize the costs and time expended in the regulatory

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[23] See § 220 Illinois Compiled Statutes, sec. 13-506.1.

process...."[24] In response, the commission effectively detariffed competitive services and allowed them to be introduced with essentially no regulatory scrutiny. In Wisconsin, the commission revised its procedures to ensure that approval for new services would be granted after 10 days unless suspended for investigation, down from about a month under rate of return regulation. The intent of the new regulation in each state was to ensure that structural regulatory delay be smaller in period 2 under the alternative regulatory schemes.

Another source of evidence is to examine the data themselves. Table 2 shows that the mean and median tariff approval delay dropped in Illinois, Indiana, and Wisconsin (no data are available for Ohio). Results from estimations lead to similar conclusions. I estimate the entire distribution of regulatory delay in the two periods via the Kaplan-Meier (Kalbfleisch and Prentice, 1980) non-parametric method (Figure 6). The figure presents the survival curves (defined to be $1 - CDF$) for regulatory delay and indicates that delay in period 2 stochastically dominates period 1 delay. Estimated means and medians from the curves are in Table 5. Mean and median regulatory delay is smaller in period 2 in each state. The confidence intervals for the median delay in periods 1 and 2 are non-overlapping in all states. In the next section I discuss further evidence from regressions that structural delay decreased in period 2.

How did Ameritech respond to the reduced structural delay? From the raw data in Table 2 it is clear that mean and median innovation delay dropped substantially from period 1 to period 2. The estimated survival curves in Figure 5 reveal convincing evidence that period 2 innovation delay stochastically dominates period 1 delay. Estimated means and medians from the curves are in Table 3, and confirm the visual evidence from the curves: the mean and median innovation delay is smaller in each state in period 2. Although the confidence intervals for the medians are non-overlapping only in Indiana and Wisconsin, if a slightly higher quantile is chosen, e.g. the 0.6 quantile (which corresponds to the ordinate 0.4 on the survival curves), the confidence intervals are non-overlapping in all states. Furthermore, a log-rank test formally rejects the hypothesis that

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[24] See Ohio Revised Code § 4927.04.

the two distributions are the same.[25] Thus it appears that innovation delay fell in each state in period 2, confirming the prediction of the model that innovation delay moves in the same direction as structural regulatory delay.

Since the nonparametric method does not allow covariates, I turn next to a semiparametric model to control for economic conditions and other factors that may change over time and influence the firm's behavior apart from the strategic considerations that I want to isolate. Estimates from a Cox proportional hazards model are in Table 4. In the Cox model, the hazard rate of the innovation delay durations is

$$\lambda(t, x_i) = \exp\left(x_i'\beta\right)\lambda_0(t), \tag{23}$$

where λ_0 is an arbitrary, unspecified baseline hazard and x_i is a vector of covariates for spell i.[26] Positive coefficients for β increase the hazard and therefore decrease mean duration. The first estimation replicates the finding from the survival curve estimation. When only fixed effects are included—state dummies, state-specific indicators for period 2 (*STATE:reg change*), and an indicator that delay is calculated from the federal access tariff—the coefficients for the regulatory change all indicate shorter delay times in period 2 (see Estimation I1 in Table 4). Also reported for each estimation are the χ^2 statistic for the joint significance of all coefficients and Grambsch and Therneau's (1994) $T(G)$ statistic. The latter is for a test of the proportional hazards assumption of the Cox model. In all estimations, the coefficients are jointly significant and the proportional hazards assumption is not rejected.

Estimation I2 is a more flexible specification, in which stratification by state replaces the state dummy variables, which allows the baseline hazard to vary without restriction across states. The coefficients again indicate shorter delay times in period 2, although the coefficient for Illinois loses significance. This finding generally persists when state-level economic covariates are added in Estimation I3 to replace the state dummy variables and stratification. The new variables are

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[25] The test, also know as the Mantel-Haenszel test, has a p-value less than 10^{-11}.

[26] The Cox (1972; 1975) model uses a $\sqrt{N}$-consistent partial likelihood method to estimate β.

per capita income (PCI), the number of access lines in each state (a measure of market size), population density (denser areas are cheaper to serve per subscriber due to fixed costs), and lagged telecommunications industry patents.[27] These covariates are allowed to evolve over the course of a duration. Adding these variables does not remove the conclusion that innovation delay fell in period 2 except, again, for Illinois, for which the coefficient is insignificant. Taken together, then, the evidence from all estimations indicates that innovation delay is positively associated with structural regulatory delay in accordance with Propositions 2 and 4, except possibly in Illinois.

Estimating how service-specific regulatory delay varies with innovation delay. To examine how discretionary regulatory delay a changes as innovation delay s varies, I perform Cox estimations for regulatory delay where innovation delay for the service is included as a regressor. By including innovation delay as a regressor, I assume it is exogenous (or predetermined) with respect to regulatory delay. The assumption of exogeneity may not hold if observed regulatory and innovation delay are jointly determined by behind-the-scenes negotiations between the firm and the regulator. For example, the firm could agree to not submit a product for approval until the regulator gathers information on the relevant issues, shortening observed regulatory delay. However, such maneuvering would induce negative correlation between regulatory and innovation delay, the opposite of what I find.

To anticipate the concavity test of Proposition 6, innovation delay enters the regression function non-linearly. I include an indicator variable for zero innovation delay, because 35% of the observations are truncated at zero. For positive innovation delay, I include a two-part spline with the knot at the median innovation delay.[28] Estimation R1 presented in Table 6 includes innovation delay only (as in Estimation I2, the sample is stratified by state). The coefficients on the state dummy variables for period 2 indicate increased hazards and shorter regulatory delay time in each

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[27] The Bell Operating Companies take out few patents themselves, and typically create new services from underlying technology patented by others.

[28] If a second knot is added at the third quartile, the slope coefficient for the third piece of the spline does not differ significantly from the second piece.

state during the second regulatory period. In this and all other estimations, the coefficients for Indiana and Wisconsin are statistically significant at the 1% level, but those for Illinois are not. Since these coefficients capture average regulatory delay in the state and period when controlling for service-specific innovation delay, this is further evidence that structural delay $\bar{a}$ decreased in period 2.

More interesting in the estimation, however, are the results for innovation delay. Proposition 5 states that there must be a positive relationship between a and s. The coefficients for the innovation delay spline are negative in all specifications in Table 6, implying that the hazard rate for regulatory delay decreases (and average delay increases) as innovation delay increases. For estimation R1, the estimates imply that if innovation delay rises from its mean value by one standard deviation, then regulatory delay increases by 8.0 days. I discuss the statistical significance of the estimates in the next section. This result is robust to various changes in the controls used. In estimation R2 in Table 6, the stratification by state is replaced with state-specific political economy variables used in other studies of regulatory change (Donald and Sappington, 1997): the log annual budget of the regulatory authority, an indicator for Republican control of both houses of the state legislature and a Republican governor (*Republican*), and the average value of *Republican* from 1984 up to the previous year (*Republican history*).[29] The coefficients for innovation delay change little from estimation R1.

In estimations R3 and R4, the first two specifications are repeated including the observation's rank in the order of introduction of that particular service across the states.[30] As discussed above, after controlling for innovation delay, the rank proxies the unobserved complexity of the service. One expects that holding the length of innovation delay constant, services introduced in later states

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[29] The other political economy variable used in Donald and Sappington (1997), an indicator for elected public utility commissioners, can not be used here because commissioners are not elected in any state. Other variables I explored included the size of the PUC staff and the political composition of the legislature and governor's office separately; none of these was significant.

[30] Estimation R4 is stratified by state, because when not the proportional hazard assumption is rejected by the $T(G)$ statistic.

are less complex and should be approved quicker. This is indeed what estimations 3 and 4 reveal in Table 6: the hazard rate increases monotonically with the introduction order of the service, implying that the average regulatory delay time decreases as the rank increases. More importantly, for the purposes of testing the theoretical model, the coefficients on the innovation delay variables remain negative. Taken together, the evidence from all estimations suggests that greater innovation delay is positively associated with greater discretionary regulatory delay, in accordance with the prediction of the model.

Finally, note that the relationship between regulatory and innovation delay is concave (i.e., a piecewise linear approximation of concavity) in all estimations. Figure 7 plots expected regulatory delay as a function of innovation delay, using the spline coefficients estimated in models R1–R4.[31] Thus the data are in accord with the third prediction of the model, from Proposition 6.[32]

Summary To conclude the test of the predictions of the theoretical model, I summarize the evidence presented with a suite of hypothesis tests in Table 7. Panel A of the table reports results from the innovation delay estimations I1–I3. The tests are for $ds/d\bar{a} \leq 0$, which would violate Propositions 2 and 4. The test is implemented with the null hypothesis that the coefficients for the regime change are non-positive. Thus under the null, the hazard rate for innovation delay stays the same or decreases (or, equivalently, innovation delay did not decrease) in the period when structural regulatory delay was lower. This hypothesis is soundly rejected in all states, with the possible exception of Illinois, for which the test rejects at the 10% level or better for I1 and I2 but not for I3. The hypothesis that the relevant coefficients are zero is also rejected at the 1% level when the states are tested jointly.

Panel B of Table 7 reports results from the regulation delay estimations R1–R4, where the

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[31] Mean regulatory delay is calculated as the average across the sample of the observation-specific mean duration. Mean durations are computed from the estimated survival curves using actual covariates and the counterfactual innovation delay shown on the x-axis in the figure.

[32] The spline specification was chosen over a quadratic in innovation delay to increase robustness to outliers. If estimations R1–R4 are repeated with a quadratic replacing the spline, the coefficients on innovation delay are all negative except for the linear term in R2, which is insignificant.

tests are for $da/ds \leq 0$, which would violate Proposition 5. The test is implemented with the null hypothesis that the coefficients for the spline in innovation delay are non-negative. Thus under the null, the hazard rate for endogenous regulation delay stays the same or increases (or, equivalently, regulation delay does not increase) as innovation delay increases. Although all the spline coefficients are negative, the hypothesis is not rejected for β_1, the spline coefficient for innovation delay less than the median. Thus the best evidence that innovation and regulation delay move together is found when innovation delay is longer than usual. Innovation delays become much more spread out in the upper quartiles (e.g., the median is 35 days but the third quartile is 145 days); perhaps unusually long delays are more effective signals because they catch the eye of the regulator more. The hypothesis that the innovation delay coefficients are zero is rejected at the 5% level or better in six out of eight cases in joint tests.

Panel C of Table 7 reports results from concavity tests for Proposition 6. The null hypothesis here is that the relationship between regulatory delay and innovation delay is linear or convex. Unfortunately (from the standpoint of testing the theoretical model) the estimates of the spline coefficients are not precise enough to reject the null. On the other hand, concavity would not be rejected, either. The evidence for the third prediction from the models, while borne out visually in Figure 7, is the weakest of the three.

5 Conclusions

This paper presents a model that endogenizes innovation timing and regulatory delay. The firm uses the timing of new product introduction to signal the marginal cost of regulatory delay to the regulator. In the separating equilibrium, the regulator responds to the revealed information by rewarding firms with higher marginal cost of delay with lower regulatory delay. The model generates testable predictions, which are consistent with data on a Bell Operating Company's operations in four states. Perhaps the most important theoretical result, which is supported empirically, is that the reduction in average regulatory delay in the Ameritech states contributed toward the speedier innovation by the firm observed in the latter half of the 1990's. To the extent that regulatory delay still exists in these and other jurisdictions, the additional social cost of delay from distorting the incentive to innovate should be factored into regulators' and legislatures' social calculus.

One interesting implication of the model is that the unobservability of the cost of regulatory delay to the firm benefits consumers, because signaling requires the firm to speed product introduction. Thus if the firm were somehow able to communicate convincingly its regulatory delay costs to the regulator without costly signaling, so that the game switched to the full-information version, consumers would wait longer to receive new services.

Of course, the empirical evidence does not rule out all other explanations for the observed relationship between innovation and regulatory delay. However, external evidence suggests that regulators are becoming increasingly attuned to the costs of regulatory delay, so that the idea that a firm wishes the communicate such costs to the regulator is not far-fetched. Over the last decade, regulatory commissions (in some cases prodded by state legislatures) have placed more emphasis on the benefits from new products. The older breed of regulatory official, accustomed to tight regulatory control and a stable industry, viewed new products with suspicion. As one regulator put it, "...regulation of telecommunications remain essential to protect the public from deleterious consequences of innovation..." (Oppenheim, 1991, p.310). Contrast this view with the more recent goals adopted by regulators in the Ameritech region to "...facilitate the introduction of innovative new services in this competitive marketplace." (PSC of Wisconsin, 1998, p.47) This change of attitude about the importance of new products to consumers and firms may explain why structural regulatory delay fell so much in period 2.

The theoretical model may also apply to other regulatory settings, such as the timing of patenting and patent approval, or of pharmaceutical development and regulatory approval. With minor modifications to the objective functions, the model may also apply to decision-making within a firm, where the agents are the R&D division and management, in place of the firm and the regulator, respectively. In this setting consumer surplus would not enter management's objective function. In each of these settings, there is asymmetric information and the possibility of signaling and learning over time.

There are some interesting extensions to the model that deserve future attention. In the current formulation actions undertaken in one jurisdiction have no signaling value to regulators in the other jurisdictions (apart from alerting regulators that a certain service is technologically feasible after it is introduced in the first state), and the firm's decision is taken to be independent across states. A logical next step for the model is to expand the signaling game to include multiple receivers of the firm's multiple signals. Whether such a model will generate predictions restrictive enough to falsify the model remains to be seen.

Another extension would be to explicitly incorporate unregulated rivals into the model. The only impact of competition in the current model is indirect: it may affect the marginal cost of delay to the firm (θ) or the regulator's benefits of delay (V). Given that local telecommunications competition was just getting off the ground during the period studied, including competition in the model seems to be most useful for application to future data sets. Finally, exploring the political economy of regulatory delay in the telecommunications industry would be an interesting complement to the present work, where the regulator's taste for delay is assumed but not derived.

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6 Appendix

Proof of Proposition 2 We can find $\partial s^*/\partial b$ by differentiation of (2), since (2) holds for all b: $\frac{\partial s^*}{\partial b} = \frac{re^{-rb}\pi(\theta)}{F''(s^*)-rF'(s^*)} > 0$, where the inequality follows because $F' < 0$ and $F'' > 0$.

Proof of Proposition 3 The marginal cost of delay to the firm is the same whether the delay stems from the firm's or the regulator's choice. We can find $\partial s^*/\partial \theta$ by differentiation of (2), since (2) holds for all θ: $\frac{\partial s^*}{\partial \theta} = -\frac{e^{-rb}\pi'(\theta)}{F''(s^*)-rF'(s^*)} < 0$, where the inequality follows from the assumptions on F.

Proof of Proposition 6 The limit of da/ds as $\theta \downarrow \theta^-$ is given by $\lim_{\theta \downarrow \theta^-} (d\alpha/d\theta) \,/\, (d\sigma/d\theta)$. Since $\lim_{\theta \downarrow \theta^-} d\sigma/d\theta = -\infty$ by the discussion after equation (12), it follows that da/ds, which is positive by Proposition 5 tends to zero as θ falls to θ^-. An increasing function with a vanishing derivative at θ^- must be concave at least in a neighborhood around θ^-.

Statement and proof of Proposition 7

Proposition 7 *$\sigma(\theta) < \tau(\theta)$ for $\theta \in (\theta^-, \theta^+)$. Innovation delay is smaller under signaling than the full information case.*

From (12) we know the proposition holds in a neighborhood to the right θ^-, so if it does not hold for all types σ crosses τ from below at a type $\bar{\theta}$. But then pick a type $\theta' > \bar{\theta}$ such that $\tau(\theta') \in \sigma([\theta^-, \theta^+])$, and consider a deviation by a firm of type θ' to $\tau(\theta')$. Then the regulator infers (incorrectly) that the firm is of type θ'', where $\theta'' = \sigma^{-1}(\tau(\theta'))$. By definition of τ it must be that $\tilde{\Pi}(\theta', \theta', \sigma(\theta')) < \tilde{\Pi}(\theta', \theta', \tau(\theta'))$. Also, because $\partial\tilde{\Pi}/\partial\hat{\theta} > 0$, we have $\tilde{\Pi}(\theta', \theta', \tau(\theta')) < \tilde{\Pi}(\theta', \theta'', \tau(\theta'))$. Thus the firm of type θ' does better to play $\tau(\theta')$, and deviation to $\tau(\theta^-)$ cannot be credibly punished. Thus σ cannot cross τ.

The Mailath conditions In addition to the assumption that $\tilde{\Pi}$ is C^2, the following conditions are required to make use of Mailath's (1987) results:

1. Belief monotonicity: $\partial\tilde{\Pi}(\theta, \hat{\theta}, s)/\partial\hat{\theta} \neq 0$. Here, $\partial\tilde{\Pi}/\partial\hat{\theta} = \frac{\partial\Pi}{\partial b}\frac{db}{d\alpha}\frac{d\alpha}{d\hat{\theta}}$. Prop. 1 implies that $\partial\Pi/\partial b \neq 0$, $db/da = 1$, and equation (6) implies that $d\alpha/d\hat{\theta} \neq 0$, so $\partial\tilde{\Pi}/\partial\hat{\theta} \neq 0$.

2. Type monotonicity: $\frac{\partial^2\tilde{\Pi}}{\partial s \partial\theta} \neq 0$. Here, $\frac{\partial^2\tilde{\Pi}}{\partial s \partial\theta} = -e^{-r(s+b)}\pi'(\theta) < 0$.

3. Requirements of the full information strategy:

    (a) Existence and uniqueness: $\partial\tilde{\Pi}(\theta, \theta, s)/\partial s = 0$ has unique solution in s, which maximizes $\tilde{\Pi}(\theta, \theta, s)$. Here, $\frac{\partial\tilde{\Pi}}{\partial s} = 0 \Rightarrow rF(s) - F'(s) = e^{-rb}\pi(\theta)$ as in equation (2). Under the assumptions on F in the footnote by equation (2), a unique solution exists.

(b) "Strict" quasiconcavity. $\frac{\partial^2\tilde{\Pi}(\theta,\theta,\tau(\theta))}{\partial s^2} < 0$. Evaluated at $(\theta, \theta, \tau(\theta))$, and using equation (2), we have $\frac{\partial^2\tilde{\Pi}}{\partial s^2} = e^{-rs}\left(rF'(s) - F''(s)\right) < 0$.

4. Boundedness. For all $(\theta, s) \in [\theta^-, \theta^+] \times \mathbb{R}$ there exists a $k > 0$ $\forall$ such that $\frac{\partial^2\tilde{\Pi}(\theta,\theta,s)}{\partial s^2} \geq 0$ $\Rightarrow \left|\frac{\partial\tilde{\Pi}(\theta,\theta,s)}{\partial s}\right| > k$. In this application this condition does not hold, because (due to the exponential terms in s) as $s \to \infty$, $\partial\tilde{\Pi}(\theta, \theta, s)/\partial s \to 0$. However, this condition is sufficient but not necessary, and is stronger than needed. The condition is used in Mailath (1987) to bound the set $\mathbb{S} = \{s \in \mathbb{R} | \exists\theta$ such that $\tilde{\Pi}(\theta, \theta, s) \geq \tilde{\Pi}(\theta, \theta^-, \tau(\theta^-)\}$ for arbitrary τ. The inequality condition may be written as

$$e^{-r\left(s-\tau(\theta^-)\right)} \geq \frac{\left(-rF(\tau(\theta^-)) + e^{-r\left(\bar{a}+\alpha(\theta^-)\right)}\pi(\theta)\right)}{\left(-rF(s) + e^{-r(\bar{a}+\alpha(\theta))}\pi(\theta)\right)} \tag{24}$$

As $s \to \infty$, the left side of inequality (24) goes to zero for arbitrary τ. As $s \to \infty$, the numerator on the right side of (24) is unaffected, the denominator has $F(s) \to 0$ and $e^{-r(\bar{a}+\alpha(\theta))}\pi(\theta) > 0$, and so the right side is a positive number bounded away from zero. Thus $\mathbb{S}$ is bounded above as required.

5. Initial condition: equation (12). Assume not: suppose σ is one-to-one and incentive compatible but that $\sigma(\theta^-) \neq \tau(\theta^-)$. Consider a deviation by the firm of type θ^- to $\tau(\theta^-)$. If $\tau(\theta^-) = \sigma(\theta')$ for some $\theta' \in [\theta^-, \theta^+]$, then the regulator will infer (incorrectly) that the firm is of type θ'. By definition of τ it must be that $\tilde{\Pi}(\theta^-, \theta^-, \sigma(\theta^-)) < \tilde{\Pi}(\theta^-, \theta^-, \tau(\theta^-))$. Also, because $\partial\tilde{\Pi}/\partial\hat{\theta} > 0$, we have $\tilde{\Pi}(\theta^-, \theta^-, \tau(\theta^-)) < \tilde{\Pi}(\theta^-, \theta', \tau(\theta^-))$. Thus the firm does better to play $\tau(\theta^-)$. On the other hand, if $\tau(\theta^-) \notin \sigma([\theta^-, \theta^+])$, then a sensible refinement such as the intuitive criterion can ensure that the regulator holds the pessimistic belief that the firm's type is θ^-. If so, then (by definition of τ) the firm does no worse playing $\tau(\theta^-)$ than by playing $\sigma(\theta^-)$. In either case, then, deviation to $\tau(\theta^-)$ cannot be credibly punished. Thus it must be that $\sigma(\theta^-) = \tau(\theta^-)$.

6. Single crossing condition: $\frac{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial s}{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial\hat{\theta}}$ is monotonic in θ. We have

$$\frac{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial s}{\partial\tilde{\Pi}(\theta,\hat{\theta},s)/\partial\hat{\theta}} = \frac{-e^{-rs}\left[-rF(s)+F'(s)+e^{-rb}\pi(\theta)\right]}{\left[-e^{-r(s+b)}\pi(\theta)\right]\left[-\frac{\partial^2 W}{\partial\hat{\theta}\partial b}\Big/\frac{\partial^2 U}{\partial b^2}\right]} \tag{25}$$

Since neither W nor U depend on θ, the relevant terms are $\left(rF(s)-F'(s)-e^{-rb}\pi(\theta)\right)/\pi(\theta)$, which has derivative in θ of $-\left(rF(s)-F'(s)\right)\pi'(\theta)/\pi(\theta)^2$. This derivative has the sign of $-rF(s)+F'(s)<0$. So the single crossing condition is satisfied, as asserted in (8).

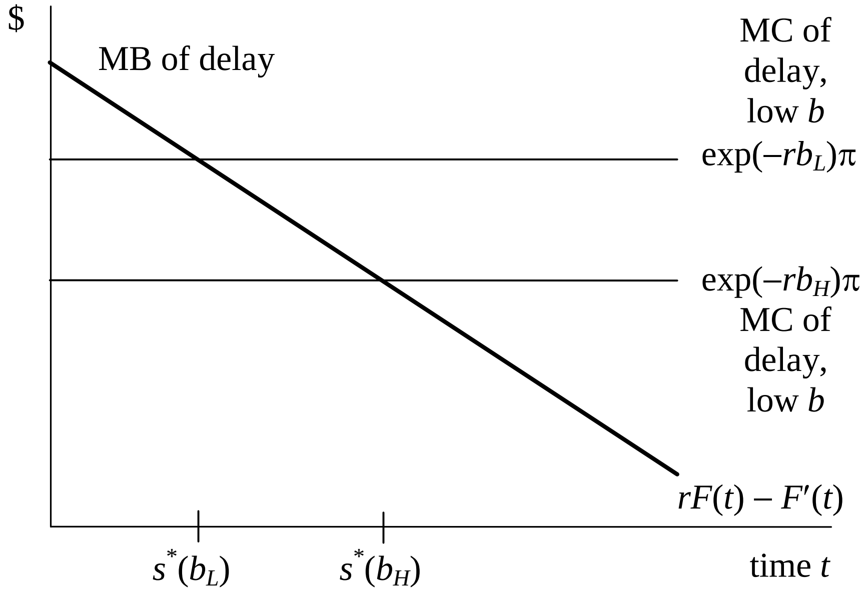

Figure 1: Determination of Optimal Innovation Date

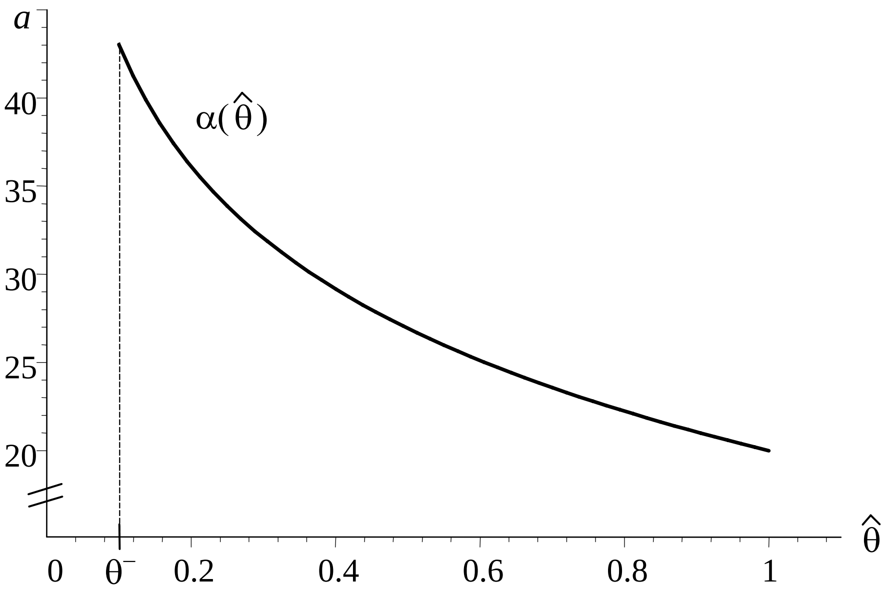

Figure 2: The regulator's optimal strategy for regulatory delay

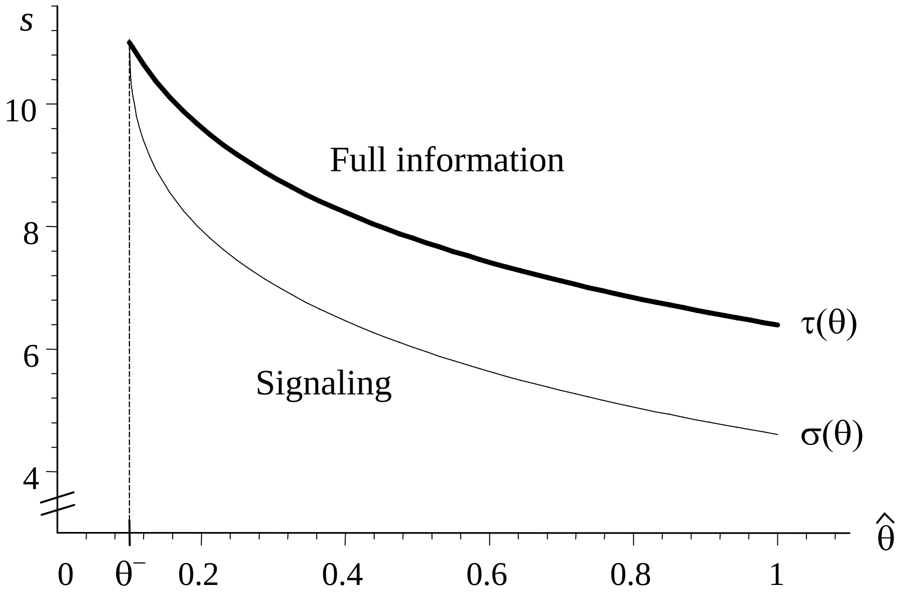

Figure 3: The firm's optimal strategy for innovation delay under full and asymmetric information

	Sample	**Innovation Delay Before Regulatory Change** Period 1 (1991–mid 1994)					**Innovation Delay After Regulatory Change** Period 2 (mid 1994–1999)				
State	*N*	*min*	*mean*	*median*	*max*	*N*	*min*	*mean*	*median*	*max*	*N*
IL	95	0	128	34	665	34	0	45	0	503	62
IN	77	0	457	199	2605	29	0	159	45	1,318	48
OH	65	361	1,267	1,235	2,518	8	0	98	26	1,071	62
WI	106	0	357	150	2,441	40	0	100	18	1,667	66
Total	349					111					238

Table notes: figures are in days. See text for calculation of s.

Table 1: Change in Innovation Delay Between Periods

	Sample	**Regulatory Delay Before Regulatory Change** Period 1 (1991–mid 1994)					**Regulatory Delay After Regulatory Change** Period 2 (mid 1994–1999)				
State	*N*	*min*	*mean*	*median*	*max*	*N*	*min*	*mean*	*median*	*max*	*N*
IL	97	1	36	46	48	29	1	30	16	248	68
IN	69	43	103	83	217	15	1	13	3	152	54
WI	103	2	106	44	752	25	1	9	10	48	78
Total	269					69					200

Table notes: figures are in days. Regulatory delay data are not available for Ohio.

Table 2: Change in Regulatory Delay Between Periods

State	**Period**	**Mean (s.e.)**		**Median**	**Lower 95% conf. limit for median**	**Upper 95% conf. limit for median**
IL	1	126.5	(32.4)	32	0	53
	2	45.0	(13.1)	0	0	0
IN	1	320.7	(97.6)	106	76	221
	2	133.5	(38.2)	42	28	53
OH	1	1,413.0	(309)	1,493	0	1,493
	2	87.3	(23.2)	19	13	32
WI	1	356.6	(81.6)	143	77	201
	2	99.5	(31.4)	19	3	23

Table notes: figures (in days) are based on survival curve estimates (see Figure 5). period 1 is 1991 to mid 1994, period 2 is thereafter.

Table 3: Estimated innovation delay s

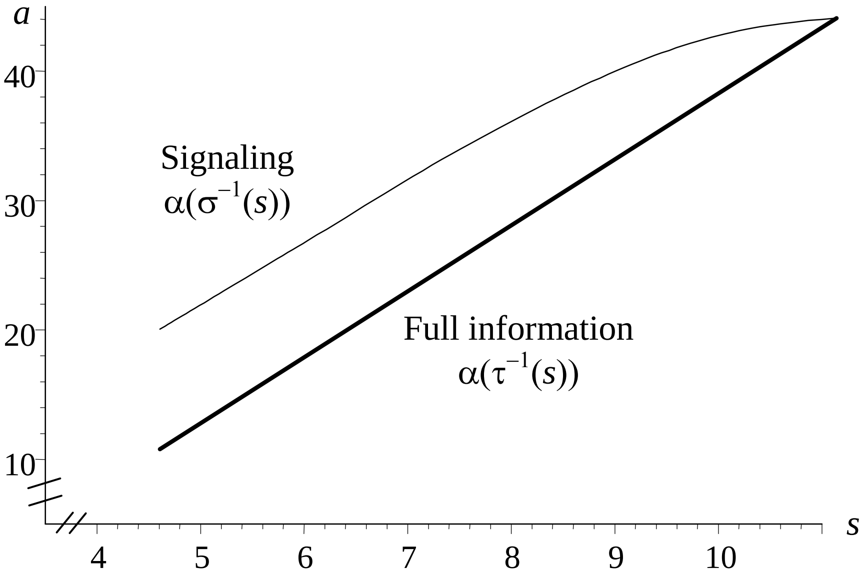

Figure 4: The equilibrium relationship between regulatory and innovation delay

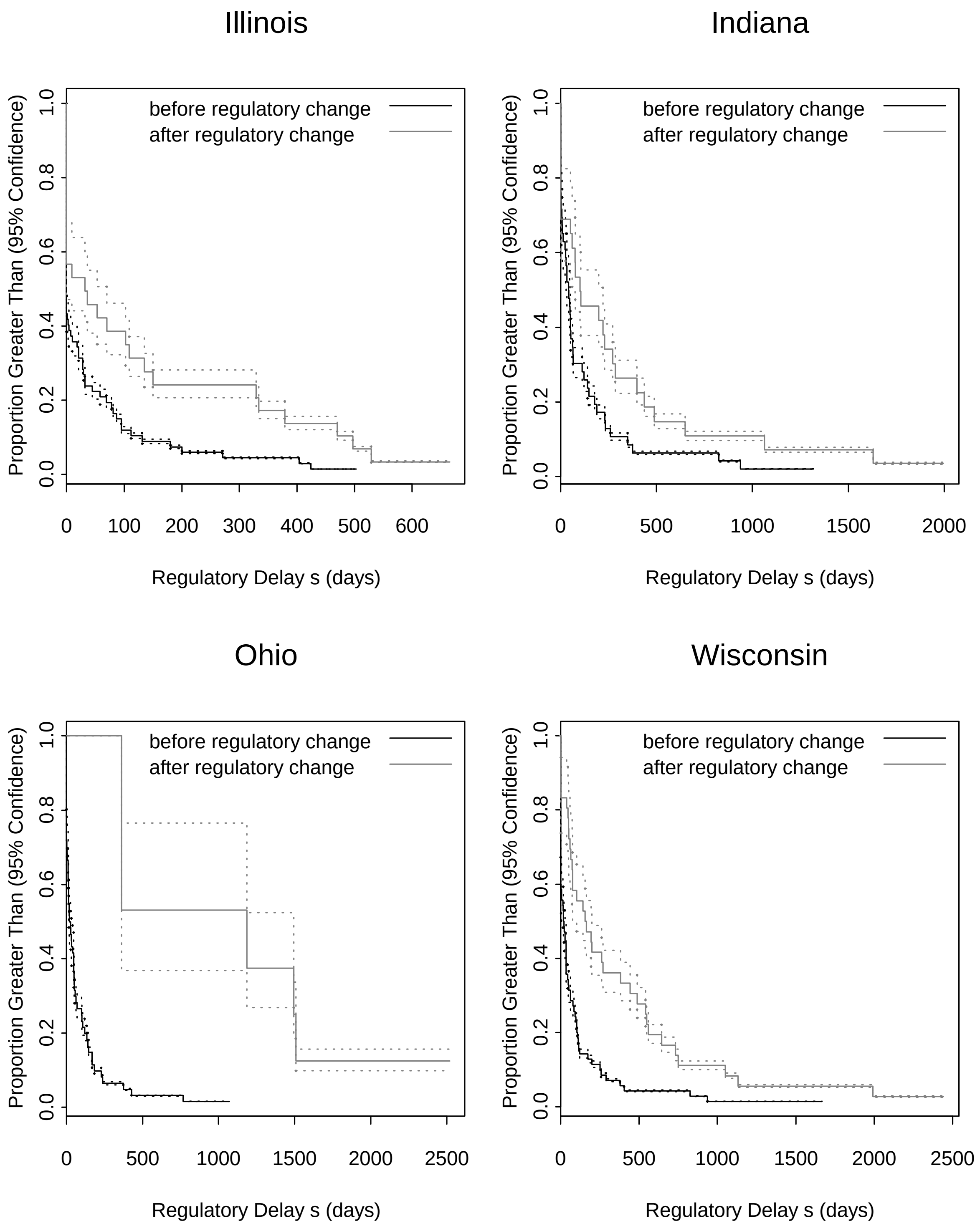

Figure 5: Nonparametric survival curves for innovation delay s

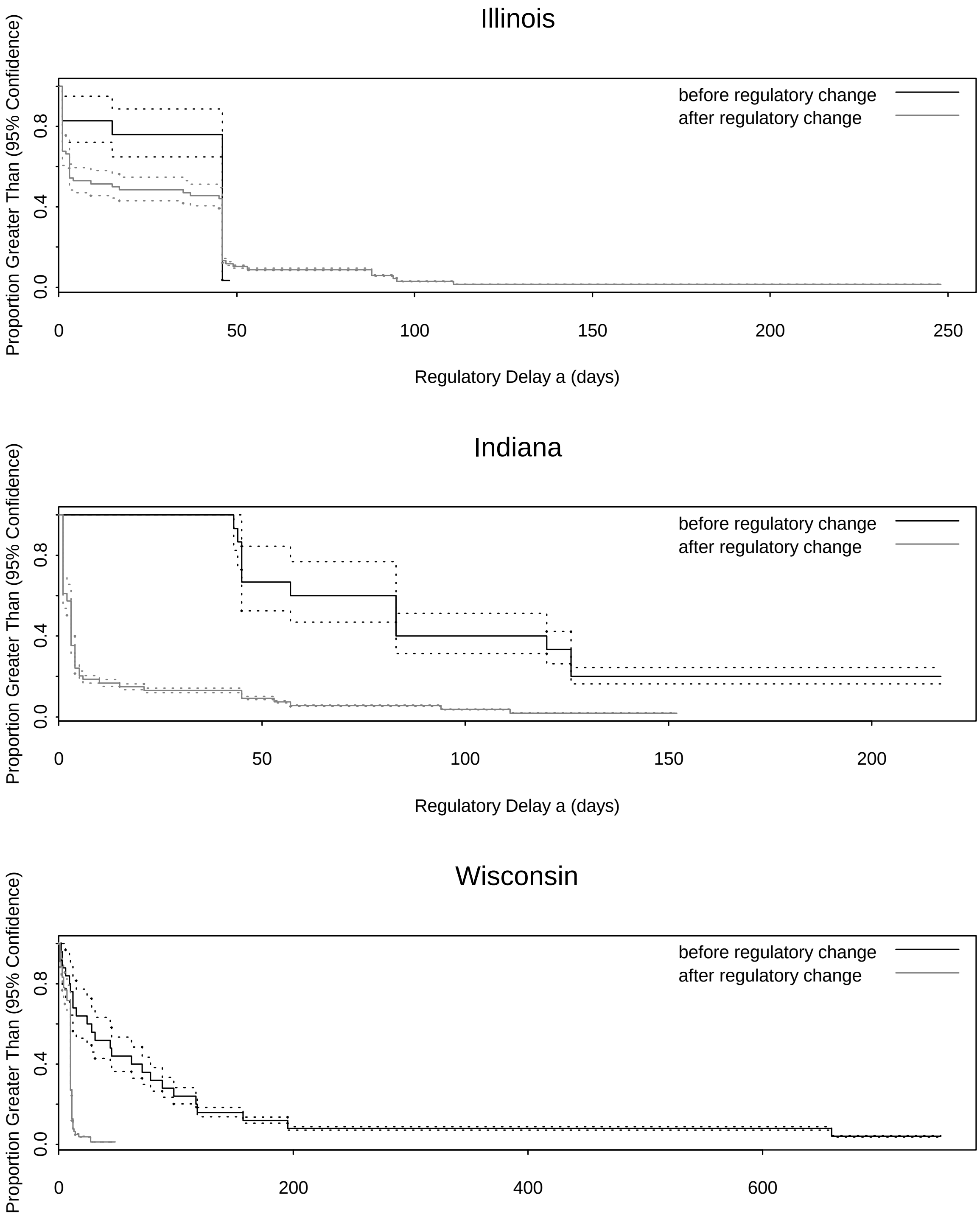

Figure 6: Nonparametric survival curves for regulatory delay a

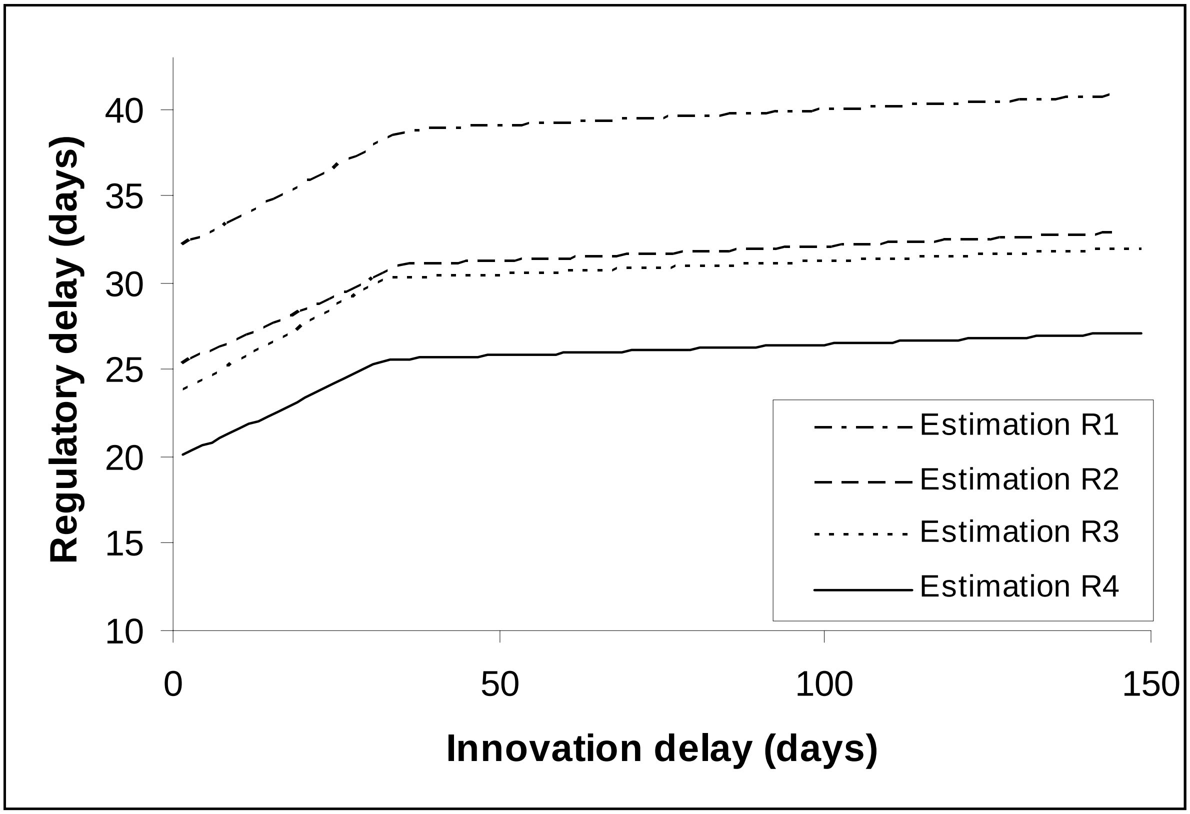

Figure 7: The Curvature of Mean Regulatory Delay

	Cox Proportional Hazards Models for Innovation Delay					
	Estimation I1		Estimation I2		Estimation I3	
	coef.	*s.e.*	*coef.*	*s.e.*	*coef.*	*s.e.*
IL:reg change	0.365*	0.214	0.291	0.208	−0.006	0.260
IN:reg change	0.727***	0.277	0.710**	0.281	0.487**	0.218
WI:reg change	1.355***	0.220	1.402***	0.219	0.875***	0.243
Indiana	−0.649**	0.290				
Ohio	0.160	0.203				
Wisconsin	−1.029***	0.246				
Federal tariff first	−0.654***	0.137	−0.695***	0.144	−0.616***	0.138
PCI					0.928	1.887
Access lines					0.413	0.364
Population density					0.477	0.304
Telecom patents$_{t-1}$					0.409	0.413
Stratification	none		by state		none	
N	349		349		349	
χ^2 statistic (d.f.)	80.9 (7)	$p = 0.00$	63.27 (4)	$p = 0.00$	90.70 (8)	$p = 0.00$
$T(G)$ statistic (d.f.)	1.57 (7)	$p = 0.98$	1.09 (4)	$p = 0.99$	3.17 (8)	$p = 0.92$
Log likelihood	$-1,626.3$		$-1,172.4$		$-1,620.9$	

* = 10% level significance; ** = 5% level significance; *** = 1% level significance.

Table notes: The model incorporates time-varying covariates. Larger positive coefficients imply shorter delays. Excluded state dummy is Illinois. *Federal tariff first* is an indicator for innovation delays calculated from the initial date the service was filed in the Federal Access Tariff; other delays calculated from the date of the first filing in a state tariff (with first state's delay changed from 0 to 0.5). PCI is per capita personal income in the state. Access lines is the number of access lines of Ameritech's subscribers in the state. *Telecom patents*$_{t-1}$ is the one-year lagged count of patents approved in the classes relevant to telecommunications services (359, 370, 379, and 395). χ^2 statistic is for the null hypothesis that all coefficients are zero. Figures in parentheses are degrees of freedom. $T(G)$ statistic is for a global test of the proportional hazards assumption and has a χ^2 distribution; rejection would indicate that the model is misspecified (test 4 of Grambsch and Therneau (1994)).

Table 4: Semiparametric estimation results for innovation delay s

State	**Period**	**Mean**	**(s.e.)**	**Median**	**Lower 95% conf. limit for median**	**Upper 95% conf. limit for median**
IL	1	36.2	(3.3)	46	46	46
	2	30.1	(4.7)	17	3	45
IN	1	103.4	(16.4)	83	57	120
	2	13.0	(4.0)	3	3	3
WI	1	105.6	(36.9)	44	24	62
	2	9.5	(0.7)	10	10	10

Table notes: figures (in days) are based on survival curve estimates (see Figure 6). period 1 is 1991 to mid 1994, period 2 is thereafter. Regulatory delay data are not available for Ohio.

Table 5: Estimated regulation delay a

	Cox Proportional Hazards Models for Regulatory Delay							
	Estimation R1		Estimation R2		Estimation R3		Estimation R4	
	coef.	*s.e.*	*coef.*	*s.e.*	*coef.*	*s.e.*	*coef.*	*s.e.*
IL:reg change	0.218	0.187	0.228	0.236	0.168	0.199	0.163	0.384
IN:reg change	1.669***	0.292	1.957***	0.336	1.420***	0.323	1.399***	0.367
WI:reg change	1.855***	0.348	1.483***	0.184	1.566***	0.388	1.649***	0.449
Innovation delay = 0	−0.445	0.340	−0.527	0.395	−0.344	0.504	−0.425	0.477
$\in$ [1,median]	-4.51E-03	0.010	-4.21E-03	0.012	-7.56E-03	0.011	−0.008	0.011
$>$ median	-3.78E-04	2.39E-04	-3.79E-04	2.79E-04	-4.86E-04**	2.08E-04	-5.16E-04**	2.08E-04
Order: second					0.149	0.361	0.080	0.331
Order: third					0.450	0.382	0.388	0.355
Order: fourth					1.047***	0.386	1.007***	0.356
PUC budget			1.577***	0.567			1.734	2.696
Republican			−0.094	0.162			−0.230	0.243
Republican history			0.664	0.660			−0.227	1.499
Stratification	by state		none		by state		by state	
N	267		267		246		246	
χ^2 statistic (d.o.f.)	65.2 (6)	$p = 0.00$	84.4 (9)	$p = 0.00$	114.1 (9)	$p = 0.00$	117.3 (12)	$p = 0.00$
$T(G)$ statistic (d.o.f.)	4.06 (6)	$p = 0.67$	14.899 (9)	$p = 0.09$	7.7 (9)	$p = 0.57$	9.8 (12)	$p = 0.64$
Log likelihood	−914.2		−1,193.9		−821.1		−819.8	

* = 10% level significance; ** = 5% level significance; *** = 1% level significance.

Table notes: Regulatory delay data are not available for Ohio. *PUC budget* is the log budget of the state public utility commission. *Republican* is an indicator for a Republican governor and majority in both houses of the state legislature. *Republican history* is the average value of *Republican* from 1984 to the previous year of the observation. See also notes to Table 4.

Table 6: Semiparametric estimation results for regulatory delay a

Panel A: Evidence that innovation delay fell when structural regulatory delay fell

	Estimation I1 *p-value*	Estimation I2 *p-value*	Estimation I3 *p-value*
H_0: $\beta_j \leq 0$ vs. H_A: $\beta_j > 0$			
IL:reg change	0.045	0.081	0.492
IN:reg change	0.004	0.006	0.013
OH:reg change	*	*	*
WI:reg change	0.000	0.000	0.000
Joint test: H_0: $\boldsymbol{\beta} = 0$ vs. H_A: $\boldsymbol{\beta} \neq 0$	0.000	0.000	0.001

Panel B: Evidence that discretionary regulatory delay is positively correlated with innovation delay

	Estimation R1 *p-value*	Estimation R2 *p-value*	Estimation R3 *p-value*	Estimation R4 *p-value*
H_0: $\beta_j \geq 0$ vs. H_A: $\beta_j < 0$				
β_1 for innovation delay $\in$ [1,median]	0.328	0.360	0.245	0.240
β_2 for innovation delay > median	0.057	0.087	0.010	0.006
Joint test: H_0: $\boldsymbol{\beta} = 0$ vs. H_A: $\boldsymbol{\beta} \neq 0$				
β_1 and β_2	0.208	0.311	0.028	0.016
β_1, β_2, and β_0 for innovation delay = 0	0.044	0.023	0.027	0.015

Panel C: Evidence that regulatory delay is concave in innovation delay

H_0: $\beta_2 \leq \beta_1$ vs. $\beta_2 > \beta_1$	0.342	0.373	0.261	0.256

*None of the delay durations in Ohio are completed in the period before the change in regulatory regime, and so $\hat{\beta}$ for the *OH:reg change* variable would be $+\infty$ and the hypothesis test is moot.

Table notes: One-sided tests are computed with one-sided t tests. Joint tests are computed with Wald tests.

Table 7: Hypothesis Tests of Outcomes That Would Reject the Theoretical Model