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Motivating regulated suppliers to assess alternative technologies, protocols, and capital structures ☆

Mark Jamison [a], David M. Mandy [b], David E.M. Sappington [c,*]

[a] Warrington College of Business Administration, University of Florida, United States
[b] Department of Economics, University of Missouri, United States
[c] Department of Economics, Matherly Hall, University of Florida, Gainesville, FL 32611-7140, United States

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ABSTRACT

Regulated firms can be tempted to adopt cost-saving technologies, operating procedures, or capital structures without fully assessing the associated risks. We demonstrate how a regulator can costlessly preclude such behavior if she can impose substantial penalties on the firm in the event of poor realized performance. When these penalties are more limited, the regulated firm secures rent from its privileged ability to assess the riskiness of potential technologies. If these penalties are sufficiently limited, the regulator optimally affords the firm no choice among technologies. Consequently, the regulated firm prefers moderate penalties to very limited penalties.

1. Introduction

Regulators typically face considerable uncertainty about many factors, including the efficacy and risks associated with new technologies, different operating procedures, and alternative capital structures. Such uncertainty can lead to what, in retrospect, appear to be regulatory mistakes. To illustrate, in 1990, the Tennessee Public Service Commission directed the telephone companies under its jurisdiction to implement new SS7, ISDN, and digital switching technologies. Although the technologies were considered to be "state of the art" at the time, they were soon eclipsed by the internet protocols that emerged from the rapid development of the World Wide Web. Consequently, the substantial investment in Tennessee's communications infrastructure in the early 1990s was ultimately deemed to be a "mistake" (Read and Youtie, 1996, pp. 22-23).[1]

To limit such "mistakes," regulators continually seek better information about prevailing and likely future industry conditions. The regulated utility is an important potential source of such information. In light of its industry experience, the expertise of its staff, and its daily interactions with consumers, a utility often is well situated to acquire useful information about the likely benefits and costs of new policies, technologies, and operating procedures. However, the acquisition and analysis of such information typically are costly. Consequently, a regulator must design regulatory policy to motivate the firm to engage in costly information gathering.

A primary purpose of this research is to determine the features of regulatory policy that best induce the regulated firm to acquire and employ valuable planning information. We consider settings in which the switch from a prevailing technology (or operating procedure or capital structure) is under consideration. The alternative technology reduces the firm's costs by $S > 0$, but entails a risk of social loss $D > 0$. At personal cost $k > 0$, the regulated firm can determine the probability this loss will arise. Welfare is highest if the alternative technology is adopted when and only when the associated loss probability is sufficiently small.

Our model has many applications. For instance, the alternative technology might entail a more modern communications infrastructure (e.g., digital vs. analogue switching) or a different means for generating electricity (e.g., nuclear vs. coal generation). Considerable uncertainty regarding the risk of obsolescence or the inherent local environmental risk often prevails in such settings. As a second example, the alternative

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* Corresponding author. Tel.: +1 352 392 3904.
E-mail address: sapping@ufl.edu (D.E.M. Sappington).

[1] Similarly, the cost of the massive investment in nuclear-powered electricity generation by the Washington Public Power Supply System in the 1970s and 1980s exceeded the corresponding benefits when the anticipated demand for electricity did not materialize, leading to the largest default in the history of the U.S. municipal bond market (Emery and Sierck, 1996; Goldberg, 1983). The Tennessee Valley Authority experienced similar problems (Smothers, 1988). Some authors also suggest that the U.S. Federal Communications Commission may have erred in delaying the development of cellular telephony by as much as ten years, with an associated social cost in excess of $300 billion in 1994 dollars (Hausman, 1997).

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operating procedure might represent less stringent maintenance protocols, including less frequent trimming of vegetation around power lines, for instance. Although relaxed maintenance protocols reduce short-run operating costs, they can introduce increased risk of diminished service quality, including lengthy service interruptions.

A third application of our model entails the choice of capital structure. Although an increased proportion of debt can sometimes reduce a utility's capital costs, it can also increase the likelihood that the utility will experience financial distress. Such distress can result in diminished service quality, increased future borrowing costs and associated higher retail prices, the expenditure of costly public funds to bail out the regulated firm, and/or damage to the professional careers of regulators. Scholars, regulators, and policymakers alike have expressed concern about the "flight of equity" and the "dash to debt" in regulated industries throughout the world, noting that it can "damage the legitimacy of the entire [regulated] sector" (Cox, 2013).[2] This concern has led OFWAT, the UK water regulator, to recommend more stringent oversight of utility capital structures.[3]

This research characterizes the optimal such oversight and accompanying policy design in the setting described above. In this setting, the regulator knows the firm can discern the probability (p) of social loss D under the alternative technology (or operating procedure or capital structure). However, the regulator cannot observe whether the firm has incurred cost k to learn p. She also cannot verify whether the firm's report on p is accurate.

Despite these limitations, if the regulator can credibly threaten to punish the firm severely should loss D arise after the firm adopts the alternative technology, then the regulator can induce the firm to learn p and adopt the alternative technology if and only if the probability of social loss D is sufficiently small (i.e., if $p = p_L$). Furthermore, the regulator can achieve this desirable outcome without affording the firm any rent. When the regulator's ability to penalize the firm is more limited, she can still induce the firm to learn p and adopt the appropriate technology. However, she must cede rent to the firm in order to do so. When the regulator's ability to penalize the firm is sufficiently limited, the regulator finds it too costly to motivate the firm to learn p. Instead, she simply instructs the firm to operate with the prevailing technology, and affords the firm no choice among technologies.

The optimal regulatory policy leaves the firm with no rent when the regulator has substantial or very limited ability to penalize the firm. In contrast, the firm secures rent when the regulator can impose moderate penalties on the firm. Consequently, the firm benefits from expanded regulatory ability to penalize the firm, within limits. The firm may enhance this ability by, for example, posting a moderate financial bond that it forfeits should it experience financial distress after adopting the alternative capital structure.

Our analysis complements other studies of the capital structure of regulated enterprises by focusing on the design of incentives to induce the firm to learn the prevailing risks before choosing a capital structure. Some studies (e.g., Cambini et al., 2014; Spiegel, 1994; Spiegel and Spulber, 1994) examine how a regulated firm that is well informed about the risks of potential capital structures will choose its capital structure before the regulator sets consumer prices. These studies demonstrate how the firm can employ debt to limit regulatory opportunism. When the firm adopts a highly leveraged capital structure, the regulator will set higher retail prices in order to limit the risk of financial insolvency. Consequently, increased debt can promote higher retail prices and expanded investment.[4] Other studies (e.g., Jensen and Meckling, 1976; Ross, 1977; Spiegel and Spulber, 1997) examine how a well-informed firm might choose its capital structure in order to signal future financial prospects or limit managerial moral hazard.[5] Our analysis incorporates as a special case the setting in which the regulated firm is well informed from the outset about the risks inherent in the capital structures it might implement. However, we focus on the arguably more relevant setting in which costly study is required to acquire this information.

This focus implies that our formal analysis reflects principles developed in the literature that examines the design of reward structures to induce an agent to undertake costly study of the environment in which he operates before acting (e.g., Bergemann and Välimäki, 2006; Crémer et al., 1998; Iossa and Martimort, 2013; Lewis and Sappington, 1997; Szalay, 2009).[6] Our analysis complements these studies in part by focusing on the impact of a regulator's limited ability or incentive to impose penalties and by identifying conditions under which the firm can gain as the penalties it faces become more severe.[7] We also extend the standard model in the literature by accounting for the endogeneity of the likelihood of the detrimental outcome. If loss D arises when the firm experiences financial distress, then the firm's authorized revenue directly affects the likelihood of loss D. Under such circumstances, the regulator will choose authorized revenues both to induce the firm to acquire valuable planning information and to limit the likelihood of loss D.

The analysis proceeds as follows. We begin by analyzing the setting in which the probability of loss D under the alternative technology is beyond the regulator's control. Section 2 describes the basic model and Section 3 characterizes the optimal regulatory policy in this setting. Section 4 identifies the corresponding optimal policy when the regulator can influence the probability of loss D under the alternative technology. Section 5 provides concluding observations and suggests directions for future research. The proofs of all formal conclusions are presented in the Appendix.

2. The basic setting

We begin by considering a basic setting in which a profit-maximizing regulated firm can employ either the prevailing technology (or operating procedure) or an alternative.[8] The firm incurs operating cost K_0 if it adopts the prevailing technology. This cost declines to $K_0 - S$ if the firm employs

[2] DTI and HM Treasury (2004) describe the prevalence and potential hazards of the "flight of equity" in regulated sectors in the UK. Cambini et al. (2014) discuss the "dash to debt" and note the concerns of Italian regulators and others in this regard. In characterizing the optimal capital structure for a regulated utility, Cowan (2013) observes that price cap regulation may encourage utilities to finance their operations with an excessive proportion of debt. Under pure price cap regulation, the prices the regulated firm can charge for its products are not linked to its prevailing operating costs or capital costs. Consequently, the firm's short-term profit may increase as it reduces its operating costs and/or its capital costs.

[3] When the newly privatized water utilities in the UK were first regulated in 1989, they were financed almost entirely with equity. In 2012, debt accounted for nearly 70% of utility financing on average, and the leverage (the ratio of debt to the sum of debt and equity) was nearly 80% for several companies (OFWAT, 2013). In light of these developments, Jonson Cox, the chairman of OFWAT's board, observed that "The regulator has previously taken the view that the capital structure of the companies (and consequent risks) is for the boards and shareholders to determine. This remains the case only as long as a structure does not create risks (sic) which could, on failure of a company to meet its obligations, pass liability or risk back to customers or to the public purse — or indeed damage the legitimacy of the entire sector. Public interest rightly expects the economic regulator to ensure that vital public services today and the ability to fund investment in the future are not put at risk by corporate structures. The regulator has a role in ensuring structural risks are managed effectively" (Cox, 2013).

[4] Taggart (1985), Dasgupta and Nanda (1993), Resende (2009), Bortolotti et al. (2011), and Cambini and Rondi (2012) all provide empirical evidence consistent with these predictions. De Fraja and Stones (2004) and Cowan (2013) examine the design of pricing policies and the choice of capital structure in models closer to our model in that the regulator can commit to policy parameters before the regulated firm chooses its capital structure. These important studies are discussed further in Section 5.

[5] Harris and Raviv (1991) review the early literature along these lines.

[6] Iossa and Stroffolini (2002) examine how to motivate a regulated supplier to acquire information about its unit cost of production under price cap regulation and under optimal regulation. The authors demonstrate that the regulator must concede substantial rent to the firm to induce information acquisition under price cap regulation. Iossa and Stroffolini (2005) conclude that revenue sharing plans can provide stronger incentives for information acquisition than price cap regulation.

[7] Yehezkel (2014) analyzes a setting in which a buyer seeks to induce a supplier to learn the quality of his product before selling it to the buyer. Yehezkel shows how limited supplier wealth is constraining for the buyer.

[8] For expositional ease, the ensuing discussion will focus on a change in the firm's technology. The formal analysis also applies to changes in the firm's operating procedure. Section 4 considers changes in the firm's capital structure.

the alternative technology. The cost saving (S) might reflect the lower cost of generating electricity using nuclear energy rather than coal or reduced maintenance costs from a less aggressive tree-trimming policy, for example. Although the alternative technology provides cost saving $S > 0$, it entails an increased probability of social loss, D. This loss could stem from environmental damage or from customer inconvenience due to a service outage, for example.

Because adoption of the alternative technology entails both benefits (S) and costs (D), the merits of such adoption depend on the magnitudes of S and D and on the probabilities with which loss D arises under the two technologies. The probability of loss D is known to be $p_0 \in (0, 1)$ under the prevailing technology. In this basic setting, the probability of loss D under the alternative technology (p) is not affected by regulatory policy, and is either low ($p_L \in (p_0, 1)$) or high ($p_H \in (p_L, 1)$).[9] The probability that $p = p_i$ is $\phi_i \in (0, 1)$, for $i = L, H$. Consequently, the ex ante expected probability of loss D under the alternative technology is $\widetilde{p} \equiv \phi_L p_L + \phi_H p_H$.

The social benefit of adopting the alternative technology is assumed to exceed the corresponding social cost if and only if the probability of loss D under the alternative technology is low (p_L). The social benefit of adopting the alternative technology is the associated reduction in operating cost, S. The corresponding cost is the increased expected social loss, $[p - p_0]D$. Formally, we assume:

$$[p_L - p_0]D < S < [\widetilde{p} - p_0]D < [p_H - p_0]D. \tag{1}$$

Inequality (1) implies that if the probability of loss D under the alternative technology (p) is not known, social surplus is higher when the prevailing technology is employed than when the alternative technology is adopted.[10]

Although the probability of loss D under the alternative technology (p) is initially unknown, the regulated firm can employ its unique industry experience and knowledge to learn p by incurring personal cost k. This cost includes the firm's opportunity cost of fully understanding the unavoidable risk the alternative technology entails. The regulator is unable to discover p herself, perhaps because of limited expertise and associated staff support. The regulator is also unable to verify whether the firm has incurred cost k to learn the realization of p.[11]

We will refer to the policy under which the firm incurs cost k to learn p and adopts the alternative technology if and only if $p = p_L$ as the *efficient adoption policy*. This policy is efficient because, by assumption:

$$k < \phi_L[S - (p_L - p_0)D]. \tag{2}$$

Inequality (2) states that k, the cost of learning p, is less than the corresponding expected social value. Because the alternative technology is adopted under the efficient adoption policy only when $p = p_L$, the social value of learning p is the product of ϕ_L, the probability that $p = p_L$, and the reduction in expected social cost from adopting the alternative technology when $p = p_L$. This expected cost saving is the difference between the reduction in operating cost (S) and the associated increase in expected social loss ($[p_L - p_0]D$) from employing the alternative technology rather than the prevailing technology.

To induce the firm to pursue the efficient adoption policy, the regulator must structure authorized revenues to ensure the firm finds it more profitable to learn p than to remain uninformed about p. Let R_D denote the firm's authorized revenue when it implements the alternative technology and loss D arises. Let R denote the corresponding revenue when loss D does not arise. Then $\widetilde{R}(p_i) = p_i R_D + [1 - p_i]R$ is the firm's expected revenue when it adopts the alternative technology, knowing the probability of loss D is p_i ($i = L, H$). The firm's corresponding (expected) profit is $\pi_i = \widetilde{R}(p_i) - K_0 + S$. The firm's expected profit when it implements the prevailing technology is denoted π_0.

Under the efficient adoption policy, the firm incurs cost k, implements the alternative technology when it learns that $p = p_L$, and implements the prevailing technology when it learns that $p = p_H$. Therefore, the firm's expected profit under the efficient adoption policy is $\pi \equiv \phi_L \pi_L + \phi_H \pi_0 - k$. To induce the firm to pursue this policy, the regulator must ensure that π exceeds the maximum profit the firm could secure without learning p, i.e., the following incentive compatibility constraint must be satisfied:[12]

$$\pi \geq max\{\pi_0, \phi_L \pi_L + \phi_H \pi_H\}. \tag{3}$$

The regulator must also ensure that, after learning p, the firm implements the alternative technology if and only if $p = p_L$. The firm will do so if $\pi_H \leq \pi_0 \leq \pi_L$. These inequalities will be satisfied when inequality (3) holds because:

$$\pi \geq \pi_0 \Leftrightarrow \phi_L \pi_L + \phi_H \pi_0 - k \geq \pi_0 \Leftrightarrow \pi_0 \leq \pi_L - \frac{k}{\phi_L}, \text{and} \tag{4}$$

$$\pi \geq \phi_L \pi_L + \phi_H \pi_H \Leftrightarrow \pi_0 \geq \pi_H + \frac{k}{\phi_H}. \tag{5}$$

Expressions (4) and (5) imply constraint (3) can be written as:

$$\pi_H + \frac{k}{\phi_H} \leq \pi_0 \leq \pi_L - \frac{k}{\phi_L}. \tag{6}$$

When setting authorized revenues and associated profits, the regulator must respect relevant political, legal, and institutional restrictions. For instance, bankruptcy laws and/or concern with attracting future industry investment may limit the financial penalty a regulator can credibly threaten to impose on a regulated firm. A regulator may also decline to impose a large financial penalty on the firm in order to avoid any associated deleterious consequences for consumers (e.g., reduced service quality due to financial distress). As we demonstrate below, the rent the regulator must afford the firm to induce it to pursue the efficient adoption policy is influenced by the magnitude of the loss the regulator can credibly impose on the firm when loss D arises under the alternative technology. We will denote by Δ the maximum financial loss the regulator can credibly force the regulated firm to bear. Therefore, authorized profits must satisfy:

$$\pi_0 \geq -\Delta, \quad R - K_0 + S \geq -\Delta, \quad \text{and } R_D - K_0 + S \geq -\Delta. \tag{7}$$

The regulator seeks to maximize expected consumer welfare. Consequently, when she induces the firm to pursue the efficient adoption policy, the regulator will act to minimize the firm's expected profit (because the firm's costs, the potential social loss, and the associated probabilities are all fixed from the regulator's perspective). Therefore, the regulator's formal problem, [RP-I], when she induces the firm to pursue the efficient adoption policy is to:

$$\underset{R, R_D, \pi_0}{\text{Minimize}} \quad \phi_L \ \pi_L + \phi_H \ \pi_0 \tag{8}$$

subject to inequalities (6), (7), and:

$$\pi \geq 0. \tag{9}$$

Inequality (9) is a participation constraint that ensures the regulated firm initially anticipates at least its reservation profit, which is normalized to 0.

[9] The setting in which the regulatory policy affects the probability the firm experiences financial distress under the chosen capital structure is considered in Section 4.

[10] The key qualitative conclusions drawn below do not depend on this assumption. See footnote 16.

[11] In practice, a regulator can observe whether the regulated firm has produced a report that purports to assess the risks associated with the use of an alternative technology or operating procedure. However, the regulator may lack the resources required to determine the validity and accuracy of the report, and thus whether the firm has put forth the effort required to fully assess the relevant risks.

[12] We assume that when the firm is indifferent among actions, it undertakes the action preferred by the regulator.

3. Findings in the basic setting

We begin our analysis of the optimal regulatory policy in this environment by identifying conditions under which the regulator's limited ability to monitor the firm's activities is not constraining. Proposition 1 explains when the *full-information outcome* is feasible. Under this outcome, the regulator induces the firm to undertake the efficient adoption policy and cedes no rent to the firm. The proposition refers to $\Delta_F \equiv \frac{1}{\theta}[1-\widetilde{p}]k$, where $\theta \equiv \phi_L[\widetilde{p}-p_L]$.

Proposition 1. *The full-information outcome is a feasible solution to [RP-I] if and only if* $\Delta \geq \Delta_F$.

Proposition 1 indicates that the regulator can achieve the full-information outcome when the penalty she can impose on the firm (Δ) in the event of social loss D is sufficiently large relative to the firm's cost (k) of learning p. In this case, the regulator achieves her preferred outcome by imposing a large penalty on the firm if the loss arises under the alternative technology. This large penalty can be offset by substantial rent under the alternative technology in the absence of loss D. When Δ is large, R can be set well above R_D while ensuring zero expected profit for the firm when it undertakes the efficient adoption policy. The large difference between R and R_D ensures that the firm's expected profit under the alternative technology is much greater when the firm knows that loss D is unlikely (i.e., when the firm knows that $p = p_L$) than when the firm does not know p.[13] Consequently, even when authorized revenues under the alternative technology are set to compensate the firm for incurring cost k, the firm will find it unprofitable to adopt the alternative technology without learning p.

Corollary 1 identifies elements of the environment that enhance the regulator's ability to achieve the full-information outcome.

Corollary 1. *The set of* Δ *values for which the full-information outcome is feasible (i.e.,* $[\Delta_F, \infty)$*) increases as* k *declines, as* p_H *increases, or as* p_L *decreases, ceteris paribus.*

When k is relatively small, the regulator does not need to promise the firm substantial rent when it adopts the alternative technology in order to compensate the firm for learning p. Consequently, the firm will not find it highly profitable to systematically adopt the alternative technology without learning p, and so the regulator is able to achieve the full-information outcome even when Δ is relatively small.

When p_H is relatively large, $\widetilde{p}-p_L$ is also relatively large. Consequently, the assessed likelihood of loss D under the alternative technology is substantially greater when the firm does not know p than when the firm knows that $p = p_L$. Therefore, for a given value of $R - R_D > 0$, the difference between the firm's expected profit under the alternative technology when the firm knows that $p = p_L$ and when the firm does not know p is large. As a result, the regulator is better able to induce the firm to learn p without ceding rent to the firm.

In contrast, when p_L is relatively large, $\widetilde{p}-p_L$ is relatively small. Consequently, for a given value of $R - R_D$, the difference between the firm's expected profit under the alternative technology when the firm knows that $p = p_L$ and when the firm is uninformed about p is small. Consequently, it is more difficult to induce the firm to learn p without affording the firm rent.

Corollary 2 emphasizes an additional implication of Proposition 1.

Corollary 2. *Suppose* $\Delta \geq 0$*, so the regulator can always hold the firm to zero profit. Then the full-information outcome is feasible if* $k = 0$.

Corollary 2 implies that the optimal regulatory policy typically is straightforward when the regulated firm is fully informed (or can costlessly become informed) about the relevant risks of the alternative technology. The regulator can simply adjust the firm's authorized revenue to fully reflect the reduction in operating costs the firm experiences if it adopts the alternative technology. Such a policy leaves the firm indifferent among technologies. Consequently, the firm is willing to (costlessly) learn the realization of p and implement the alternative technology if and only if $p = p_L$. In essence, the regulator's problem only becomes challenging when it is costly for the firm to assess the risks associated with the alternative technologies and when the regulator seeks to induce the firm to better assess these risks before choosing a technology.

Proposition 1 establishes that the regulator can achieve her preferred outcome when she has substantial ability to penalize the firm should loss D arise. In practice, though, regulators often lack the authority to impose large financial penalties on the firms they regulate.[14] Regulators also can lack the will to do so if such penalties threaten to disrupt service or otherwise diminish service quality in the industry.[15] When Δ is less than Δ_F in the present setting, the regulator cannot reduce R_D sufficiently far below R to ensure that the firm: (i) anticipates a financial loss if it adopts the alternative technology without learning p; but (ii) recovers cost k when it adopts the alternative technology after learning that $p = p_L$. In this case, when the regulator sets R and R_D to ensure that the firm is able to recover k when it adopts the alternative technology after learning that $p = p_L$, she unavoidably delivers rent ($\phi_L\pi_L + \phi_H\pi_H > 0$) to the firm if it adopts the alternative technology without learning p. Proposition 2 characterizes the solution to [RP-I] under these circumstances.

Proposition 2. *Suppose* $\Delta < \Delta_F$*. Then the solution to [RP-I]:*

$$R_D = K_0 - S - \Delta;\ \ R = R_D + \frac{k}{\theta};\ \text{ and }\ \pi_0 = \Delta_F - \Delta.$$

$$\text{Consequently,}\ \pi = \pi_0 = \phi_L\,\pi_L + \phi_H\,\pi_H \quad \text{and} \quad \pi_L = \pi_0 + \frac{k}{\phi_L}.$$

Proposition 2 reflects the following considerations. To minimize the rent required to induce the firm to learn p, the regulator affords the firm only the profit it could secure by adopting either the prevailing or the alternative technology without learning p (i.e., inequality (3) holds as an equality). To limit the firm's profit from implementing the alternative technology without learning p, the regulator delivers only the minimum feasible profit to the firm when social loss D occurs under the alternative technology (i.e., $R_D - K_0 + S = -\Delta$). The regulator then sets R and the firm's profit under the prevailing technology to ensure that $\pi = \pi_0 = \phi_L\pi_L + \phi_H\pi_H$, so both inequalities in expression (6) hold as equalities.

The firm's ex ante expected profit under this compensation structure is $\Delta_F - \Delta$. Therefore, the rent the firm must be afforded to induce it to pursue the efficient adoption policy ($\pi = \Delta_F - \Delta$) increases dollar for dollar as the maximum penalty the regulator can impose on the firm (Δ) declines below Δ_F. Consequently, the regulator will find it too costly to induce the firm to learn p once Δ declines below a critical level, denoted $\hat{\Delta}$. In this event, the regulator will simply instruct the firm to implement the prevailing technology rather than induce the firm to learn p. The efficient adoption policy would generate greater surplus. However, when limits on the penalties that can be imposed on the firm make it unduly costly to induce the firm to pursue this policy, the regulator optimally employs her own limited information to choose the firm's technology and denies the firm any choice among technologies. This conclusion is recorded formally in Proposition 3.

Proposition 3. *The regulator will afford the firm a non-trivial choice between technologies (and induce the firm to learn p) if* $\Delta > \hat{\Delta} \equiv \Delta_F -$

[13] Observe that $\pi_L - (\phi_L\pi_L + \phi_H\pi_H) = [\widetilde{p}-p_L][R-R_D]$, which is increasing in $R - R_D$.

[14] To illustrate, regulatory penalties are limited to $20,000 in the State of California (California Public Utilities Code, Division 1, Article 5, Section 826 (2013), http://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=PUC&division=1.&title=&part=1.&chapter=4.&article=5).

[15] See Kornai (1986) and Kornai et al. (2003) for discussions of the origins of and problems associated with such "soft budget constraints."

$(\phi_L[S-(p_L-p_0)D]-k)$. *In contrast, the regulator will instruct the firm to always operate with the prevailing technology if* $\Delta<\hat{\Delta}$.[16]

Corollary 3. *The range of penalties* $(\Delta_F-\hat{\Delta})$ *for which the firm earns rent as it is optimally induced to undertake the efficient adoption policy: (i) increases as S or* ϕ_L *increases; and (ii) decreases as* p_L, *D, or k increases.*

Corollary 3 identifies the factors that render the regulator willing to concede greater rent to the firm in order to induce it to pursue the efficient adoption policy. This policy generates greater expected surplus when the alternative technology provides a more substantial reduction in operating costs (so S is larger), when it is less likely to impose social loss D (so p_L is smaller), and when this loss is smaller. The efficient adoption policy also generates greater surplus when it is less costly to undertake (so k is smaller) and when the alternative technology is relatively likely to entail the small loss probability (so ϕ_L is relatively large).

Because the regulator affords the firm no choice among technologies when the maximum penalty she can impose on the firm (Δ) is below $\hat{\Delta}$, the firm's equilibrium profit is a non-monotonic function of Δ. Recall from Proposition 2 that when Δ exceeds Δ_F, the regulator is able to limit the firm's ex ante expected profit to zero even as she induces the firm to pursue the efficient adoption policy. Also, recall from Proposition 2 that as Δ declines below Δ_F, the regulator optimally continues to induce the firm to learn p, but is forced to cede some rent to the firm. As Fig. 1 illustrates, this rent continues to increase as Δ declines further below Δ_F until Δ reaches the critical value, $\hat{\Delta}$. When Δ is less than $\hat{\Delta}$, the regulator finds it unduly costly to implement the efficient adoption policy. Instead, the regulator simply instructs the firm to operate under the prevailing technology, and affords the firm no choice among technologies. The firm secures no rent in this case.

The implications of this regulatory policy for the firm's equilibrium profit are summarized formally in Corollary 4.

Corollary 4. *The firm's equilibrium ex ante expected profit,* π^*, *its equilibrium expected profit when it implements the prevailing technology,* π_0^*, *and its equilibrium expected profit when it implements the alternative technology,* π_L^*, *are all non-monotonic functions of* Δ. *In particular:*

$$\pi^* = \begin{cases} 0 & \text{if } \Delta<\hat{\Delta} \\ \Delta_F-\Delta & \text{if } \Delta\in\left[\hat{\Delta},\Delta_F\right] \\ 0 & \text{if } \Delta>\Delta_F. \end{cases}$$

Furthermore, $\pi_0^*=\pi^*$ *and* $\pi_L^*=\pi^*+\frac{k}{\phi_L}$.

Corollary 4 implies that although the firm benefits when the penalties it can be forced to bear are limited, the firm does not wish these penalties to be too limited. When the regulator is unable to impose meaningful penalties on the firm, she optimally rescinds the firm's discretion to choose among technologies, and thereby eliminates the rent the firm can otherwise secure from its privileged ability to discern the prevailing loss under the alternative technology.[17] When she can impose more substantial penalties on the firm, the regulator affords the firm some discretion in choosing its technology, and provides some rent to the firm in order to induce it to use this discretion in the best interests of consumers.

A regulated firm may sometimes be able to enhance a regulator's ability and incentive to impose moderate financial penalties by posting as a financial bond a fraction of the extranormal profit the firm earns over time. When the bond is funded from extranormal profit, the act of posting the bond is unlikely to jeopardize the firm's financial integrity or limit its ability to deliver uninterrupted, high-quality service to consumers. Furthermore, when the accumulated bond is sufficiently large, the regulator can use the bond to finance the penalty she imposes on the firm if the social loss arises under the alternative technology without jeopardizing the firm's financial integrity (and thus without serious risk of consumer inconvenience). The regulator's threat to impose the penalty on the firm can be particularly credible under such circumstances. A credible threat can encourage the regulator to offer the firm a meaningful choice among technologies, to the benefit of consumers and the firm alike.

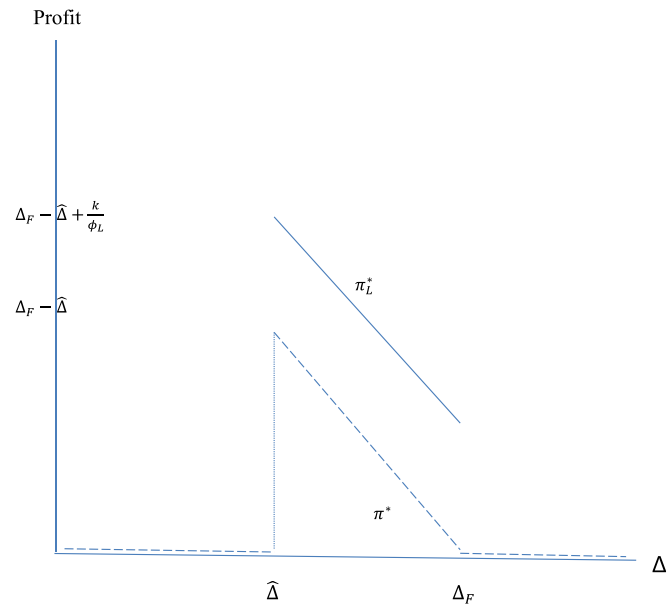

Fig. 1. The firm's ex ante expected profit (π^*) and its profit (π_L^*) under the alternative technology when $\boldsymbol{p}=\boldsymbol{p_L}$.

4. The setting with endogenous *p*

The analysis to this point has assumed that the probability of loss D is not affected by the firm's authorized revenue. This assumption may be reasonable when the loss arises from environmental damage, for instance. The assumption is less plausible when D reflects the social loss that arises when the regulated firm experiences bankruptcy, i.e., when the firm's realized cost exceeds its revenue.[18] The larger the firm's revenue, the less likely it is to incur bankruptcy, ceteris paribus.

To identify the additional considerations that arise when the probability of loss D is endogenous, we consider a streamlined setting in which the regulated firm can adopt either the prevailing capital structure or a more highly leveraged alternative capital structure. The firm experiences cost saving $S\in\left[\underline{S},\ \overline{S}\right]$ if it adopts the alternative capital structure, where $\underline{S}<0<\overline{S}$. The distribution function for S under the alternative capital structure is either $F_L(\cdot)$ or $F_H(\cdot)$.[19] The firm can learn the actual distribution of S by incurring personal cost $k>0$.[20] The ex ante probability if the distribution is $F_i(S)$ is $\phi_i\in(0,1)$ $(i\in\{L,H\})$. Higher S realizations are systematically more likely under $F_L(\cdot)$ than under $F_H(\cdot)$ in

[16] A corresponding conclusion emerges if, when p is not known, social surplus is higher if the alternative technology is employed than if the prevailing technology is employed. In this case, the regulator simply instructs the firm to operate under the alternative technology when Δ is less than $\hat{\Delta}$.

[17] Lewis and Sappington (1995) also find that a regulator may optimally decline to offer a regulated firm a choice among capital structures. This behavior reflects the regulator's risk aversion, though, rather than a limited ability to impose substantial penalties on the regulated firm.

[18] As observed in Section 1 Introduction, social losses from bankruptcy can include "damage [to] the legitimacy of the entire [regulated] sector" (Cox, 2013). These losses can also include the personal and professional losses the regulator experiences, the social cost of funds employed to pay the creditors of the bankrupt firm, and higher future borrowing costs and associated retail prices.

[19] The corresponding density functions, $f_L(\cdot)$ and $f_H(\cdot)$, are continuous.

[20] Regulated firms typically have finance departments, staffed by individuals with considerable financial training and expertise. Consequently, a regulated firm often will be better situated than its regulator to assess the merits and the likely returns from various capital structures.

the sense of strict first-order stochastic dominance, i.e., $F_L(\cdot) < F_H(\cdot)$ for all $S \in \left(\underline{S}, \overline{S}\right)$. Therefore, $S_L > S_H$, where S_i denotes the expected cost saving from adopting the alternative capital structure under distribution $F_i(\cdot)$. K_0 represents all components of the firm's cost other than the cost saving S (and the information acquisition cost, k).

The firm's authorized revenue has two components. Revenue R_D is always awarded to the firm, regardless of its ultimate financial state. $R - R_D \geq 0$ is additional revenue that is delivered to the firm only if it does not experience bankruptcy, i.e., only if $R_D \geq K_0 - S$.[21] $p_i(R_D) = F_i(K_0 - R_D)$ denotes the probability that the firm experiences bankruptcy when it adopts the alternative capital structure and the distribution of S is $F_i(\cdot)$ ($i \in \{L, H\}$). The firm's corresponding (expected) profit is $\pi_i = p_i(R_D)R_D + [1 - p_i(R_D)]R - K_0 + S_i$.

To capture most simply the smaller risk of bankruptcy under the prevailing capital structure, we assume that S is always 0, so the firm's cost is not stochastic under this capital structure. Consequently, the firm will avoid bankruptcy under the prevailing capital structure if its authorized revenue is at least K_0, and so its profit, π_0, is non-negative. Suppose:

$$S_L \geq p_L(R_D)D \text{ and } S_H \leq p_H(R_D)D. \tag{10}$$

Then expected total surplus is maximized when the firm operates under the alternative capital structure if and only if the distribution is $F_L(\cdot)$. Expected total surplus is also maximized when the firm incurs cost k to learn the distribution of S under the alternative capital structure if:

$$\phi_L[S_L - p_L(R_D)D] \geq k. \tag{11}$$

To ensure that conditions (10) and (11) hold for all relevant values of R_D, we assume that the conditions hold even if bankruptcy always arises when $F_i(\cdot) = F_L(\cdot)$ and never arises when $F_i(\cdot) = F_H(\cdot)$ under the alternative capital structure. Formally, we assume:

$$\phi_L[S_L - D] \geq k \text{ and } S_H \leq 0. \tag{12}$$

Eq. (12) implies that $S_L > D$.

In pursuing the best interests of consumers, the regulator seeks to minimize the sum of the firm's expected profit and the expected social loss from bankruptcy. Therefore, employing the conclusions developed in Section 2, it is readily verified that when she induces the firm to pursue the efficient adoption policy (i.e., to incur cost k to learn the distribution of S and adopt the alternative capital structure if and only if the distribution is $F_L(\cdot)$), the regulator's problem, [RP-I]′ is:

$$\underset{R,\ R_D,\ \pi_0}{\text{Minimize}} \quad M \equiv \phi_L \pi_L + \phi_H \pi_0 + \phi_L p_L(R_D)D \tag{13}$$

subject to:

$$\pi_H + \frac{k}{\phi_H} \leq \pi_0 \leq \pi_L - \frac{k}{\phi_L}; \tag{14}$$

$$\pi_0 \geq 0; \tag{15}$$

$$R \geq R_D; \text{ and} \tag{16}$$

$$R_D \geq K_0 - \underline{S} - \Delta. \tag{17}$$

Proposition 4 reports that the regulator's inability to monitor the firm's information acquisition activity is always limiting in this setting.

Proposition 4. *The regulator cannot simultaneously: (i) induce the efficient adoption policy via $R \geq R_D$; (ii) eliminate loss D by precluding bankruptcy under the alternative capital structure; and (iii) eliminate the firm's rent under the prevailing capital structure.*[22]

Proposition 4 reflects the fact that when the firm's revenue is set to preclude bankruptcy, the firm secures nonnegative profit when it systematically adopts the alternative capital structure, i.e., when it adopts the alternative capital structure without first learning $F_i(\cdot)$. Consequently, the firm will prefer to systematically adopt the alternative capital structure than to implement the efficient adoption policy unless it is afforded rent under the prevailing capital structure and/or it faces some risk of bankruptcy, with attendant social loss D, under the alternative capital structure.[23]

It is costly for the regulator to penalize the firm when it experiences bankruptcy in the present setting. The smaller is R_D, the greater is the probability of bankruptcy and associated social loss D, ceteris paribus. This cost of penalizing the firm when bankruptcy arises can lead the regulator to refrain from doing so, as Proposition 5 reports.

Proposition 5. *Suppose $S_L - S_H \geq \frac{k}{\phi_L \phi_H}$. Then $R = R_D \in \left[K_0 - S_L + \frac{k}{\phi_L},\ K_0 - \underline{S}\right]$ at the solution to [RP-I]′.*

Proposition 5 considers a setting where $S_L - S_H$, the difference in expected cost saving under the alternative capital structure according to whether the distribution of S is $F_L(\cdot)$ or $F_H(\cdot)$, is large relative to k, the firm's cost of learning the distribution of S. The relatively large difference in expected cost saving, $S_L - S_H$, ensures that the firm's expected profit varies substantially with the distribution of S under the alternative capital structure even when the firm faces no explicit financial penalty for incurring bankruptcy, i.e., even when $R = R_D$.[24] Consequently, even without reducing R_D below R, the regulator can dissuade the firm from systematically adopting the alternative capital structure. Therefore, because any reduction in R_D increases the probability of bankruptcy and associated loss D, the regulator does not reduce R_D below R at all.

When k is larger relative to $S_L - S_H$, the regulator's problem of inducing the firm to incur k becomes more constraining. Consequently, even though it is costly for the regulator to penalize the firm when it experiences bankruptcy (because the imposition of the penalty increases the likelihood of bankruptcy and social loss D), the regulator optimally imposes such a penalty, just as she does in the basic setting of Section 3.

Proposition 6. *Suppose $S_L - S_H < \frac{k}{\phi_L \phi_H}$. Then $R = R_D + \frac{S_H - S_L + \frac{k}{\phi_L \phi_H}}{p_H(R_D) - p_L(R_D)} > R_D$ and $\pi = \pi_0 = \phi_L \pi_L + \phi_H \pi_H$ at the solution to [RP-I]′.*

Propositions 2 and 6 imply that when k is relatively large, the regulator's optimal policy has the same key qualitative features whether the probability of loss D is exogenous or endogenous. In particular, even when the probability of loss D increases as the firm's revenue in the event of bankruptcy (R_D) declines, the regulator optimally reduces R_D below R. Furthermore, the firm's authorized revenues are structured to ensure that the firm's equilibrium expected profit is precisely its

[21] The regulator might be viewed as collecting R from consumers and specifying that R will be fully awarded to the firm only if it avoids bankruptcy, given its initial authorized revenue, R_D. The amount $R - R_D$ is returned to consumers if the firm experiences bankruptcy. Profit-sharing and revenue-sharing policies are examples of policies in which the regulator sets prices to generate a target level of revenue initially and subsequently may rebate a portion of the revenue to consumers, depending upon the firm's financial performance.

[22] Proposition 1 identifies conditions under which the regulator can achieve the ideal (full-information) outcome in the basic setting analyzed in Sections 2 and 3. Proposition 4 indicates that the regulator can never achieve her ideal outcome in the present setting. The difference arises because loss D never occurs in the ideal outcome here, whereas it occurs with strictly positive probability under the efficient adoption policy in the basic setting.

[23] This conclusion does not depend on the magnitude of Δ. Even if the regulator could, in principle, impose a very large penalty on the firm, she may decline to do so because imposing the penalty can be costly since it can increase the probability of bankruptcy and associated social loss D.

[24] When $R = R_D$, $\pi_L - \pi_H = R - K_0 + S_L - (R - K_0 + S_H) = S_L - S_H$.

expected profit if it systematically adopts either the prevailing or the alternative capital structure without incurring cost k. For the reasons explained in Section 3, this compensation structure best limits the firm's rent and the expected social loss from bankruptcy while inducing the firm to implement the efficient adoption policy.[25]

5. Conclusions

We have examined the optimal design of regulatory policy in settings where the regulated firm can acquire privileged knowledge of the likelihood that an alternative technology (or operating procedure or capital structure) will generate a social loss. We found that if the regulated firm can acquire this information costlessly, the regulator can simply adjust the firm's authorized revenues to reflect the firm's realized operating costs. Such a policy induces the firm to adopt the alternative technology if and only if doing so increases the difference between expected social benefits and social costs.

It is more challenging for the regulator to induce the firm to acquire superior knowledge about the risks inherent in the alternative technology when this knowledge is costly for the firm to acquire. This is the case even when the firm's authorized revenue does not affect the likelihood of the social loss. However, if the regulator can credibly threaten to punish the firm severely should a social loss arise under the alternative technology in this case, the regulator can induce the firm to acquire the valuable information and employ it to adopt the alternative technology if and only if such adoption entails benefits that exceed the associated costs. Furthermore, the regulator can do so without ceding any rent to the firm. Some sacrifice of rent is required when the regulator has more limited ability to penalize the firm. If this ability is sufficiently limited, the regulator will not afford the firm any choice among technologies. Instead, she will simply employ her limited knowledge to determine the most appropriate technology and instruct the firm to employ this technology.

When the firm's authorized revenue does not affect the likelihood of a social loss, the optimal regulatory policy affords the firm no rent if the financial penalties it can be forced to bear are very large or very small. In contrast, the firm secures rent when these penalties are intermediate in magnitude. Therefore, consumers and the firm both gain when the regulator can credibly threaten to impose a moderate penalty on the firm if a social loss arises. The credibility of such a threat can sometimes be enhanced if the firm is required to post a financial bond that it forfeits if (and only if) the loss arises after the firm adopts the alternative technology.

In practice, regulators routinely determine the fraction of industry losses (e.g., losses from reduced service quality, service interruptions, or environmental damage caused by the firm's operation) for which the regulated firm will be held responsible. Thus, the variation in authorized revenue that arises in our model is consistent with industry practice. However, regulators typically do not specify ex ante how the firm's liability for realized losses will vary with the technology (or operating protocol or capital structure) it implements. A central message of our research is that such explicit ex ante linkage between the firm's liability and its choice of technology can help induce the firm to acquire valuable planning information.

In some settings, the firm's authorized revenue can affect the likelihood of the social loss. This is the case, for instance, when the loss arises from bankruptcy. Additional considerations arise in such settings. For example, the regulator may sometimes refrain from penalizing the firm when the social loss arises in order to limit the likelihood of the loss. Under many circumstances, though, the optimal regulatory policy when the likelihood of the social loss is endogenous shares the key features of the corresponding policy when this likelihood is exogenous.

Several extensions of our model await further research. For instance, the firm might be able to undertake activities that limit the likelihood of the social loss. In practice, a regulated firm may be able to take special precautions to limit environmental damage from its operations or devote extra effort to control its operating costs in order to avoid financial distress, for example. In such settings, the revenue risk ($R - R_D$) the firm faces under the alternative technology can motivate the firm to deliver effort (e) that reduces the likelihood of social loss D. Consequently, the equilibrium probability of social loss D under the alternative technology ($p(e^*)$) may be considerably less than the corresponding innate probability ($p(0)$) that prevails in the absence of effort to reduce this probability. The firm's knowledge of $p(\cdot)$ can serve an additional purpose in such settings. In addition to helping assess the relative merits of the available technologies, knowledge of $p(\cdot)$ can help to determine the efficient level of effort to reduce the likelihood of social loss D.[26]

Future research might also consider a richer set of technologies and social losses. The quality of the firm's information might also vary continuously with the firm's information acquisition effort.[27] The optimal simultaneous design of financial incentives for the regulated supplier and retail pricing structures might also be considered. De Fraja and Stones (2004) and Cowan (2013) analyze the simultaneous design of capital structures and retail prices when the regulated firm is fully informed about the risks inherent in potential technologies. The authors find that price cap regulation typically does not produce an optimal price structure even when consumers are risk averse. Retail prices that track realized production costs to some extent are desirable because they reduce the risk borne by investors and can reduce the cost of capital.[28]

Appendix A

Proof of Proposition 1. First suppose $\Delta < \Delta_F$. Proposition 2 establishes that $\pi = \Delta_F - \Delta > 0$ under the reward structure that minimizes the firm's expected profit while inducing the firm to incur k to learn p. Therefore, the full-information outcome is not feasible.

Now suppose $\Delta \geq \Delta_F$ and the regulator sets:

$$R_D = K_0 - S - \Delta,\ \ R = R_D + \frac{1}{1-p_L}\left[\Delta + \frac{k}{\phi_L}\right],\ \text{ and }\ \pi_0 = 0. \tag{18}$$

It is readily verified that this reward structure ensures that $\pi = \pi_0 = 0$, $\phi_L\pi_L + \phi_H\pi_H = \frac{\theta[\Delta_F - \Delta]}{\phi_L[1-p_L]} \leq 0$, and $\pi_H + \frac{k}{\phi_H} < \pi_0 < \pi_L - \frac{k}{\phi_L}$. Therefore, the firm will pursue the efficient adoption policy and secure no rent, so the full-information outcome is feasible. ∎

Lemma 1. *Inequalities (6), (7), and (9) are satisfied if and only if:*

$$\pi_H + \frac{k}{\phi_H} \leq \pi_0 \leq \pi_L - \frac{k}{\phi_L} + \frac{min\ \{0,\ \pi_0\}}{\phi_L},\ \text{ and} \tag{19}$$

$$R_D - K_0 + S \geq -\Delta. \tag{20}$$

[25] A complete characterization of the optimal values of R and R_D is relatively complex when the probability of loss D is endogenous. This is the case in part because these optimal values vary with the precise manner in which a reduction in R_D increases the probabilities of bankruptcy under the $F_L(\cdot)$ and $F_H(\cdot)$ distributions. Jamison et al. (2014) provide additional characterization of the optimal values of R and R_D in a particular case of interest.

[26] The firm's cost-reducing effort is endogenous in Iossa and Stroffolini (2002). Consequently, the firm's equilibrium effort is influenced by its knowledge of its innate production cost (β). Under price cap regulation, the firm's knowledge of β also enables it to determine whether the specified price cap exceeds the profit-maximizing price, and thus whether the firm should reduce its price below the cap.

[27] Szalay (2009) develops useful analytic techniques in this regard.

[28] See Cowan (2004) for related observations.

Proof. First suppose Eqs. (19) and (20) hold. Eq. (19) clearly implies that Eq. (6) holds. Now define $\widetilde{R}(p) \equiv pR_D + [1-p]R$ and $\widetilde{R} \equiv p_0 R_D + [1-p_0]R$. Then Eq. (19) implies:

$$\begin{aligned}\widetilde{R}(p_H) - K_0 + S + \frac{k}{\phi_H} &\le \widetilde{R}(p_L) - K_0 \\ &+ S - \frac{k}{\phi_L} \Leftrightarrow [p_H - p_L][R_D - R] \le -k\left[\frac{1}{\phi_H} + \frac{1}{\phi_L}\right] \Rightarrow R > R_D.\end{aligned} \tag{21}$$

Eqs. (20) and (21) imply the second and third inequalities in (7) hold. Eqs. (19), (20), and (21) imply:

$$\pi_0 \ge \pi_H + \frac{k}{\phi_H} > \pi_H = \widetilde{R}(p_H) - K_0 + S = p_H R_D + [1-p_H]R - K_0 + S > R_D - K_0 + S \ge -\Delta.$$

Therefore, the first inequality in (7) holds.

Finally, Eq. (9) holds because Eq. (19) implies that if $\pi_0 \le 0$, then:

$$\pi_0 \le \pi_L - \frac{k}{\phi_L} + \frac{\pi_0}{\phi_L} \Leftrightarrow \phi_L[\pi_0 - \pi_L] \le \pi_0 - k \Leftrightarrow \phi_L \pi_L + \phi_H \pi_0 - k \ge 0; \tag{22}$$

whereas if $\pi_0 \ge 0$, then:

$$\pi_0 \le \pi_L - \frac{k}{\phi_L} \Leftrightarrow \phi_L \pi_0 \le \phi_L \pi_L - k \Leftrightarrow \phi_L \pi_L + \phi_H \pi_0 - k \ge \pi_0 \ge 0. \tag{23}$$

Now suppose Eqs. (6), (7), and (9) hold. Eq. (7) clearly implies that Eq. (20) holds. Also, Eq. (6) clearly implies that the first inequality in Eq. (19) holds. Furthermore, Eqs. (9), (22), and (23) imply that the second inequality in Eq. (19) holds. ∎

Proof of Proposition 2. Lemma 1 implies [RP-I] can be solved by minimizing Eqs. (8) subject to (19) and (20). The regulator's objective in (8) is strictly increasing in R, R_D, and π_0. Therefore, the minimum occurs at the smallest values of these choice variables that are consistent with Eqs. (19) and (20).

π_L declines more rapidly than π_H declines as R declines because $1 - p_L > 1 - p_H$. Therefore, the second inequality in Eq. (19) provides the relevant lower bound on R (and hence on π_L), and so this inequality binds at the solution to [RP-I], i.e.:

$$\pi_0 = \pi_L - \frac{k}{\phi_L} + \frac{min\ \{0,\ \pi_0\}}{\phi_L}. \tag{24}$$

Eq. (24) provides a unique optimal value for R for any (π_0, R_D) pair.

We now show $\pi_0 > 0$. Suppose otherwise. Then Eq. (24) implies:

$$\pi_0 = \pi_L - \frac{k}{\phi_L} + \frac{\pi_0}{\phi_L} \Rightarrow \pi_L = \frac{k}{\phi_L} - \frac{\phi_H}{\phi_L}\pi_0 \Rightarrow \pi_L \ge \frac{k}{\phi_L} \Rightarrow R \ge -\frac{p_L R_D - K_0 + S - \frac{k}{\phi_L}}{1-p_L}. \tag{25}$$

Eqs. (19) and (25) imply:

$$\begin{aligned}\pi_0 &\ge \pi_H + \frac{k}{\phi_H} = p_H R_D + [1-p_H]R - K_0 + S + \frac{k}{\phi_H} \\ &\ge p_H R_D - \frac{1-p_H}{1-p_L}\left[p_L R_D - K_0 + S - \frac{k}{\phi_L}\right] - K_0 + S + \frac{k}{\phi_H} \\ &= \frac{1}{1-p_L}\{R_D[p_H(1-p_L) - p_L(1-p_H)] + [S-K_0][1-p_L-(1-p_H)] \\ &\quad + \frac{k}{\phi_L\phi_H}[\phi_L(1-p_L) + \phi_H(1-p_H)]\} \\ &= \frac{p_H - p_L}{1-p_L}\left[R_D - K_0 + S + \frac{k(1-\widetilde{p})}{\phi_L\phi_H(p_H-p_L)}\right] \\ &= \frac{p_H - p_L}{1-p_L}[R_D - K_0 + S + \Delta_F] > 0.\end{aligned} \tag{26}$$

The strict inequality in Eq. (26) reflects Eq. (7).

The contradiction in Eq. (26) implies that $\pi_0 > 0$. Therefore, Eq. (24) implies that $\pi_0 = \pi_L - \frac{k}{\phi_L}$, so the regulator's objective in Eq. (8) is $\pi_0 + k$, which is minimized by ensuring $\pi_0 = \pi_H + \frac{k}{\phi_H}$. π_H is minimized by setting:

$$R_D = K_0 - S - \Delta. \tag{27}$$

Given this (R_D, π_0) pair, the optimal R is derived by equating the first and last of the three terms in Eq. (19). Consequently, from Eq. (21):

$$R = R_D + \frac{k}{\phi_L\phi_H[p_H - p_L]} = R_D + \frac{k}{\phi_L[\phi_H p_H - (1-\phi_L)p_L]} = R_D + \frac{k}{\theta}. \tag{28}$$

Therefore, Eqs. (24), (27), and (28) provide:

$$\begin{aligned}\pi_0 &= p_L R_D + [1-p_L]R - K_0 + S - \frac{k}{\phi_L} = -\Delta + k\left[\frac{1-p_L}{\theta} - \frac{1}{\phi_L}\right] \\ &= -\Delta + \frac{k}{\theta}[1 - p_L - \phi_H(p_H - p_L)] = -\Delta + \frac{[1-\widetilde{p}]k}{\theta} = \Delta_F - \Delta.\end{aligned} \tag{29}$$

Eqs. (24) and (29) provide:

$$\pi = \phi_L\left[\pi_0 + \frac{k}{\phi_L}\right] + \phi_H \pi_0 - k = \pi_0 = \Delta_F - \Delta.$$

Eqs. (27) and (29) provide:

$$\pi_H = p_H R_D + [1-p_H]R + S - K_0 = \frac{1}{\theta}[1-p_H]k - \Delta. \quad ∎ \tag{30}$$

Proof of Corollary 1. $\Delta_F \equiv \frac{[1-\widetilde{p}]k}{\phi_L[\widetilde{p}-p_L]}$ is clearly increasing in k. Furthermore:

$$\frac{\partial \widetilde{p}}{\partial p_H} = \frac{\partial}{\partial p_H}\{\phi_L p_L + \phi_H p_H\} = \phi_H \text{ and } \frac{\partial \widetilde{p}}{\partial p_L} = \frac{\partial}{\partial p_L}\{\phi_L p_L + \phi_H p_H\} = \phi_L.$$

Therefore:

$$\frac{\partial \Delta_F}{\partial p_H} \overset{s}{=} [\widetilde{p} - p_L]\left(-\frac{\partial \widetilde{p}}{\partial p_H}\right) - [1-\widetilde{p}]\frac{\partial \widetilde{p}}{\partial p_H} = -[1-p_L]\frac{\partial \widetilde{p}}{\partial p_H} = -\phi_H[1-p_L] < 0;$$

and

$$\begin{aligned}\frac{\partial \Delta_F}{\partial p_L} &\overset{s}{=} [\widetilde{p} - p_L]\left(-\frac{\partial \widetilde{p}}{\partial p_L}\right) - [1-\widetilde{p}]\left[\frac{\partial \widetilde{p}}{\partial p_H} - 1\right] = -[1-p_L]\frac{\partial \widetilde{p}}{\partial p_L} + 1 - \widetilde{p} \\ &= 1 - \widetilde{p} - \phi_L[1-p_L] = 1 - \phi_L - \phi_H p_H = \phi_H[1-p_H] > 0. \quad ∎\end{aligned}$$

Proof of Corollary 2. The proof follows immediately from the statement of Proposition 2. ∎

Proof of Proposition 3. From Eq. (2), the social value of inducing the firm to learn p is $\phi_L[S - (p_L - p_0)D]$. When $\Delta \in [\hat{\Delta},\ \Delta_F]$, the regulator's cost of inducing the firm to learn p is $k + \pi$. Therefore, the regulator will induce the firm to learn p if:

$$\phi_L[S - (p_L - p_0)D] > k + \pi = k + \Delta_F - \Delta \Leftrightarrow \Delta > k + \Delta_F - \phi_L[S - (p_L - p_0)D]. \tag{31}$$

The equality in Eq. (31) reflects Proposition 2. ∎

Proof of Corollary 3. From Proposition 3, $\Delta_F - \hat{\Delta} = \phi_L[S - (p_L - p_0)D] - k$. This expression is increasing in S and decreasing in p_L and k. The expression is also decreasing in D, since $p_L > p_0$. Eq. (2) implies that the expression is increasing in ϕ_L. ∎

Proof of Corollary 4. The proof follows immediately from Propositions 2 and 3. ∎

Proof of Proposition 4. To preclude bankruptcy under the alternative capital structure when $F_i(\cdot) = F_L(\cdot)$, i.e., to ensure $p_L(R_D) = 0$, the regulator must set:

$$R_D \geq K_0 - \underline{S}. \tag{32}$$

$\pi_i = R - K_0 + S_i$ for $i = L, H$ when inequality (32) holds.

If $\pi_0 = 0$ and bankruptcy is precluded under the alternative capital structure, then to ensure that the firm pursues the efficient adoption policy instead of remaining uninformed about $F_i(\cdot)$ and systematically adopting the alternative capital structure, we must have:

$$\phi_L\pi_L + \phi_H[0] - k \geq \phi_L\pi_L + \phi_H\pi_H \Leftrightarrow \pi_H \leq -\frac{k}{\phi_H} \Leftrightarrow R \leq K_0 - S_H - \frac{k}{\phi_H}. \tag{33}$$

To ensure that $R \geq R_D$, conditions (32) and (33) imply we must have:

$$K_0 - S_H - \frac{k}{\phi_H} \geq K_0 - \underline{S} \Leftrightarrow S_H - \underline{S} \leq -\frac{k}{\phi_H}. \tag{34}$$

The inequality in condition (34) cannot hold, because $S_H \geq \underline{S}$. ∎

Proof of Proposition 5. π_L, and thus M, are strictly increasing in R provided bankruptcy is not certain to arise. (We demonstrate below that bankruptcy is avoided with strictly positive probability under the alternative capital structure at the solution to [RP-I]′). Therefore, for a given R_D, M is minimized at the smallest values of R and π_0 consistent with the constraints in [RP-I]′. To characterize the solution to [RP-I]′, we will identify these smallest values of R and π_0 conditional on R_D, and then choose R_D to minimize M.

Eq. (14) requires $\pi_H + \frac{k}{\phi_H} \leq \pi_L - \frac{k}{\phi_L} \Leftrightarrow$.

$$\begin{aligned} &p_H(\cdot)R_D + [1 - p_H(\cdot)]R + S_H + \frac{k}{\phi_H} \leq p_L(\cdot)R_D + [1 - p_L(\cdot)]R + S_L - \frac{k}{\phi_L} \\ &\Leftrightarrow [p_H(\cdot) - p_L(\cdot)][R_D - R] \leq S_L - \frac{k}{\phi_L} - \left(S_H + \frac{k}{\phi_H}\right) = S_L - S_H - \frac{k}{\phi_L\phi_H}. \end{aligned} \tag{35}$$

Eqs. (14) and (15) require:

$$\pi_L - \frac{k}{\phi_L} \geq 0. \tag{36}$$

π_0 can be chosen to satisfy Eqs. (14) and (15) if and only if Eqs. (35) and (36) hold. Therefore, we will identify the smallest R that satisfies Eqs. (16), (35), and (36) for a given R_D, and then choose:

$$\pi_0 = max\left\{0,\ \pi_H + \frac{k}{\phi_H}\right\}, \tag{37}$$

where π_H is evaluated at the given R_D and the identified smallest R. The relevant minimization problem, then, is to choose R_D, subject to Eq. (17).

We need only consider values of $R_D \in (K_0 - \overline{S},\ K_0 - \underline{S}]$. If $R_D > K_0 - \underline{S}$, then $p_L(R_D) = 0$ and so $M = \phi_L[R - K_0 + S_L] + \phi_H\pi_0$, which is independent of R_D. Eq. (14) is also independent of R_D in this case because both π_L and π_H are independent of R_D. Furthermore, Eq. (16) becomes more constraining if values above $K_0 - \underline{S}$ are considered. If $R_D \leq K_0 - \overline{S}$, then $p_L(R_D) = 1$ and $\pi_L = R_D - K_0 + S_L \leq S_L - \overline{S} < 0$. This violates Eq. (36), and so is infeasible.

When $S_L - S_H \geq \frac{k}{\phi_L\phi_H}$, for a given R_D, every $R \geq R_D$ satisfies Eq. (35) since the left-hand side of Eq. (35) is non-positive. Consequently, we can ignore Eq. (35) and choose R to satisfy Eqs. (16) and (36). Differentiating π_L provides the slope of the boundary defined by the equality in Eq. (36):

$$\begin{aligned} &[p_L(R_D) + p_L'(R_D)R_D - p_L'(R_D)R]dR_D + [1 - p_L(R_D)]dR = 0 \\ &\Rightarrow \frac{\partial R}{\partial R_D} = -\frac{p_L'(R_D)[R_D - R] + p_L(R_D)}{1 - p_L(R_D)} \leq 0 \text{ for } R \geq R_D. \end{aligned}$$

Observe that $R \to \infty$ as R_D approaches $K_0 - \overline{S}$ from above because $p_L(R_D) \to 1$; if R was bounded, $\pi_L \to R_D - K_0 + S_L = -\left(\overline{S} - S_L\right) < 0$. This cannot be the case, since $\pi_L > 0$, from Eq. (36).

The value of R_D at which the $\pi_L = \frac{k}{\phi_L}$ and $R = R_D$ loci intersect is given by $R_D - K_0 + S_L = \frac{k}{\phi_L} \Leftrightarrow R_D = K_0 - S_L + \frac{k}{\phi_L}$. Therefore, the smallest feasible value of R lies on the $\pi_L = \frac{k}{\phi_L}$ locus for $R_D \in \left(K_0 - \overline{S}, K_0 - S_L + \frac{k}{\phi_L}\right)$ and on the $R = R_D$ locus for $R_D \in \left[K_0 - S_L + \frac{k}{\phi_L},\ K_0 - \underline{S}\right]$.

$\pi_L - \frac{k}{\phi_L} = 0$ when $R_D \in (K_0 - \overline{S}, K_0 - S_L + \frac{k}{\phi_L}]$, so $\pi_0 = 0$ is feasible (and optimal). Also, from (13):

$$M = \phi_L\left[\frac{k}{\phi_L}\right] + \phi_L[0] + \phi_L p_L(R_D)D = k + \phi_L p_L(R_D)D.$$

This expression for M is strictly decreasing in R_D since $p_L'(R_D) < 0$. Therefore, M is minimized on this interval at the largest value of R_D, i.e., at $R_D = K_0 - S_L + \frac{k}{\phi_L}$. Consequently, the optimal R_D lies in the interval $\left[K_0 - S_L + \frac{k}{\phi_L},\ K_0 - \underline{S}\right]$, where $R = R_D$ is optimal. ∎

Proof of Proposition 6. When $S_L - S_H < \frac{k}{\phi_L\phi_H}$, for a given R_D, every R that satisfies Eq. (35) also satisfies Eq. (16). Therefore, we can ignore Eq. (16) and choose R to satisfy Eqs. (35) and (36). Geometrically, the boundary defined by the equality in Eq. (35) lies everywhere above the $R = R_D$ line in (R_D, R) space but need not lie above the boundary defined by the equality in Eq. (36).

The analysis of values of R_D on the boundary defined by the equality in Eq. (36) is as specified in the Proof of Proposition 5. Therefore, only the largest R_D on the boundary that also satisfies Eq. (35) is a potential minimum. Consequently, we need only consider points on the boundary defined by the equality in Eq. (35) to the right of its right-most intersection with the boundary defined by the equality in Eq. (36), if any such intersection exists.

$R_D = K_0 - \underline{S}$ cannot arise when $S_L - S_H < \frac{k}{\phi_L\phi_H}$. If $R_D = K_0 - \underline{S}$, then $p_L(R_D) = p_H(R_D) = 0$, and so the left-hand side of Eq. (35) is 0, which is not possible. Therefore, the boundary defined by the equality in Eq. (35) has a vertical asymptote at $R_D = K_0 - \underline{S}$, which ensures that part of this boundary lies above the boundary defined by the equality in Eq. (36) on $\left(K_0 - \overline{S}, K_0 - \underline{S}\right)$. Hence, the values of R_D and R that minimize M lie on the boundary defined by the equality in Eq. (35).

Since Eq. (35) holds as an equality, π_0 is optimally set to ensure:

$$\pi_0 = \pi_H + \frac{k}{\phi_H} = \pi_L - \frac{k}{\phi_L} \Leftrightarrow \pi = \pi_0 = \phi_L\pi_L + \phi_H\pi_H. \tag{38}$$

Finally, from Eq. (35):

$$\begin{aligned} \pi_H + \frac{k}{\phi_H} = \pi_L - \frac{k}{\phi_L} &\Leftrightarrow [p_H(R_D) - p_L(R_D)][R - R_D] = S_H - S_L + \frac{k}{\phi_L\phi_H} \\ &\Leftrightarrow R = R_D + \frac{S_H - S_L + \frac{k}{\phi_L\phi_H}}{p_H(R_D) - p_L(R_D)} > R_D. \quad ∎ \end{aligned} \tag{39}$$

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijindorg.2014.07.002.

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