Regulatory risk, vertical integration, and upstream investment

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Abstract

We investigate the impact of regulatory risk on vertical integration and upstream investment by a regulated firm that provides an essential input to downstream competitors. Regulatory risk reflects uncertainty about the regulator's commitment to a regulatory policy that promotes the regulated firm's unobservable investment effort. We show that, when the regulator sets the regulatory policy after the vertical industry structure has been established, some degree of regulatory risk is ex ante socially beneficial. Regulatory risk makes vertical integration profitable and stimulates upstream investment at a lower social cost. This occurs for moderate costs of investment effort and firm small risk aversion. Our analysis sheds new light on some relevant empirical patterns in vertically related markets.

Keywords: commitment, moral hazard, regulatory risk, upstream investment, vertical integration, vertically related markets.

JEL classification: D82, L43, L51.

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1 Introduction

A major challenge for modern countries is the promotion of upstream investments in vertically related markets where a firm controls the essential facility used by downstream competitive operators. Prominent examples include electricity, gas, telecommunications, transportation and water network industries. The aim of upstream investments ranges from the reduction in operating costs to the improvement in the quality of existing services or the provision of new services, such as broadband infrastructure in telecommunications (e.g., Cambini and Jiang 2009).[1] The upstream firm's investment incentives generally vary with the prevailing vertical industry structure, namely, vertical separation or vertical integration. Under vertical separation, the upstream firm only supplies the essential facility. Under vertical integration, the upstream firm also competes in the downstream market.

Given the natural monopoly feature of the essential facility, the upstream firm that controls this facility is usually subject to regulatory intervention. A crucial driver of the regulated firm's investment activities is the regulator's ability to commit to future policies. This is especially the case in infrastructure industries, where the investment effort is typically unobservable (or unverifiable) by the regulator and the investment process is irreversible, because the physical capital deployed by the firm is industry-specific and cannot be economically recovered and used elsewhere (e.g., Guthrie 2006; Newbery 2002; Pedell 2006). The uncertainty about future regulation is known as regulatory risk. Surveys on business risks (e.g., Allianz 2019; EIU 2005; EY 2013) systematically identify regulatory risk as one of the main business risks for firms. The presence of regulatory risk has been also explicitly recognized in the law. The US Supreme Court ruled in case Duquesne Light Company v. Barash (488 US 299, 1989) that the uncertainty about future regulatory policies imposes a special class of risk on the regulated firm.

In the light of the practical relevance of the aforementioned issues, we attempt to provide a theoretical framework that allows for a comprehensive analysis. The purpose of this paper is to investigate the impact of regulatory risk on vertical integration and upstream investment in a vertically related market where a regulated firm exerts unobservable investment effort for the provision of an essential input to downstream competitors.

We consider a setting where the regulator determines the regulatory policy after the vertical industry structure has been established.[2] An important task of the regulatory policy is to deal with the moral hazard problem associated with the unobservability (or unverifiability) of the investment effort exerted by the regulated firm, once the decision about vertical integration has been taken. A moral hazard problem emerges because the unobservable investment effort cannot be included in the terms of the regulatory policy and the firm has an incentive to underprovide effort in order to save the associated costs. In our framework, the upstream firm's effort is socially valuable because it makes investment more likely to generate positive economic

[1] The deployment of broadband infrastructure is a timely issue in the telecommunications industry, where network effects emerge because of the interaction among different groups of users, such as content providers (or advertisers) and final consumers. Broadband investments can foster content providers' innovation and mitigate negative network effects, typically associated with some form of congestion.

[2] Hence, the regulatory policy cannot affect the vertical industry structure. Practical evidence indicates that regulatory policies are generally revised after a limited period of time (some years) and cannot prescribe long-term rules that induce a particular industry structure.

effects, typically in the form of improvement in cost efficiency or quality of the input provided to downstream competitors. Vertical integration alters the investment incentives of the upstream firm, which internalizes the downstream payoff associated with the investment outcome.

Two extreme regulatory regimes have been commonly investigated in the literature. Under full commitment, the regulator can perfectly enforce the regulatory policy announced prior to the investment stage, specifying irrevocably the remuneration that induces the firm to supply the desired level of investment effort. Under no commitment, the regulator invariably succumbs to the temptation to revise the regulatory policy after the investment costs have been sunk. In practice, the extension of the regulator's commitment powers does not take such extreme values. This entails uncertainty about the regulator's future behavior, i.e., regulatory risk. The degree of regulatory risk depends on the features of the institutional and legal system where the regulator operates. We model regulatory risk as the probability that the regulatory policy announced prior to the investment stage is actually enforced by the regulator. With complementary probability, the regulator revises its policy and offers a new, sequentially optimal policy after the investment effort has been exerted. Any probability of regulatory enforcement that strictly lies between zero (no commitment) and one (full commitment) involves regulatory uncertainty and therefore regulatory risk. We show that, contrary to conventional wisdom, under certain circumstances, some degree of regulatory risk is ex ante socially beneficial. Perhaps counterintuitively, this occurs in the presence of some level of firm risk aversion.[3] To appreciate the rationale for our results, it is helpful to begin with the case of full commitment, where regulatory risk is absent. When the costs of investment effort are not too large, a regulator with full commitment powers can promote high investment effort with lower compensation to the regulated firm under vertical integration than under vertical separation. This is because the vertically integrated firm internalizes the higher downstream payoff associated with the upstream investment and commands lower remuneration. For moderate costs of investment effort, the regulator induces the upstream regulated firm to exert high effort irrespective of the vertical industry structure. This implies that the (expected) aggregate utility under vertical separation exceeds the (expected) utility of the vertically integrated firm. Hence, vertical separation emerges in equilibrium, and the regulator must provide the upstream firm with relatively large remuneration in order to exert high effort.

Regulatory uncertainty aggravates the risk borne by the regulated firm. In the presence of risk aversion, the firm requires larger compensation to provide high effort. This reduces the social desirability of high effort compared to full regulatory commitment. As the vertically integrated firm's internalization of the downstream payoff mitigates the moral hazard problem, for moderate costs of investment effort, some degree of regulatory risk implies that, differently from full commitment, high effort is incentivized under vertical integration but not under vertical separation. This makes vertical integration profitable and promotes high effort at a lower social cost than under full commitment. Given that in the presence of risk aversion a vertically integrated firm values any upstream transfer in addition to the downstream payoff relatively less than a vertically separated firm, the transfer associated with high effort under vertical

[3]In an ideal environment where the regulator could perfectly enforce a regulatory policy contingent on all possible events (including the vertical integration decision), full regulatory commitment would trivially be ex ante optimal. At the end of Section 1, we provide theoretical and empirical support for firm risk aversion.

integration must increase with the cost of effort to a larger extent than under vertical separation. Therefore, regulatory risk is socially optimal for moderate costs of investment effort. Moreover, firm risk aversion inflates the firm's remuneration to exert high effort, which makes regulatory risk more likely to be optimal when firm risk aversion is small enough.

Our analysis is presented in a fairly general setting without imposing any particular assumptions either on functional forms or on the mode of downstream competition. As discussed in Section 8, establishing a unified framework that incorporates regulatory risk, vertical integration and upstream investment, our study provides potentially relevant empirical and policy implications in vertically related markets.

Related literature Despite the practical relevance of regulatory risk, the economic literature has devoted so far relatively little attention to this phenomenon. Woroch (1988) examines the welfare effects of uncertainty about the regulatory constraints on the rate of return, price and entry. Ahn and Thompson (1989) study the impact of regulatory risk on the cost of capital. More recently, Panteghini and Scarpa (2008) compare price cap and profit sharing rules in the presence of regulatory risk. In a classical optimal monopoly regulation setting, Strausz (2011) shows that regulatory risk can benefit the regulated firm and consumers under certain conditions on the demand function. Extending the previous analysis, Strausz (2017) identifies the political motives for regulatory risk.

Our paper is also related to the recent literature about the positive impact of uncertainty on investment activities and social welfare. Pawlina and Kort (2005) establish that some degree of uncertainty about a policy change accelerates a firm's investment process. Analyzing partial commitment in a lender-borrower relationship, Kovrijnykh (2013) shows that, when the borrower cannot be forced to make repayments, a lower probability of contractual enforcement by the lender can be welfare improving. Katsoulacos and Ulph (2017) find that, for any level of decision errors made by the enforcement authority, social welfare can increase in the presence of higher legal uncertainty. Lang (2017) demonstrates that legal uncertainty acts as a welfare enhancing screen because the actions of a firm with negative externalities are discouraged in case of low private benefits but they are encouraged in case of high private benefits.

Our work also pertains to the literature on investment and innovation incentives in vertically related markets. We refer to Guthrie (2006) for a seminal survey of the literature on investments in regulated infrastructure industries and to Armstrong and Sappington (2007) for an authoritative review of the literature on optimal regulation. Foros (2004) examines the impact of access price regulation on the vertically integrated firm's incentives to improve the quality of the input used by downstream competitors. Building on Foros (2004), Kotakorpi (2006) explores the vertically integrated firm's incentives for infrastructure investments in a vertical differentiation model with a competitive fringe. Chen and Sappington (2009, 2010) investigate upstream investment incentives according to the vertical industry structure and the nature of downstream competition. Klumpp and Su (2010, 2015) construct a model of open access where a vertically integrated firm shares an upstream essential resource with downstream competitors at a regulated tariff, and provide empirical support for their results. Investments in the Internet services have recently attracted increasing attention in the theoretical and practical debate, often in association with the issue of net neutrality. Bourreau et al. (2015) show that, in the presence of Internet platform competition, a discriminatory regime leads to an increase in broadband investments and content innovation compared to net neutrality regulation.

Our model allows for firm risk aversion. As empirically documented by Greenwald and Stiglitz (1993), financial market imperfections induce firms to act in a risk-averse manner, because they can diversify risks only partially. Such risk attitude may also stem from control delegation to risk-averse managers (e.g., Gervais 2018). Asplund (2002) and Banal-Estañol and Ottaviani (2006) report that there exist a multiplicity of reasons why firms, including large companies, can be risk averse, such as concentrated ownership, limited hedging, managerial control, costly bankruptcy, limited debt capacity, liquidity constraints, costly financial distress, imperfect risk management, and nonlinear tax systems. Firm risk aversion has been also explored in the literature about asymmetric information. Laffont and Rochet (1998) characterize the optimal regulation of a risk-averse firm. Iossa and Martimort (2016) examine risk allocation and contractual choices in a public procurement setting where the contractor is risk averse. Arve and Martimort (2016) investigate the optimal dynamic contract when the procurement process involves future add-ons, and provide significant support for the firm's reluctance to bear risks. To the best of our knowledge, our paper is the first contribution that includes significant elements identified by Chen and Sappington (2009, p. 398) for future research in vertically related markets, such as stochastic outcomes driven by unobservable investment effort and endogenous choice of vertical integration, particularly in the presence of firm risk aversion.

Structure of the paper The rest of the paper is organized as follows. Section 2 sets out the formal model. After exploring the case of full commitment, Section 3 investigates regulatory risk and derives the main results. Using explicit functions, Section 4 provides additional results. Section 5 discusses the robustness of the model and various extensions. Section 6 examines the determinants of regulatory risk. Section 7 concludes with some empirical and policy implications. The main formal proofs are collected in the Appendix. Additional formal results and associated proofs are available in the Supplementary Appendix.

2 The model

Setting We consider a vertically related market where an upstream regulated firm exerts an investment effort e that is unobservable (or unverifiable) by the regulator. The investment effort can be either low or high. The cost of effort ψ_e is normalized to zero for low effort and is equal to $\psi > 0$ for high effort. If the firm chooses high effort, the investment outcome is a "success" with probability $\nu_h \in (0, 1)$, whereas it is a "failure" with complementary probability $1-\nu_h$. The investment outcome may refer to cost efficiency or input quality. If the firm chooses low effort, the probabilities of investment success and failure are respectively $\nu_l \in (0, 1)$ and $1 - \nu_l$, where $\Delta\nu \equiv \nu_h - \nu_l > 0$. Intuitively, high effort makes the investment more likely to be successful. Our framework identifies a classical moral hazard problem, which is suitable to describe investment activities in regulated industries.

The upstream firm receives a transfer $t \in \mathbb{R}$ determined by the regulator and incurs the cost of effort ψ_e. Without any loss of generality, additional production costs are normalized to zero.

The upstream firm's utility is

$$\Pi_u = u(t) - \psi_e, \tag{1}$$

where $u(\cdot)$ is an increasing and (weakly) concave utility function, i.e., $u'(\cdot) > 0$ and $u''(\cdot) \leq 0$, with $u''(\cdot) < 0$ under firm risk aversion.[4] We adopt the standard normalization $u(0) = 0$. The upstream regulated firm is protected by limited liability that allows the firm to obtain nonnegative payoffs (e.g., Guthrie 2006). The opportunity to provide costless low effort implies that the limited liability constraint is $t \geq 0$. As the firm's effort is unobservable (or unverifiable) by the regulator, the upstream transfer can only depend on the investment outcome, i.e., $t \in \{\overline{t}, \underline{t}\}$, where $\overline{t}$ identifies the transfer conditional on the investment success and $\underline{t}$ the corresponding transfer conditional on the investment failure.

The downstream market is served by competitive firms. We denote by $u(\pi)$ the utility of a downstream firm associated with the payoff $\pi \geq 0$, where $u(\cdot)$ is defined above.[5] The upstream firm's investment success provides each downstream firm with a higher payoff (and utility) compared to investment failure, i.e., $\pi \in \{\overline{\pi}, \underline{\pi}\}$ and $\overline{\pi} > \underline{\pi}$. This formulation admits different natural economic interpretations. A successful investment can reduce the price or improve the quality of the input provided to downstream firms, which in turn decreases their costs or increases the willingness to pay of their customers. Moreover, technological spillovers can enhance the efficiency of downstream firms.

The upstream firm decides whether to integrate with a downstream firm. The vertically integrated firm's utility is

$$\Pi_{vi} = u(t + \pi) - \psi_e. \tag{2}$$

Under vertical integration, the firm receives the transfer t from the upstream regulated activities and the payoff π from the downstream competitive activities, with associated utility $u(\cdot)$, and incurs the cost of effort ψ_e. Vertical integration is profitable if and only if the (expected) utility of the vertically integrated firm exceeds the (expected) aggregate utility under vertical separation, i.e., $\mathbb{E}[\Pi_{vi}] \geq \mathbb{E}[\Pi_{vs}]$, where $\Pi_{vs} \equiv \Pi_u + u(\pi)$.[6] Note from (1) and (2) that, under firm risk aversion, vertical separation is preferred to vertical integration for a given transfer. The choice of vertical integration comes at a cost and, as shown in the subsequent analysis, it depends on the regulatory regime in a nontrivial manner. Since in practice regulatory intervention is limited to the monopolistic input and cross-subsidization between regulated and competitive activities is prohibited, the regulator focuses on the viability of regulated activities (e.g., Vickers 1995, p.

[4] The assumption of additively separable preferences is standard in the moral hazard literature and simplifies the analysis substantially, without involving a relevant loss of generality (e.g., Armstrong and Sappington 2007; Laffont and Martimort 2002; Macho-Stadler and Pérez-Castrillo 2001). In the Supplementary Appendix, we show that our results still hold when preferences are not additively separable.

[5] Nothing substantial would change with heterogeneous firms. Moreover, as explained in Section 5.1, the formalization of the access price for the upstream input does not alter our qualitative results.

[6] Common regulatory practices prescribe that regulated and competitive activities must be legally unbundled. Hence, the downstream division of the vertically integrated firm operates as under vertical separation, and the downstream payoff π is independent of the vertical industry structure. A fortiori, this holds in our setting where the upstream payoff is fully determined at the regulation stage. We refer to Section 5.2 for further discussion on this point. As will be clear in the sequel, privately beneficial vertical integration is also welfare enhancing but the converse may not be true. Remarkably, vertical integration does not necessarily increase welfare in our setting.

14). Then, the limited liability constraint $t \geq 0$ still applies under vertical integration.

The regulator's social welfare function is

$$W = S - t. \tag{3}$$

The gross surplus from investment $S > 0$ is higher in case of investment success than in case of failure, i.e., $S \in \left\{\overline{S}, \underline{S}\right\}$ and $\Delta S \equiv \overline{S} - \underline{S} > 0$.[7] A successful investment leads to lower final prices or higher quality of the good. A natural interpretation for S is the consumer surplus from purchasing the good in the downstream market. This reflects the mandate of modern regulatory agencies. For instance, the UK Office of Gas and Electricity Markets (Ofgem) states that "[o]ur principal duty is to protect the interests of current and future consumers". In the same vein, the mission of the US Federal Energy Regulatory Commission (FERC) is to "[a]ssist consumers in obtaining economically efficient, safe, reliable, and secure energy services".[8] The transfer t accruing to the upstream regulated firm reduces social welfare in (3). A significant portion of the regulated firm's revenues typically stems from public subsidies.[9]

Regulation Following the relevant literature and the regulatory practices worldwide, we assume that regulation takes place after the vertical industry structure has been established (e.g., Chen and Sappington 2009, 2010; Foros 2004; Klumpp and Su 2010, 2015; Kotakorpi 2006; Vickers 1995). The regulatory policy offered prior to the investment stage is enforced with probability $\alpha \in [0, 1]$. With complementary probability $1 - \alpha$, the regulator revises its policy and offers a new, sequentially optimal policy after the regulated firm's investment has been undertaken. Any probability $\alpha \in (0, 1)$ of regulatory enforcement involves uncertainty about the regulator's behavior and therefore regulatory risk. This formalization is in line with the determinants of regulatory risk discussed in Section 6.

Timing and equilibrium concept The timing of the game unfolds as follows.

(I) The regulatory regime is determined, which entails a probability $\alpha \in [0, 1]$ of regulatory enforcement.

(II) The upstream regulated firm decides whether to integrate with a downstream firm.

(III) The regulator offers a regulatory policy to the (vertically separated or integrated) regulated firm. If the offer is rejected, the game ends. If the offer is accepted, the regulated firm exerts unobservable investment effort and the investment outcome is realized.

(IV) The regulatory policy is enforced with probability $\alpha \in [0, 1]$. With probability $1 - \alpha$, the regulator makes a new offer, which is either rejected (the game ends) or accepted by the

[7]Following the main literature, the regulator is risk neutral. The gross surplus S is independent of the vertical industry structure because vertical integration does not alter the downstream outcome, as previously discussed.

[8]These quotations are respectively taken from Ofgem's website https://www.ofgem.gov.uk/about-us/how-we-engage/engaging-consumer-issues and FERC's website https://www.ferc.gov/about/about.asp (last retreived in December 2019). Fiocco and Strausz (2015) provide theoretical support for the regulator's adoption of a pure consumer surplus mandate. Our qualitative results remain valid when social welfare is a weighted sum of consumer surplus and firms' utilities, provided that the weight on firms' utilities is not too large.

[9]Socially costly transfers reflect distributional considerations (Baron and Myerson 1982) or the social cost of public funds due to distortionary taxation (Laffont and Tirole 1986). Miniaci et al. (2016) conduct an empirical analysis of subsidies in energy markets. Information about public funds in the US transportation industry is available at https://www.bts.gov/topics/national-transportation-statistics (last retrieved in December 2019).

regulated firm.

(V) Downstream competition takes place and firms' payoffs materialize.

The regulation stage precedes the competition stage. This reflects the greater rigidity of regulatory procedures with respect to market activities. The order of the fourth and fifth stage is irrelevant, because firms' payoffs do not depend on the actual enforcement of the regulatory policy (although they depend on the investment outcome in the third stage). The equilibrium concept is the subgame perfect Nash equilibrium. We solve this game by backward induction.

3 Main results

In the following lemma we summarize what happens when the cost of high investment effort is relatively small.

Lemma 1 *Suppose $\psi \leq \psi_0 \equiv \Delta\nu \left[u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right]$. Then, the equilibrium probability of regulatory enforcement is $\alpha^* = 0$. Vertical integration emerges, and high investment effort is provided at no social cost.*

When the probability of regulatory enforcement is zero, the regulator invariably revises the policy offered to the regulated firm before the investment stage and determines a new, sequentially optimal policy after the investment costs have been sunk. As transfers are socially costly, the regulated firm receives the lowest transfer compatible with limited liability irrespective of the investment outcome, i.e., $\overline{t} = \underline{t} = 0$. A vertically integrated firm provides high effort as long as the corresponding cost is outweighed by the expected increase in the downstream utility arising from the investment, i.e., $\psi \leq \psi_0 \equiv \Delta\nu \left[u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right]$. Conversely, under vertical separation, the upstream firm prefers to exert (costless) low effort to avoid a loss equal to the cost of high effort ψ. Anticipating that high effort will be exerted under vertical integration but low effort will be exerted under vertical separation, the upstream firm and a downstream firm prefer to vertically integrate. As Lemma 1 indicates, the equilibrium probability of regulatory enforcement $\alpha^* = 0$ allows the regulator to promote high effort with zero transfers, and the decision of vertical integration is welfare enhancing.

Under the condition stated in Lemma 1, the moral hazard problem associated with unobservable investment effort is costlessly removed by vertical integration. Throughout the analysis, we impose the following assumption.

Assumption 1 $\psi > \psi_0 \equiv \Delta\nu \left[u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right]$.

Assumption 1 ensures that the cost of high effort is sufficiently large that the moral hazard problem requires (costly) regulatory intervention to incentivize the effort provision.

3.1 Full commitment

To better appreciate the role of regulatory risk, we begin with the case of a regulatory regime characterized by full commitment. The regulatory policy offered prior to the investment stage is enforced with certainty, i.e., $\alpha = 1$, and therefore regulatory risk is absent. Under vertical separation, when the regulator wants to induce (unobservable) high effort, the upstream firm's (expected) utility from high effort must exceed the corresponding utility from low effort. This identifies the moral hazard incentive constraint $\mathbb{E}_h[\Pi_u] \geq \mathbb{E}_l[\Pi_u]$, where Π_u is given by (1). Analogously, under vertical integration, when the regulator wishes to promote high effort, the vertically integrated firm's (expected) utility from high effort must exceed the corresponding utility from low effort. Hence, the moral hazard incentive constraint becomes $\mathbb{E}_h[\Pi_{vi}] \geq \mathbb{E}_l[\Pi_{vi}]$, where Π_{vi} is given by (2). If investment has failed, the regulator sets the lowest (socially costly) transfer compatible with the regulated firm's limited liability irrespective of the vertical industry structure. The limited liability constraint is binding in equilibrium, and the full commitment transfers are zero in case of investment failure. If investment has succeeded, the full commitment transfers under vertical separation and vertical integration respectively make the moral hazard incentive constraints $\mathbb{E}_h[\Pi_u] \geq \mathbb{E}_l[\Pi_u]$ and $\mathbb{E}_h[\Pi_{vi}] \geq \mathbb{E}_l[\Pi_{vi}]$ binding in equilibrium. As in any classical moral hazard problem, the transfer is higher in case of investment success than in case of failure in order to incentivize high effort. Intuitively, the upstream expected transfers increase with the cost of high effort ψ. In the following lemma, we compare the expected transfers that ensure high effort in the two vertical industry structures.

Lemma 2 *Under firm risk neutrality ($u''(\cdot) = 0$), it holds $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$. Under firm risk aversion ($u''(\cdot) < 0$), there exists a threshold ψ_1, with $\psi_1 > \psi_0$, such that $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$ if and only if $\psi < \psi_1$.*

Under firm risk neutrality, the full commitment expected transfer that induces high effort is unambiguously lower under vertical integration than under vertical separation, i.e., $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$. The vertically integrated firm's internalization of the downstream payoff mitigates the moral hazard problem, which allows the regulator to provide a lower transfer than under vertical separation when high effort is desired. However, in the presence of firm risk aversion, the vertically integrated firm values any transfer in addition to its downstream payoff relatively less than under vertical separation. This strengthens the vertically integrated firm's reluctance to exert high effort. Therefore, the transfer that promotes high effort must increase with the cost of effort to a larger extent under vertical integration than under vertical separation. As Lemma 2 indicates, the expected transfer is still lower under vertical integration as long as the cost of high effort is below a certain threshold, i.e., $\psi < \psi_1$. Notably, the threshold ψ_1 may be significantly large, especially with a small degree of firm risk aversion.

We are now in a position to formalize the results under full commitment, where the regulatory policy is enforced with certainty.

Proposition 1 *Suppose that the probability of regulatory enforcement is $\alpha = 1$.*
(i) If $\mathbb{E}_h[t^c_{vs}] < \Delta\nu\Delta S$, vertical separation emerges, and high investment effort is provided.
(ii) If $\mathbb{E}_h[t^c_{vi}] < \Delta\nu\Delta S \leq \mathbb{E}_h[t^c_{vs}]$, vertical integration emerges, and high investment effort is provided.
(iii) Otherwise, i.e., if $\min\{\mathbb{E}_h[t^c_{vi}], \mathbb{E}_h[t^c_{vs}]\} \geq \Delta\nu\Delta S$, the vertical industry structure is inconsequential, and low investment effort is provided.

The results in Proposition 1 are summarized in Table 1. As point (i) of Proposition 1 indicates, vertical separation arises and high investment effort is exerted if the (expected) transfer

Expected transfers	industry structure	investment
$\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S$	vertical separation	high
$\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$	vertical integration	high
$\min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \mathbb{E}_h\left[t_{vs}^c\right]\right\} \geq \Delta\nu\Delta S$	vertical integration or vertical separation	low

Table 1: Full commitment ($\alpha = 1$).

under vertical separation is lower than the (expected) social welfare gain from high effort, i.e., $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$. This occurs when the cost of high effort ψ is relatively small with respect to the social welfare gain. Note that the outcome in point (i) holds irrespective of the magnitude of the expected transfer $\mathbb{E}_h\left[t_{vi}^c\right]$ under vertical integration. To understand the rationale for this result, it is useful to recall from Lemma 2 that the expected transfer associated with high effort is lower under vertical integration than under vertical separation ($\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$) in case of firm risk neutrality as well as risk aversion for a cost of high effort below a certain threshold, i.e., $\psi < \psi_1$. This implies that the regulator prefers vertical integration to vertical separation. Given the condition in point (i) of Proposition 1, anticipating that high effort will be incentivized regardless of the vertical industry structure and that the expected transfer is lower under vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$), the upstream firm and a downstream firm find vertical separation more attractive. The regulator must provide the vertically separated upstream firm with relatively large compensation to induce high effort. In the presence of firm risk aversion, when the cost of high effort is above the aforementioned threshold, i.e., $\psi \geq \psi_1$, the interests of the regulator are aligned with those of the firms. We know from Lemma 2 that the expected transfer under vertical integration is higher than under vertical separation ($\mathbb{E}_h\left[t_{vi}^c\right] \geq \mathbb{E}_h\left[t_{vs}^c\right]$). Hence, the regulator now prefers vertical separation when high effort is promoted. Given the condition in point (i) of Proposition 1, anticipating that high effort will be incentivized at least under vertical separation ($\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$), the firms still find vertical separation more profitable. This is because, if high effort is also induced under vertical integration, the internalization of the downstream payoff alleviates the moral hazard problem, and therefore the firms obtain lower (expected) aggregate utility under vertical integration than under vertical separation, despite a higher transfer. If low effort is induced under vertical integration, the firms' incentives for vertical separation are amplified.

Point (ii) of Proposition 1 shows that vertical integration emerges and high effort is provided for intermediate costs of high effort such that the (expected) transfer under vertical integration is lower but the (expected) transfer under vertical separation is higher than the (expected) social welfare gain, i.e., $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$. It follows from Lemma 2 that the outcome in point (ii) requires that the cost of high effort ψ must be below the threshold ψ_1 in the presence of firm risk aversion. Differently from point (i), the regulator promotes high effort under vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S$) and low effort under vertical separation ($\mathbb{E}_h\left[t_{vs}^c\right] \geq \Delta\nu\Delta S$). Therefore, the upstream firm and a downstream firm prefer to vertically integrate, and the regulator stimulates high effort at a lower social cost.

As point (iii) of Proposition 1 reveals, when the cost of high effort is so large that low effort is socially desirable irrespective of the vertical industry structure, i.e., $\min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \mathbb{E}_h\left[t_{vs}^c\right]\right\} \geq \Delta\nu\Delta S$, the regulator induces low effort and provides zero transfers. This implies that the firms (and the regulator) are indifferent about the vertical industry structure.

The results in Proposition 1 are related to the literature about the optimal institutional design of regulated industries in the presence of asymmetric information. In a setting where production requires complementary inputs in fixed proportions (as in vertically related markets) and the cost of each input is privately known by its supplier, Baron and Besanko (1992) and Gilbert and Riordan (1995) show that, under relevant circumstances, vertically integrated supply leads to higher welfare than component supply. The reason is that under component supply each firm is charged with the provision of a different input and does not internalize the negative externality of its actions on the other firm. This magnifies the firm's incentives to exaggerate input costs in order to obtain larger remuneration from the regulator. Along these lines, Severinov (2008) demonstrates that integrated supply increases welfare with respect to component supply if the degree of complementarity between inputs is not too large. Incorporating firm risk aversion into the model of Gilbert and Riordan (1995), Li (2010) shows that integrated supply still generates higher welfare than component supply as long as the degree of firm risk aversion is sufficiently small. In the spirit of the existing literature, we also find that vertical integration is socially desirable in a relevant number of cases, because it relaxes the regulator's incentive problem. As discussed after Proposition 1, this occurs when the cost of high effort is not significantly large and the degree of firm risk aversion is small enough (which makes the condition $\psi < \psi_1$ more likely to hold). Remarkably, we endogenize the firms' decision whether to vertically integrate or not. As a consequence, even under these circumstances, vertical separation can emerge in equilibrium.

3.2 Regulatory risk

We now turn to the investigation of a general regulatory regime that allows for regulatory risk. This is formalized through the probability $\alpha \in [0, 1]$ that the regulator enforces the regulatory policy offered prior to the investment stage. With complementary probability $1 - \alpha$, the regulatory policy is not enforced and the regulator offers a new, sequentially optimal policy after the regulated firm's investment costs have been sunk. The sequentially optimal policy prescribes the lowest (socially costly) transfer compatible with the regulated firm's limited liability irrespective of the investment outcome, i.e., $\bar{t} = \underline{t} = 0$. Our specification of regulatory risk is in line with some relevant theoretical and empirical contributions (e.g., Armstrong and Vickers 1996; Cambini et al. 2012; Iossa and Martimort 2015; Panteghini and Scarpa 2008; Woroch 1988). Analyzing partial commitment in debt contracts, Kovrijnykh (2013) adopts the same formulation to capture the probability of contractual enforcement. Strausz (2011) models regulatory risk as mean-preserving spreads of the regulator's policy variables. In the subsequent analysis, we show that our approach is consistent with Strausz's (2011) characterization of regulatory risk. Interestingly, Strausz (2011, p. 759) identifies the uncertainty about the regulator's commitment as an alternative formulation of regulatory risk that constitutes a fruitful direction for future research.

As discussed after Lemma 1, with the probability $\alpha = 0$ of regulatory enforcement, under vertical separation the upstream firm anticipates zero transfers with certainty and therefore provides low effort. It follows from Assumption 1 that for $\alpha = 0$ low effort is also exerted under vertical integration because the cost of high effort exceeds the expected increase in the downstream utility arising from the investment. Given that the moral hazard problem is essentially associated with the provision of high effort, we restrict our attention to $\alpha \in (0,1]$. Any probability $\alpha \in (0,1)$ of regulatory enforcement involves regulatory risk.[10] Note that, when exerting effort, the regulated firm now faces two layers of uncertainty. As under full commitment, the firm does not know the realization of the investment outcome. In addition, the regulatory policy may be revised after the investment costs have been incurred. In the sequel, we show that introducing this second layer of uncertainty — i.e., regulatory risk — can be welfare enhancing. In the spirit of the backward induction logic, we treat the probability α of regulatory enforcement as exogenous in the following analysis. Then, we derive the value for α that generates the highest welfare.

Under vertical separation, if the regulator wishes to induce high effort, the upstream firm's (expected) utility from high effort must exceed the corresponding utility from low effort. The moral hazard incentive constraint writes as

$$\alpha \mathbb{E}_h \left[\Pi_u^e\right] + (1-\alpha)\, \mathbb{E}_h \left[\Pi_u^{ne}\right] \geq \alpha \mathbb{E}_l \left[\Pi_u^e\right] + (1-\alpha)\, \mathbb{E}_l \left[\Pi_u^{ne}\right]. \tag{4}$$

With probability α, the regulatory policy is enforced and the upstream firm receives expected utility $\mathbb{E}_h \left[\Pi_u^e\right]$ from high effort and $\mathbb{E}_l \left[\Pi_u^e\right]$ from low effort. With complementary probability $1-\alpha$, the regulatory policy is not enforced and a new, sequentially optimal policy is offered by the regulator. This gives the upstream firm expected utility $\mathbb{E}_h \left[\Pi_u^{ne}\right]$ from high effort and $\mathbb{E}_l \left[\Pi_u^{ne}\right]$ from low effort.

Under vertical integration, when the regulator wants to promote high effort, the moral hazard incentive constraint becomes

$$\alpha \mathbb{E}_h \left[\Pi_{vi}^e\right] + (1-\alpha)\, \mathbb{E}_h \left[\Pi_{vi}^{ne}\right] \geq \alpha \mathbb{E}_l \left[\Pi_{vi}^e\right] + (1-\alpha)\, \mathbb{E}_l \left[\Pi_{vi}^{ne}\right]. \tag{5}$$

If the regulatory policy is enforced (which occurs with probability α), the vertically integrated firm obtains (expected) utility $\mathbb{E}_h \left[\Pi_{vi}^e\right]$ from high effort and $\mathbb{E}_l \left[\Pi_{vi}^e\right]$ from low effort. If the regulatory policy is not enforced and a new, sequentially optimal policy is offered by the regulator (which occurs with complementary probability $1-\alpha$), the vertically integrated firm's (expected) utility is $\mathbb{E}_h \left[\Pi_{vi}^{ne}\right]$ from high effort and $\mathbb{E}_l \left[\Pi_{vi}^{ne}\right]$ from low effort.

If investment has failed, the regulated firm receives the lowest (socially costly) transfer compatible with limited liability in the two vertical industry structures. This holds irrespective of whether the regulatory policy offered prior to the investment stage is enforced or not. Therefore, the limited liability constraint is binding in equilibrium, and the regulated firm obtains zero transfers in case of investment failure. If investment has succeeded, the regulated firm's remuneration that induces high effort depends on the enforcement of the regulatory policy. With probability α, the regulatory policy is enforced, and the equilibrium transfers under vertical separation and vertical integration are respectively designed so that the moral hazard incentive constraints (4) and (5) are binding in equilibrium. With probability $1-\alpha$, the regulatory policy

[10] As Strausz (2011, p. 743) emphasizes, regulatory risk crucially differs from regulatory opportunism in the form of no commitment ($\alpha = 0$). The reason is that regulatory risk entails uncertainty about future regulatory changes, while under no commitment the firm can fully anticipate these changes.

is not enforced and the new, sequentially optimal policy yields zero transfers. Anticipating a positive transfer in case of investment success only with probability α, in each vertical industry structure the regulated firm commands larger compensation than under full commitment, unless $\alpha = 1$. Clearly, an increase in the cost of high effort ψ leads to higher expected transfers. In the following lemma, we investigate the impact of the probability α of regulatory enforcement upon the expected transfers that induce high effort in the two vertical industry structures.

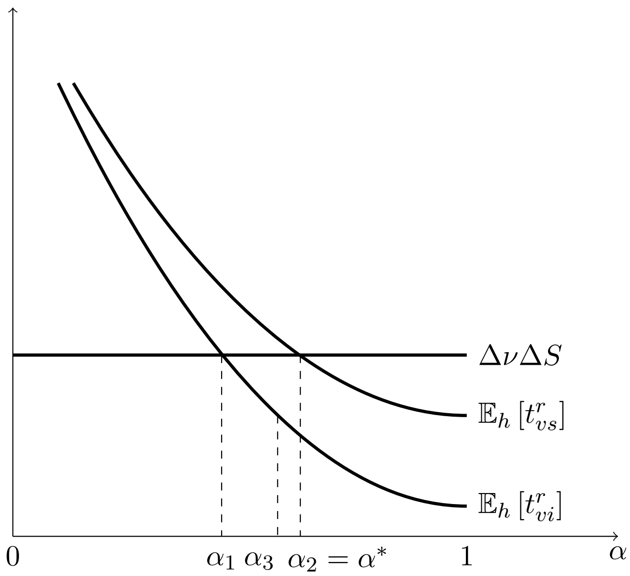
Lemma 3 *It holds* $\frac{\partial \mathbb{E}_h[t_{vs}^r]}{\partial \alpha} \leq 0$ *and* $\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial \alpha} \leq 0$*, where the strict inequalities follow under firm risk aversion* ($u''(\cdot) < 0$)*.*

Lemma 3 indicates that the expected transfers $\mathbb{E}_h[t_{vs}^r]$ and $\mathbb{E}_h[t_{vi}^r]$ that promote high effort in the presence of regulatory risk are independent of the probability α of regulatory enforcement under firm risk neutrality, but they decrease with α under firm risk aversion. Hence, a risk-neutral firm is indifferent about the degree of regulatory risk. However, a risk-averse firm commands a larger expected transfer when α decreases. Since the transfer is zero with probability $1 - \alpha$, the transfer provided with probability α (in case of investment success) must increase when α declines in order to ensure a given expected value. Therefore, for a given mean, the variance of transfers decreases with α. Specifically, a distribution of transfers with low α is a mean-preserving spread of a distribution of transfers with high α. This implies that a reduction in α aggravates the risk borne by the firm. As Lemma 3 establishes, the firm requires a larger (expected) transfer when α becomes smaller. In our setting, the probability α can be interpreted as an inverse measure of regulatory risk. This shares some similarities with Strausz's (2011) formulation of regulatory risk as mean-preserving spreads of the regulator's policy variables. While in Strausz (2011) regulatory risk is unalterable and exogenous, we aim at deriving the optimal degree of regulatory risk.

Lemma 3 delivers two relevant implications. Under firm risk neutrality, the magnitude of regulatory risk is inconsequential, because the expected transfer to the regulated firm does not depend on the probability α of regulatory enforcement. Therefore, any degree of regulatory risk generates the same welfare. Things change significantly in the presence of firm risk aversion. For a given vertical industry structure, full regulatory commitment ($\alpha = 1$) minimizes the expected transfer that the regulated firm requires, because regulatory risk is fully removed. The establishment of a regulator with full commitment powers would be welfare enhancing. In the following proposition, we show that, when the vertical industry structure is endogenized, some degree of regulatory risk can be socially beneficial.

Proposition 2 *Suppose* $\mathbb{E}_h[t_{vs}^c] < \Delta\nu\Delta S$ *and firm risk aversion* ($u''(\cdot) < 0$)*. Then, there exists a threshold* ψ^**, with* $\psi_0 < \psi^* < \psi_1$*, such that for* $\psi < \psi^*$ *some degree of regulatory risk is optimal. The equilibrium probability of regulatory enforcement is* $\alpha^* \in (0, 1)$*, where* α^* *is the unique value for* α *such that* $\mathbb{E}_h[t_{vs}^r(\alpha^*)] = \Delta\nu\Delta S$*. Vertical integration emerges, and high investment effort is provided.*

To appreciate the rationale for this result as substantiated in the introduction, it is helpful to consider the conditions stated in Proposition 2, i.e., $\mathbb{E}_h[t_{vs}^c] < \Delta\nu\Delta S$ and $\psi < \psi^*$, where ψ^* is defined by (A16) in the Appendix. As $\psi^* < \psi_1$, it follows from Lemma 2 that $\mathbb{E}_h[t_{vi}^c] <$



$\mathbb{E}_h[t^c_{vs}] < \Delta\nu\Delta S$. In this case, under full commitment, the regulator prefers vertical integration that entails a lower expected transfer to the regulated firm ($\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$). However, Proposition 1 indicates that vertical separation emerges in equilibrium. Anticipating that high effort is induced irrespective of the vertical industry structure and that the expected transfer is higher under vertical separation ($\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}] < \Delta\nu\Delta S$), the firms obtain higher (expected) aggregate utility under vertical separation than under vertical integration and therefore they prefer to remain vertically separated. We know from Lemma 3 that, in the presence of firm risk aversion, the expected transfers $\mathbb{E}_h[t^r_{vs}]$ and $\mathbb{E}_h[t^r_{vi}]$ decrease with the probability α of regulatory enforcement. This means that regulatory risk reduces the social desirability of high effort. As Figure 1 illustrates, if $\alpha_1 < \alpha \leq \alpha_2$, high effort is still socially beneficial under vertical integration ($\mathbb{E}_h[t^r_{vi}] < \Delta\nu\Delta S$) but not under vertical separation ($\mathbb{E}_h[t^r_{vs}] \geq \Delta\nu\Delta S$). Anticipating this, the upstream firm and a downstream firm now find vertical integration more profitable. The vertically integrated firm's internalization of the downstream payoff mitigates the moral hazard problem and stimulates upstream investment at a lower social cost. As the expected transfer decreases with α, the optimal degree of regulatory risk is determined by the highest probability of regulatory enforcement $\alpha^* = \alpha_2$ such that low effort would be only exerted under vertical separation, i.e., $\mathbb{E}_h[t^r_{vs}(\alpha^*)] = \Delta\nu\Delta S$.

The conditions $\mathbb{E}_h[t^c_{vs}] < \Delta\nu\Delta S$ and $\psi < \psi^*$, with $\psi_0 < \psi^* < \psi_1$, stated in Proposition 2 imply that regulatory risk is socially optimal for intermediate costs of effort. In particular, the condition $\psi < \psi^*$ ensures that the expected transfer in the presence of regulatory risk is lower than the expected transfer under full commitment. To gain some intuition, recall from Lemma 3 that, for a given vertical industry structure, full commitment yields the lowest (expected) transfer to the regulated firm. As previously discussed, we have $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}] < \Delta\nu\Delta S$, which implies that under full commitment high effort is promoted irrespective of the vertical industry structure and therefore vertical separation emerges. Regulatory risk generates higher welfare than full commitment if and only if vertical integration driven by regulatory risk stimulates upstream investment with a lower (expected) transfer compared to vertical separation driven by full commitment, i.e., $\mathbb{E}_h[t^r_{vi}(\alpha^*)] < \mathbb{E}_h[t^c_{vs}]$. As Figure 1 illustrates, this requires that the interval $\alpha_3 < \alpha \leq \alpha_2$ is nonempty, where α_3 is such that $\mathbb{E}_h [t^r_{vi} (\alpha_3)] = \mathbb{E}_h [t^c_{vs}]$. We know from the analysis after Lemma 2 that, under firm risk aversion, the transfers increase with the cost of effort to a larger extent under vertical integration than under vertical separation. As shown in the proof of Proposition 2 in the Appendix, there exists a threshold ψ^* for the cost of effort such that $\mathbb{E}_h [t^r_{vi} (\alpha^*)] < \mathbb{E}_h [t^c_{vs}]$ if and only if $\psi < \psi^*$. This implies that the interval $\alpha_3 < \alpha \leq \alpha_2$ is nonempty and regulatory risk is social welfare enhancing.[11] The threshold ψ^* depends on the degree of firm risk aversion. It turns out that regulatory risk is more likely to be socially optimal under firm small risk aversion. For a high degree of risk aversion, the regulated firm commands large remuneration in the presence of regulatory risk, which makes full commitment socially preferable.

Given that $\mathbb{E}_h [t^r_{vs} (\alpha^*)] = \Delta\nu\Delta S$, differentiating α^* with respect to ψ yields

$$\frac{\partial \alpha^*}{\partial \psi} = -\frac{\frac{\partial \mathbb{E}_h[t^r_{vs}]}{\partial \psi}}{\frac{\partial \mathbb{E}_h[t^r_{vs}]}{\partial \alpha}} > 0,$$

where the inequality follows from $\frac{\partial \mathbb{E}_h[t^r_{vs}]}{\partial \psi} > 0$ and $\frac{\partial \mathbb{E}_h[t^r_{vs}]}{\partial \alpha} < 0$ (see Lemma 3). To understand why, note that an increase in the cost of high effort ψ leads to a higher expected transfer $\mathbb{E}_h [t^r_{vs} (\cdot)]$. As $\mathbb{E}_h [t^r_{vs} (\cdot)]$ decreases with α, the equilibrium probability α^* of regulatory enforcement must increase in order to ensure that $\mathbb{E}_h [t^r_{vs} (\alpha^*)] = \Delta\nu\Delta S$. Therefore, a higher cost of investment effort mitigates the scope for regulatory risk.

In the following proposition, we consider the situation where regulatory risk is no longer optimal.

Proposition 3 *Suppose that the conditions $\mathbb{E}_h [t^c_{vs}] < \Delta\nu\Delta S$ and $\psi < \psi^*$ stated in Proposition 2 do not simultaneously hold. Moreover, suppose firm risk aversion ($u'' (\cdot) < 0$).*

(i) If either $\mathbb{E}_h [t^c_{vi}] \leq \mathbb{E}_h [t^c_{vs}] < \Delta\nu\Delta S$ and $\psi > \psi^*$ or $\mathbb{E}_h [t^c_{vs}] < \min \{\mathbb{E}_h [t^c_{vi}], \Delta\nu\Delta S\}$, the equilibrium probability of regulatory enforcement is $\alpha^* = 1$. Vertical separation emerges, and high investment effort is provided.

(ii) If $\mathbb{E}_h [t^c_{vi}] < \Delta\nu\Delta S \leq \mathbb{E}_h [t^c_{vs}]$, the equilibrium probability of regulatory enforcement is $\alpha^* = 1$. Vertical integration emerges, and high investment effort is provided.

(iii) Otherwise, i.e., if $\min \{\mathbb{E}_h [t^c_{vi}], \mathbb{E}_h [t^c_{vs}]\} \geq \Delta\nu\Delta S$, the equilibrium probability of regulatory enforcement is any $\alpha^* \in [0, 1]$. The vertical industry structure is inconsequential, and low investment effort is provided.

The results in Propositions 2 and 3 are summarized in Table 2. Points (i) and (ii) of Proposition 3 indicate the conditions under which the establishment of a regulator with full commitment powers is socially optimal, and therefore the equilibrium probability of regulatory enforcement is $\alpha^* = 1$. Specifically, under the conditions in point (i), full regulatory commitment is optimal and vertical separation emerges in equilibrium. This outcome reflects the one in point (i) of Proposition 1. Consider first the case where $\mathbb{E}_h [t^c_{vi}] \leq \mathbb{E}_h [t^c_{vs}] < \Delta\nu\Delta S$ and $\psi > \psi^*$. It follows from the discussion after Proposition 2 that regulatory risk involves a higher expected transfer than full commitment. Hence, larger costs of investment effort ($\psi > \psi^*$) make full commitment more socially desirable than regulatory risk. Although the regulator

[11] A fortiori, the interval $\alpha_1 < \alpha \leq \alpha_2$ previously discussed is also nonempty.

Expected transfers	regulatory regime	industry structure	investment
$\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ and $\psi < \psi^*$	$\alpha^* \in (0,1)$	vertical integration	high
$\mathbb{E}_h\left[t_{vi}^c\right] \leq \mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ and $\psi > \psi^*$ or $\mathbb{E}_h\left[t_{vs}^c\right] < \min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \Delta\nu\Delta S\right\}$	$\alpha^* = 1$	vertical separation	high
$\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \ \leq \mathbb{E}_h\left[t_{vs}^c\right]$	$\alpha^* = 1$	vertical integration	high
$\min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \mathbb{E}_h\left[t_{vs}^c\right]\right\} \geq \Delta\nu\Delta S$	any $\alpha^* \in [0,1]$	vertical integration or vertical separation	low

Table 2: Main results

prefers vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] \leq \mathbb{E}_h\left[t_{vs}^c\right]$), the firms opt for vertical separation, because high effort is promoted irrespective of the vertical industry structure and vertical separation ensures a higher expected transfer ($\mathbb{E}_h\left[t_{vi}^c\right] \leq \mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$). Now, consider the case where $\mathbb{E}_h\left[t_{vs}^c\right] < \min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \Delta\nu\Delta S\right\}$. We know from the analysis after Proposition 1 that under full commitment the interests of the regulator are aligned with those of the firms in favor of vertical separation. Anticipating that high effort will be incentivized at least under vertical separation ($\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$), the firms prefer to be vertically separated. The regulator is also better off under vertical separation ($\mathbb{E}_h\left[t_{vs}^c\right] < \mathbb{E}_h\left[t_{vi}^c\right]$). Full regulatory commitment is optimal, because upstream transfers are minimized. Given that $\mathbb{E}_h\left[t_{vs}^c\right] < \min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \Delta\nu\Delta S\right\}$ implies $\psi > \psi_1$ (see Lemma 2), this outcome is more likely to emerge for a larger degree of firm risk aversion.

Point (ii) of Proposition 3 shows that, if $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$, full regulatory commitment is optimal and vertical integration emerges in equilibrium. This outcome corresponds to the one in point (ii) of Proposition 1. Under full commitment, the regulator and the firms share the same preferences for vertical integration. Anticipating that high effort will be incentivized under vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S$) but not under vertical separation ($\mathbb{E}_h\left[t_{vs}^c\right] \geq \Delta\nu\Delta S$), the firms want to vertically integrate. The regulator also prefers vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$). As in point (i) of Proposition 3, full regulatory commitment is optimal because it minimizes the amount of upstream transfers. Given that $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$ implies $\psi < \psi_1$, this outcome tends to emerge when firm risk aversion is relatively small.

Point (iii) of Proposition 3 reveals that, in line with the outcome in point (iii) of Proposition 1, if $\min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \mathbb{E}_h\left[t_{vs}^c\right]\right\} \geq \Delta\nu\Delta S$, the cost of high effort is so large that low effort is incentivized irrespective of the vertical industry structure. As upstream transfers are zero, the regulatory regime and the vertical industry structure become inconsequential.

4 Illustrative example

To provide additional results in a setting with explicit functions, we now consider a constant absolute risk aversion (CARA) utility function of the form

$$u(x) = \begin{cases} \frac{1-e^{-\rho x}}{\rho} & \text{if } \rho > 0 \\ x & \text{if } \rho = 0 \end{cases}, \tag{6}$$

where $x \geq 0$ is the payoff and $\rho \geq 0$ measures the degree of absolute risk aversion, with $\rho = 0$ in case of risk neutrality. We assume that there are $N \geq 2$ downstream firms competing à la Cournot and facing the (inverse) consumer demand function $P(Q) = 1 - Q$, where $P(\cdot)$ is the unit market price and Q the aggregate quantity. The upstream firm's investment affects the performance of downstream firms. In particular, a successful investment leads to lower downstream marginal costs than in case of failure, i.e., $0 \leq \overline{c} < \underline{c} < 1$ and $\Delta c \equiv \underline{c} - \overline{c} > 0$. Intuitively, our qualitative results still hold when the upstream investment influences other features of the downstream market, such as the quality of the good and the associated consumer willingness to pay. The following remark applies the result of Proposition 2 to this setting.

Remark 1 *Suppose $\mathbb{E}_h \left[t_{vs}^c\right] < \Delta\nu\Delta S$ and firm risk aversion ($\rho > 0$). Then, there exists a threshold ψ^*, with $\psi_0 < \psi^* < \psi_1$, such that for $\psi < \psi^*$ some degree of regulatory risk is optimal. The equilibrium probability of regulatory enforcement is $\alpha^* \in (0, 1)$, where α^* is the unique value for α such that*

$$\nu_h \alpha^* \ln\left(1 - \frac{\rho\psi}{\alpha^* \Delta\nu}\right) + \rho\Delta\nu \frac{\left(2 - \underline{c} - \overline{c}\right) N^2 \Delta c}{2\left(1 + N\right)^2} = 0. \tag{7}$$

Vertical integration emerges, and high investment effort is provided.

As $\psi^* > \psi_0$, there exists a nonempty interval for the cost of high effort ψ where regulatory risk is socially optimal if and only if $\psi > \psi_0$ and $\mathbb{E}_h \left[t_{vs}^c\right] < \Delta\nu\Delta S$. As formally shown in the proof of Remark 1 in the Appendix, in a downstream duopoly market ($N = 2$) the probability of investment success with high effort must be twice larger than the corresponding probability with low effort, i.e., $\nu_h > 2\nu_l$, provided that the degree of firm risk aversion ρ is small enough. This indicates that regulatory risk tends to arise exactly when the investment benefits are significantly more likely to materialize in response to high effort and therefore the promotion of investment effort is more socially valuable. If competition in the downstream market is more intense ($N > 2$), the condition for regulatory risk to emerge in equilibrium is relaxed. As will become clear in the sequel, the scope for regulatory risk becomes larger when the downstream market is more competitive.

Using the definition of α^* in (7), the following remark provides comparative statics results of some interest.

Remark 2 *It holds $\frac{\partial \alpha^*}{\partial N} < 0$ and $\frac{\partial \alpha^*}{\partial \rho} > 0$.*

Remark 2 shows that the equilibrium probability α^* of regulatory enforcement decreases with the number N of downstream firms. To gain some intuition, it is helpful to recall from Proposition 2 that in equilibrium we have $\mathbb{E}_h \left[t_{vs}^r \left(\alpha^*\right)\right] = \Delta\nu\Delta S$. More severe competition increases the (expected) consumer surplus gain associated with a successful investment, i.e., $\frac{\partial \Delta\nu\Delta S}{\partial N} > 0$. Hence, $\mathbb{E}_h \left[t_{vs}^r \left(\alpha^*\right)\right]$ must rise in order to ensure that $\mathbb{E}_h \left[t_{vs}^r \left(\alpha^*\right)\right] = \Delta\nu\Delta S$. As $\mathbb{E}_h \left[t_{vs}^r \left(\cdot\right)\right]$ decreases with α (see Lemma 3), the equilibrium probability α^* of regulatory enforcement becomes lower. In line with the discussion after Remark 1, a higher degree of regulatory risk is socially desirable when downstream competition is tougher.

Naturally, α^* increases with the degree of firm risk aversion ρ. A more risk-averse firm asks for larger (expected) compensation in the face of uncertainty, which reduces the social desirability of regulatory risk.

5 Robustness and extensions

5.1 Access pricing

In our model we assume that the upstream firm receives a transfer from the regulator, abstracting from the explicit formulation of the price that the upstream firm may charge to downstream firms for the input access. Our results carry over to a more general setting that allows for the regulation of the input access price. To fix ideas, suppose that the regulator offers the upstream firm a two-part tariff (a, T), where a is the unit access price paid by downstream firms and T is the transfer provided by the regulator. The upstream input is converted with a one-to-one technology into a final product supplied in the downstream market. Under vertical separation, the upstream firm's utility becomes

$$\Pi_u^a = u(T + aQ) - \psi_e, \tag{8}$$

where Q denotes the downstream aggregate quantity. As in the baseline model, each downstream firm obtains a payoff $\pi \geq 0$ and associated utility $u(\pi)$, where $\pi \in \{\overline{\pi}, \underline{\pi}\}$ and $\overline{\pi} > \underline{\pi}$. For instance, a successful investment reduces input costs and leads to a lower access price.

The vertically integrated firm's utility is given by

$$\Pi_{vi}^a = u(T + aQ + \pi) - \psi_e. \tag{9}$$

In accordance with the most common regulatory practices, the downstream division of the vertically integrated firm pays the same input access price as rivals, although this constitutes a mere transfer within the vertical chain. Defining $t \equiv T + aQ$, the vertically separated upstream firm's utility in (8) and the vertically integrated firm's utility in (9) reduce to (1) and (2), respectively. The regulated firm is indifferent to whether its upstream revenues stem from the access price paid by downstream firms or from the transfer provided by the regulator. As long as the regulated firm's rents are socially costly, the regulator's problem is to minimize the transfer t, in line with the baseline model. The only difference is that the access price may affect the outcome in the downstream market. However, in practice the access price does not vary substantially with the vertical industry structure. This is because the access price is usually based on the input marginal costs, irrespective of whether the upstream firm is vertically integrated or not. Even when the access price may differ according to the vertical industry structure, our qualitative results are still valid. To see this, suppose that the optimal access price under vertical separation is also implemented under vertical integration. As mentioned in Section 2, the standard regulatory practice of legal unbundling implies that the vertically integrated firm's downstream division operates in the competitive market as under vertical separation (e.g., Cremer and De Donder 2013; Fiocco 2012; Höffler and Kranz 2011; Sibley and Weisman 1998). Hence, the implementation of the same access price generates the same upstream revenues from access pricing in the two vertical industry structures. Our analysis shows that some degree of regulatory risk is optimal when vertical integration driven by regulatory risk leads to a lower (expected) upstream transfer compared to vertical separation driven by full regulatory commitment. Given that the upstream revenues from access pricing are the same in the two vertical industry structures for a given access price, regulatory risk is optimal as long as it reduces the (expected) upstream transfer net of the revenues from access pricing, consistently with the baseline model. A fortiori, regulatory risk is welfare superior when the optimal access price is chosen under vertical integration.

5.2 Discriminatory activities

Throughout the analysis, the vertically integrated firm cannot favor its division in the downstream market. This reflects the fundamental rules of the regulatory regimes worldwide, which prohibit any sort of the vertically integrated firm's discriminatory activities at the expense of downstream rivals. Although input price discrimination is generally unfeasible, in practice a vertically integrated firm may not be prevented from engaging in non-price discrimination or "sabotage" against rivals, such as input quality degradation and concealment of crucial information (e.g., Economides 1998; Höffler and Kranz 2011; Mandy and Sappington 2007; Sand 2004). Discrimination generally increases the downstream returns but reduces the upstream returns of the vertically integrated firm. When the benefits dominate the costs, discriminatory activities enhance the profitability of vertical integration. The likelihood of discrimination is an empirical issue and varies with the industry at hand (e.g., Mandy and Sappington 2007). Clearly, discrimination is welfare detrimental and reduces the social desirability of vertical integration. Given that regulatory risk makes vertical integration more profitable, our analysis suggests that regulatory risk should be accompanied by more severe regulatory deterrence policies against the vertically integrated firm's potential discriminatory activities.

5.3 Efficiency gains

A common reason for vertical integration is the realization of efficiency gains from joint production within the vertical chain. These benefits must be traded off against possible losses, such as diseconomies of firm size and legal costs associated with vertical integration. Efficiency gains may generate higher social welfare, for instance in the form of lower final prices that make consumers better off. Moreover, the regulator can capture (a portion of) efficiency gains by setting a lower upstream transfer to the vertically integrated firm. In line with the baseline model, some degree of regulatory risk is socially desirable because it facilitates vertical integration.

6 Determinants of regulatory risk

In his exhaustive work about the determinants of regulatory risk, Pedell (2006, p. 54) emphasizes that "[r]egulatory risk can be traced back to the design variables of rate regulation as ultimate *causes*. Differences in the design of regulation are reflected in different effects on the risk of the regulated firm".[12] As also pointed out by Guthrie (2006), the regulatory design variables are primarily determined by the institutional and legal system where the regulator operates. The essential feature of regulatory risk is the uncertainty about the regulator's future behavior, which affects the probability distribution of the regulated firm's cash flows. Hence, regulatory risk is intimately related to the regulator's commitment powers and to the extension of regulatory

[12]Kolbe et al. (1993) provide an earlier comprehensive analysis of regulatory risk.

discretion. It has been well established in the US judicial system since the Supreme Court decision of Smyth v. Ames (169 US 466, 1898) that a regulated firm is entitled to a "fair return upon the value of that which it employs for the public convenience". However, the exact definition of a "fair return" is not provided, which gives scope for some degree of ex post regulatory flexibility. More broadly, regulatory risk is associated with the degree of contractual enforcement. As empirically documented by La Porta et al. (1998), contractual enforcement differs across countries according to their legal system. French civil-law countries exhibit a lower degree of enforcement than Scandinavian and German civil-law countries as well as common-law countries.

Legal provisions about the recovery of the investment costs generate different degrees of regulatory risk. The regulated firm is usually allowed to recover either the costs of "used-and-useful" assets, which satisfy consumer demand from a current point of view, or the "prudently" incurred costs, whose assessment is conditional upon the information available at the time of investment. In the case Duquesne Light Company v. Barasch (488 US 299, 1989), the US Supreme Court explicitly identified as a class of regulatory risk the future regulatory disallowance of the investment costs deemed unused and unuseful from an ex post perspective. Along these lines, the regulator's adoption of "replacement costs" (based on the latest available technology) instead of "historical costs" (actually incurred by the firm) introduces an additional element of regulatory risk associated with the uncertainty about technological progress and the (discretionary) regulatory inspection of the investment costs in the light of the latest technology.[13] Regulatory risk is also affected by the timing of regulatory reviews. The typical lifetime of an investment asset in infrastructure industries is longer than the regulatory review period, which leads to the risk of future regulatory revisions about the reimbursement of investment costs.[14] The complexity of administrative procedures and the consumers' entitlement to exert pressure for a regulatory change contribute to the magnitude of regulatory risk, along with the turnover of the regulatory staff.

7 Concluding remarks

The uncertainty about future regulation — known as regulatory risk — has been systematically documented in regulated industries. In the popular debate, regulatory risk is perceived as welfare detrimental because it deters investment activities. In this paper, we investigate the role of regulatory risk in a vertically related market where an upstream regulated firm decides whether to vertically integrate and exerts unobservable investment effort for the provision of an essential input to downstream competitors. Contrary to the common view, we find that, under certain circumstances, some degree of regulatory risk is ex ante socially beneficial. This occurs for moderate costs of investment effort and firm small risk aversion. The driving force for this

[13] A prominent example is the total element long run incremental cost (TELRIC) regulatory measure, which is extensively used in the US telecommunications industry. An analogous measure based on the costs of the efficient service provision is applied in German telecommunications.

[14] Some regulatory regimes explicitly incorporate flexibility even during the regulatory period. In the UK gas and electricity sectors, the length of the regulatory period is currently eight years, with a potential mid-period review. See Decker (2015) and the references cited therein for further details about the length of regulatory period in different sectors and countries.

apparently counterintuitive result lies in the channel identified by our analysis that connects regulatory risk with vertical integration and upstream investment. A risk-averse firm commands larger compensation in response to regulatory risk, which reduces the social desirability of high investment effort with respect to full commitment, where regulatory risk is absent. For moderate costs of investment effort, differently from full commitment, the regulator prefers to promote high effort only under vertical integration. This is because the vertically integrated firm's internalization of the downstream payoff alleviates the moral hazard problem associated with unobservable investment effort and reduces the amount of the upstream transfer compared to vertical separation. In anticipation of the regulator's behavior toward investment effort, vertical integration becomes more profitable, which spurs upstream investment at a lower social cost. As a more risk-averse firm is more reluctant to operate in the face of uncertainty, regulatory risk tends to be socially optimal under firm small risk aversion.

Our work sheds new light on some empirically documented determinants of vertical integration. Fan et al. (2017) show that vertical integration is more common in regions where legal institutions are characterized by a lower degree of contractual enforcement, which creates some institutional uncertainty. We provide theoretical corroboration for the identification of regulatory risk as a source of institutional uncertainty that facilitates vertical integration. Our results are also consistent with the empirical findings of Garfinkel and Hankins (2011) that indicate the positive effect of uncertainty about firms' cash flows upon vertical integration and illustrate the role of risk management in the firms' incentives to vertically integrate. Our analysis provides further support for the well-established empirical evidence about the relevance of upstream effort to vertical integration (Lafontaine and Slade 2007). Remarkably, some empirical contributions show that regulatory risk is not necessarily an impediment to firms' investments (e.g., Buckland and Fraser 2001a, 2001b; Hoffmann et al. 2009; Lyon and Mayo 2005). The empirical studies that establish the existence of underinvestment associated with limited regulatory commitment powers typically abstract from the process of vertical integration (e.g., Lim and Yurukoglu 2018). In our setting, for a given vertical industry structure, full regulatory commitment is socially optimal, in line with these empirical studies. However, our results indicate that things change significantly if the choice of vertical integration is considered. Therefore, our analysis advocates that vertical integration should be endogenized in order to investigate the effects of limited commitment and regulatory risk on investment activities.

According to the estimates provided by Oxford Economics (2017), the average annual investment spending required in the US for the following decades (using prices in 2015) is rather large for electricity (130 billion dollars), takes intermediate values for airports, telecommunications and rail (26.7, 25.5 and 18.7 billion dollars, respectively), while it is relatively small for water (7.9 billion dollars). In the light of our result that regulatory risk is optimal in sectors characterized by intermediate investment costs, these estimates suggest that some level of regulatory risk is likely to be welfare enhancing in sectors such as airports, telecommunications and rail. Since we find that the scope for regulatory risk increases with the intensity of downstream competition, the liberalization process of downstream activities can be accompanied by a higher degree of regulatory risk. The predictions of our model are suitable to be empirically validated and can contribute to the policy debate about vertically related markets.

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Appendix

Proof of Lemma 1. Suppose that the probability of regulatory enforcement is $\alpha = 0$. This implies that the regulator certainly gives the regulated firm the lowest transfer compatible with limited liability irrespective of the investment outcome, i.e., $\overline{t} = \underline{t} = 0$. Using (1), under vertical separation the upstream firm exerts low effort instead of high effort. This is because low effort yields zero profits, while high effort entails a loss equal to $\psi > 0$. Using (2), under vertical integration the moral hazard incentive constraint $\mathbb{E}_h [\Pi_{vi}] \geq \mathbb{E}_l [\Pi_{vi}]$ is given by

$$\nu_h u(\overline{\pi}) + (1 - \nu_h) u(\underline{\pi}) - \psi \geq \nu_l u(\overline{\pi}) + (1 - \nu_l) u(\underline{\pi}),$$

which is satisfied if and only if $\psi \leq \psi_0$, where $\psi_0 \equiv \Delta\nu [u(\overline{\pi}) - u(\underline{\pi})]$. As $\mathbb{E}_l [\Pi_{vi}] = \mathbb{E}_l [\Pi_{vs}]$, we find that for $\psi \leq \psi_0$ vertical integration (which induces high effort) is more profitable than vertical separation (which induces low effort). Given that the regulator obtains high effort with zero transfers, the vertical integration decision is welfare enhancing and the equilibrium probability of regulatory enforcement is $\alpha^* = 0$. Expected social welfare is $\nu_h \overline{S} + (1 - \nu_h) \underline{S}$. ■

Proof of Lemma 2. Using (1), the moral hazard incentive constraint $\mathbb{E}_h [\Pi_u] \geq \mathbb{E}_l [\Pi_u]$ under vertical separation is given by

$$\nu_h u\left(\overline{t}\right) + (1 - \nu_h) u(\underline{t}) - \psi \geq \nu_l u\left(\overline{t}\right) + (1 - \nu_l) u(\underline{t}). \tag{A1}$$

Since upstream transfers reduce social welfare in (3), the limited liability constraint $\underline{t} \geq 0$ in case of investment failure and the moral hazard incentive constraint (A1) are binding in equilibrium. Hence, under vertical separation, when high effort is incentivized, the full commitment transfers are $\underline{t}^c_{vs} = 0$ if investment has failed and $\overline{t}^c_{vs} = u^{-1}\left(\frac{\psi}{\Delta\nu}\right) > 0$ if investment has succeeded. The function $u^{-1}(\cdot)$ is the inverse of $u(\cdot)$, where $u^{-1}(0) = 0$, $u^{-1\prime}(\cdot) > 0$, and $u^{-1\prime\prime}(\cdot) \geq 0$ (with $u^{-1\prime\prime}(\cdot) > 0$ under risk aversion).

Using (2), the moral hazard incentive constraint $\mathbb{E}_h [\Pi_{vi}] \geq \mathbb{E}_l [\Pi_{vi}]$ under vertical integration is given by

$$\nu_h u\left(\overline{t} + \overline{\pi}\right) + (1 - \nu_h) u(\underline{t} + \underline{\pi}) - \psi \geq \nu_l u\left(\overline{t} + \overline{\pi}\right) + (1 - \nu_l) u(\underline{t} + \underline{\pi}). \tag{A2}$$

In line with the case of vertical separation, since upstream transfers are socially costly, the limited liability constraint $\underline{t} \geq 0$ and the moral hazard incentive constraint (A2) are binding in equilibrium. Therefore, under vertical integration, when high effort is incentivized, the full commitment transfers are $\underline{t}^c_{vi} = 0$ if investment has failed and $\overline{t}^c_{vi} = u^{-1}\left(\frac{\psi}{\Delta\nu} + u(\underline{\pi})\right) - \overline{\pi}$ if investment has succeeded ($\overline{t}^c_{vi} > 0$ by Assumption 1).

Let $\mathbb{E}_h [t^c_{vs}] \equiv \nu_h \overline{t}^c_{vs}$ and $\mathbb{E}_h [t^c_{vi}] \equiv \nu_h \overline{t}^c_{vi}$, where $\overline{t}^c_{vs} = u^{-1}\left(\frac{\psi}{\Delta\nu}\right)$ and $\overline{t}^c_{vi} = u^{-1}\left(\frac{\psi}{\Delta\nu} + u(\underline{\pi})\right) -$

$\overline{\pi}$. Then, we find that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ if and only if

$$u^{-1}\left(\frac{\psi}{\Delta\nu}+u\left(\underline{\pi}\right)\right)-\overline{\pi}-u^{-1}\left(\frac{\psi}{\Delta\nu}\right)<0.$$

This condition is unambiguously satisfied under risk neutrality ($u''(\cdot)=0$), as $\overline{\pi} > \underline{\pi}$. Now, we turn to the case of risk aversion ($u''(\cdot)<0$). Differentiating $\mathbb{E}_h\left[t_{vs}^c\right]$ and $\mathbb{E}_h\left[t_{vi}^c\right]$ with respect to ψ yields

$$\frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial\psi}=\frac{\nu_h}{\Delta\nu}u^{-1\prime}\left(\frac{\psi}{\Delta\nu}\right) \quad \text{and} \quad \frac{\partial \mathbb{E}_h\left[t_{vi}^c\right]}{\partial\psi}=\frac{\nu_h}{\Delta\nu}u^{-1\prime}\left(\frac{\psi}{\Delta\nu}+u\left(\underline{\pi}\right)\right).$$

It follows from $\frac{\partial \mathbb{E}_h\left[t_{vi}^c\right]}{\partial\psi} > \frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial\psi} > 0$ (as $u^{-1\prime}(\cdot)>0$ and $u^{-1\prime\prime}(\cdot)>0$) and $\mathbb{E}_h\left[t_{vs}^c\right]\big|_{\psi=\psi_0} > \mathbb{E}_h\left[t_{vi}^c\right]\big|_{\psi=\psi_0}=0$ (where ψ_0 is defined in Lemma 1) that there exists a unique (possibly large) threshold ψ_1, with $\psi_1>\psi_0$, such that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ if and only if $\psi<\psi_1$. ■

Proof of Proposition 1. Using (1), the vertically separated firms' (expected) aggregate utility $\mathbb{E}_h\left[\Pi_{vs}^c\right]$ from high effort can be written as

$$\begin{aligned}
\mathbb{E}_h\left[\Pi_{vs}^c\right] &= \nu_h\left[u\left(\overline{t}_{vs}^c\right)+u\left(\overline{\pi}\right)\right]+\left(1-\nu_h\right)\left[u\left(\underline{t}_{vs}^c\right)+u\left(\underline{\pi}\right)\right]-\psi \\
&= \nu_l\frac{\psi}{\Delta\nu}+\nu_h u\left(\overline{\pi}\right)+\left(1-\nu_h\right)u\left(\underline{\pi}\right),
\end{aligned} \tag{A3}$$

where $\underline{t}_{vs}^c=0$ and $\overline{t}_{vs}^c=u^{-1}\left(\frac{\psi}{\Delta\nu}\right)$ (see the proof of Lemma 2).

Using (2), the vertically integrated firm's (expected) utility $\mathbb{E}_h\left[\Pi_{vi}^c\right]$ from high effort is given by

$$\begin{aligned}
\mathbb{E}_h\left[\Pi_{vi}^c\right] &= \nu_h u\left(\overline{t}_{vi}^c+\overline{\pi}\right)+\left(1-\nu_h\right)u\left(\underline{t}_{vi}^c+\underline{\pi}\right)-\psi \\
&= \nu_l\frac{\psi}{\Delta\nu}+u\left(\underline{\pi}\right),
\end{aligned} \tag{A4}$$

where $\underline{t}_{vi}^c=0$ and $\overline{t}_{vi}^c=u^{-1}\left(\frac{\psi}{\Delta\nu}+u\left(\underline{\pi}\right)\right)-\overline{\pi}$ (see the proof of Lemma 2).

Now, suppose that the regulator demands low effort. In this case, it suffices to set the transfer at the lowest level compatible with the regulated firm's limited liability irrespective of the investment outcome, i.e., $\overline{t}=\underline{t}=0$. It follows from the proof of Lemma 1 and Assumption 1 that low effort is provided in the two vertical industry structures. This yields

$$\mathbb{E}_l\left[\Pi_{vs}^c\right]=\mathbb{E}_l\left[\Pi_{vi}^c\right]=\nu_l u\left(\overline{\pi}\right)+\left(1-\nu_l\right)u\left(\underline{\pi}\right). \tag{A5}$$

Suppose first that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$. The following three cases arise.

(I) $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$. It follows from (3) that

$$\begin{aligned}
\mathbb{E}_h\left[W_{vi}^c\right] &= \nu_h\overline{S}+\left(1-\nu_h\right)\underline{S}-\mathbb{E}_h\left[t_{vi}^c\right] > \\
\mathbb{E}_h\left[W_{vs}^c\right] &= \nu_h\overline{S}+\left(1-\nu_h\right)\underline{S}-\mathbb{E}_h\left[t_{vs}^c\right] > \\
\mathbb{E}_l\left[W^c\right] &= \nu_l\overline{S}+\left(1-\nu_l\right)\underline{S}.
\end{aligned}$$

Then, the regulator induces high effort irrespective of the vertical industry structure. Using

(A3) and (A4), we find that

$$\mathbb{E}_h\left[\Pi_{vs}^c\right] > \mathbb{E}_h\left[\Pi_{vi}^c\right] \iff u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right) > 0, \tag{A6}$$

where the inequality follows from $\overline{\pi} > \underline{\pi}$ and $u'(\cdot) > 0$. Hence, vertical separation emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right]$.

(II) $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$. It follows from (3) that

$$\mathbb{E}_h\left[W_{vi}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vi}^c\right] > \mathbb{E}_l\left[W^c\right] = \nu_l\overline{S} + (1-\nu_l)\underline{S}$$

and

$$\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right] \leq \mathbb{E}_l\left[W^c\right] = \nu_l\overline{S} + (1-\nu_l)\underline{S},$$

where the equality holds if and only if $\mathbb{E}_h\left[t_{vs}^c\right] = \Delta\nu\Delta S$. Then, the regulator induces high effort under vertical integration and low effort under vertical separation. Using (A4) and (A5), we find that

$$\mathbb{E}_h\left[\Pi_{vi}^c\right] > \mathbb{E}_l\left[\Pi_{vs}^c\right] \iff \psi > \Delta\nu\left[u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right], \tag{A7}$$

which holds by Assumption 1. Hence, vertical integration emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vi}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vi}^c\right]$.

(III) $\mathbb{E}_h\left[t_{vi}^c\right] \geq \Delta\nu\Delta S$. It follows from (3) that

$$\begin{aligned}
\mathbb{E}_l\left[W^c\right] &= \nu_l\overline{S} + (1-\nu_l)\underline{S} \geq \\
\mathbb{E}_h\left[W_{vi}^c\right] &= \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vi}^c\right] > \\
\mathbb{E}_h\left[W_{vs}^c\right] &= \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right],
\end{aligned}$$

where the equality holds if and only if $\mathbb{E}_h\left[t_{vi}^c\right] = \Delta\nu\Delta S$. Then, the regulator induces low effort irrespective of the vertical industry structure. It follows from (A5) that the firms are indifferent to the vertical industry structure. Expected social welfare is $\mathbb{E}_l\left[W^c\right] = \nu_l\overline{S} + (1-\nu_l)\underline{S}$.

Now, suppose that $\mathbb{E}_h\left[t_{vi}^c\right] \geq \mathbb{E}_h\left[t_{vs}^c\right]$. The following two cases arise.

(IV) $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$. It follows from (3) that

$$\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right] > \mathbb{E}_l\left[W^c\right] = \nu_l\overline{S} + (1-\nu_l)\underline{S}.$$

This implies that high effort is incentivized at least under vertical separation. Using (A5), (A6) and (A7), we obtain that

$$\mathbb{E}_h\left[\Pi_{vs}^c\right] > \mathbb{E}_h\left[\Pi_{vi}^c\right] > \mathbb{E}_l\left[\Pi_{vs}^c\right] = \mathbb{E}_l\left[\Pi_{vi}^c\right].$$

Since high effort is incentivized at least under vertical separation, we find that vertical separation emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right]$.

(V) $\mathbb{E}_h [t^c_{vs}] \geq \Delta\nu\Delta S$. It follows from (3) that

$$\begin{aligned}\mathbb{E}_l [W^c] &= \nu_l \overline{S} + (1-\nu_l) \underline{S} \geq \\ \mathbb{E}_h [W^c_{vs}] &= \nu_h \overline{S} + (1-\nu_h) \underline{S} - \mathbb{E}_h [t^c_{vs}] \geq \\ \mathbb{E}_h [W^c_{vi}] &= \nu_h \overline{S} + (1-\nu_h) \underline{S} - \mathbb{E}_h [t^c_{vi}],\end{aligned}$$

where the first equality holds if and only if $\mathbb{E}_h [t^c_{vs}] = \Delta\nu\Delta S$ and the second equality holds if and only if $\mathbb{E}_h [t^c_{vi}] = \mathbb{E}_h [t^c_{vs}]$. Then, the regulator induces low effort irrespective of the vertical industry structure. It follows from (A5) that the firms are indifferent about the vertical industry structure. Expected social welfare is $\mathbb{E}_l [W^c] = \nu_l \overline{S} + (1-\nu_l) \underline{S}$.

Point (i) of the proposition follows from cases (I) and (IV). Point (ii) of the proposition follows from case (II). Point (iii) of the proposition follows from cases (III) and (V). ■

Proof of Lemma 3. Using (1), the moral hazard incentive constraint (4) under vertical separation becomes

$$\begin{aligned}&\alpha \left[\nu_h u\left(\overline{t}^e\right) + (1-\nu_h) u\left(\underline{t}^e\right)\right] + (1-\alpha)\left[\nu_h u\left(\overline{t}^{ne}\right) + (1-\nu_h) u\left(\underline{t}^{ne}\right)\right] - \psi \geq \\ &\alpha \left[\nu_l u\left(\overline{t}^e\right) + (1-\nu_l) u\left(\underline{t}^e\right)\right] + (1-\alpha)\left[\nu_l u\left(\overline{t}^{ne}\right) + (1-\nu_l) u\left(\underline{t}^{ne}\right)\right]. \qquad \text{(A8)}\end{aligned}$$

Since upstream transfers are socially costly, the limited liability constraints $\underline{t}^e \geq 0$ and $\underline{t}^{ne} \geq 0$ in case of investment failure and the moral hazard incentive constraint (A8) are binding in equilibrium. With probability α, the regulatory policy is enforced, and the vertically separated upstream firm obtains $\underline{t}^e_{vs} = 0$ in case of investment failure and $\overline{t}^e_{vs} = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu}\right) > 0$ in case of success. With complementary probability $1-\alpha$, the regulatory policy is not enforced and the new, sequentially optimal policy yields $\underline{t}^{ne}_{vs} = \overline{t}^{ne}_{vs} = 0$.

Using (2), the moral hazard incentive constraint (5) under vertical integration becomes

$$\begin{aligned}&\alpha \left[\nu_h u\left(\overline{t}^e + \overline{\pi}\right) + (1-\nu_h) u\left(\underline{t}^e + \underline{\pi}\right)\right] \\ &+ (1-\alpha)\left[\nu_h u\left(\overline{t}^{ne} + \overline{\pi}\right) + (1-\nu_h) u\left(\underline{t}^{ne} + \underline{\pi}\right)\right] - \psi \geq \\ &\alpha \left[\nu_l u\left(\overline{t}^e + \overline{\pi}\right) + (1-\nu_l) u\left(\underline{t}^e + \underline{\pi}\right)\right] \\ &+ (1-\alpha)\left[\nu_l u\left(\overline{t}^{ne} + \overline{\pi}\right) + (1-\nu_l) u\left(\underline{t}^{ne} + \underline{\pi}\right)\right]. \qquad \text{(A9)}\end{aligned}$$

In line with the case of vertical separation, since upstream transfers are socially costly, the limited liability constraints $\underline{t}^e \geq 0$ and $\underline{t}^{ne} \geq 0$ in case of investment failure and the moral hazard incentive constraint (A9) are binding in equilibrium. With probability α, the vertically integrated firm receives $\underline{t}^e_{vi} = 0$ in case of investment failure and $\overline{t}^e_{vi} = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi})-(1-\alpha)u(\overline{\pi})}{\alpha}\right) - \overline{\pi}$ in case of success ($\overline{t}^e_{vi} > 0$ by Assumption 1). With complementary probability $1-\alpha$, the transfers are $\underline{t}^{ne}_{vi} = \overline{t}^{ne}_{vi} = 0$.

Taking the derivative of $\mathbb{E}_h [t^r_{vs}] \equiv \alpha\nu_h \overline{t}^e_{vs}$, where $\overline{t}^e_{vs} = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu}\right)$, with respect to α yields

$$\frac{\partial \mathbb{E}_h [t^r_{vs}]}{\partial \alpha} = \nu_h \left[u^{-1}\left(\frac{\psi}{\alpha\Delta\nu}\right) - \frac{\psi}{\alpha\Delta\nu} u^{-1\prime}\left(\frac{\psi}{\alpha\Delta\nu}\right)\right].$$

It holds $\frac{\partial \mathbb{E}_h [t^r_{vs}]}{\partial \alpha} = 0$ under risk neutrality ($u''(\cdot) = 0$). To establish the sign of $\frac{\partial \mathbb{E}_h [t^r_{vs}]}{\partial \alpha}$ under risk aversion ($u''(\cdot) < 0$), we investigate how $\frac{\partial \mathbb{E}_h [t^r_{vs}]}{\partial \alpha}$ varies with ψ. We find that $\left.\frac{\partial \mathbb{E}_h [t^r_{vs}]}{\partial \alpha}\right|_{\psi=0} = 0$

and

$$\frac{\partial^2 \mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha\partial\psi} = -\frac{\nu_h \psi}{\alpha^2 \Delta\nu^2} u^{-1\prime\prime}\left(\frac{\psi}{\alpha\Delta\nu}\right) < 0,$$

where the inequality follows from $\psi > 0$ and $u^{-1\prime\prime}(\cdot) > 0$. This implies that $\frac{\partial \mathbb{E}_h[t_{vs}^r]}{\partial\alpha} < 0$.

Taking the derivative of $\mathbb{E}_h\left[t_{vi}^r\right] \equiv \alpha\nu_h \overline{t}_{vi}^e$, where $\overline{t}_{vi}^e = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi})-(1-\alpha)u(\overline{\pi})}{\alpha}\right) - \overline{\pi}$, with respect to α yields

$$\begin{aligned}\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha} = \nu_h \Bigg[& u^{-1}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi}) - (1-\alpha)u(\overline{\pi})}{\alpha}\right) - \overline{\pi} - \left(\frac{\psi}{\alpha\Delta\nu} - \frac{u(\overline{\pi}) - u(\underline{\pi})}{\alpha}\right) \\ & \times u^{-1\prime}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi}) - (1-\alpha)u(\overline{\pi})}{\alpha}\right)\Bigg].\end{aligned}$$

It holds $\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial\alpha} = 0$ under risk neutrality ($u''(\cdot) = 0$). To establish the sign of $\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial\alpha}$ under risk aversion ($u''(\cdot) < 0$), we investigate how $\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial\alpha}$ varies with ψ. We find that $\left.\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial\alpha}\right|_{\psi=\psi_0} = 0$ (where ψ_0 is defined in Lemma 1) and

$$\frac{\partial^2 \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha\partial\psi} = -\nu_h \frac{\psi - \Delta\nu\left[u(\overline{\pi}) - u(\underline{\pi})\right]}{\alpha^2\Delta\nu^2} u^{-1\prime\prime}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi}) - (1-\alpha)u(\overline{\pi})}{\alpha}\right) < 0,$$

where the inequality follows from $\psi > \psi_0$ (by Assumption 1) and $u^{-1\prime\prime}(\cdot) > 0$. This implies that $\frac{\partial \mathbb{E}_h[t_{vi}^r]}{\partial\alpha} < 0$. ■

Proof of Proposition 2. Using (1) along with $\mathbb{E}_h\left[\Pi_{vs}^e\right]$ and $\mathbb{E}_h\left[\Pi_{vs}^{ne}\right]$ (defined in Section 3.2), the vertically separated firms' (expected) aggregate utility $\mathbb{E}_h\left[\Pi_{vs}^r\right] \equiv \alpha\mathbb{E}_h\left[\Pi_{vs}^e\right] + (1-\alpha)\mathbb{E}_h\left[\Pi_{vs}^{ne}\right]$ from high effort is given by

$$\begin{aligned}\mathbb{E}_h\left[\Pi_{vs}^r\right] &= \alpha\left\{\nu_h\left[u\left(\overline{t}_{vs}^e\right) + u(\overline{\pi})\right] + (1-\nu_h)\left[u\left(\underline{t}_{vs}^e\right) + u(\underline{\pi})\right]\right\} \\ &\quad + (1-\alpha)\left\{\nu_h\left[u\left(\overline{t}_{vs}^{ne}\right) + u(\overline{\pi})\right] + (1-\nu_h)\left[u\left(\underline{t}_{vs}^{ne}\right) + u(\underline{\pi})\right]\right\} - \psi \\ &= \nu_l \frac{\psi}{\Delta\nu} + \nu_h u(\overline{\pi}) + (1-\nu_h)u(\underline{\pi}),\end{aligned} \tag{A10}$$

where $\overline{t}_{vs}^e = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu}\right)$ and $\underline{t}_{vs}^e = \underline{t}_{vs}^{ne} = \overline{t}_{vs}^{ne} = 0$ (see the proof of Lemma 3).

Using (2) along with $\mathbb{E}_h\left[\Pi_{vi}^e\right]$ and $\mathbb{E}_h\left[\Pi_{vi}^{ne}\right]$ (defined in Section 3.2), the vertically integrated firm's (expected) utility $\mathbb{E}_h\left[\Pi_{vi}^r\right] \equiv \alpha\mathbb{E}_h\left[\Pi_{vi}^e\right] + (1-\alpha)\mathbb{E}_h\left[\Pi_{vi}^{ne}\right]$ from high effort is given by

$$\begin{aligned}\mathbb{E}_h\left[\Pi_{vi}^r\right] &= \alpha\left[\nu_h u\left(\overline{t}_{vi}^e + \overline{\pi}\right) + (1-\nu_h)u\left(\underline{t}_{vi}^e + \underline{\pi}\right)\right] \\ &\quad + (1-\alpha)\left[\nu_h u\left(\overline{t}_{vi}^{ne} + \overline{\pi}\right) + (1-\nu_h)u\left(\underline{t}_{vi}^{ne} + \overline{\pi}\right)\right] - \psi \\ &= \nu_l \frac{\psi}{\Delta\nu} + u(\underline{\pi}),\end{aligned} \tag{A11}$$

where $\overline{t}_{vi}^e = u^{-1}\left(\frac{\psi}{\alpha\Delta\nu} + \frac{u(\underline{\pi})-(1-\alpha)u(\overline{\pi})}{\alpha}\right) - \overline{\pi}$ and $\underline{t}_{vi}^e = \underline{t}_{vi}^{ne} = \overline{t}_{vi}^{ne} = 0$ (see the proof of Lemma 3).

We now characterize the conditions under which the regulator prefers high effort to low effort according to the vertical industry structure. We find from (3) that under vertical separation the regulator prefers high effort to low effort if and only if

$$
\begin{aligned}
\alpha\mathbb{E}_h\left[W_{vs}^e\right]+(1-\alpha)\,\mathbb{E}_h\left[W_{vs}^{ne}\right]>\alpha\mathbb{E}_l\left[W^e\right]+(1-\alpha)\,\mathbb{E}_l\left[W^{ne}\right] &\iff \\
\nu_h\overline{S}+(1-\nu_h)\,\underline{S}-\mathbb{E}_h\left[t_{vs}^r(\alpha)\right]>\nu_l\overline{S}+(1-\nu_l)\,\underline{S} &\iff \\
\mathbb{E}_h\left[t_{vs}^r(\alpha)\right]<\Delta\nu\Delta S, &
\end{aligned}
\tag{A12}
$$

where $\mathbb{E}_h\left[t_{vs}^r(\cdot)\right]\equiv\alpha\nu_h\overline{t}_{vs}^e$ (see the proof of Lemma 3).

Under vertical integration, the regulator prefers high effort to low effort if and only if

$$
\begin{aligned}
\alpha\mathbb{E}_h\left[W_{vi}^e\right]+(1-\alpha)\,\mathbb{E}_h\left[W_{vi}^{ne}\right]>\alpha\mathbb{E}_l\left[W^e\right]+(1-\alpha)\,\mathbb{E}_l\left[W^{ne}\right] &\iff \\
\nu_h\overline{S}+(1-\nu_h)\,\underline{S}-\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]>\nu_l\overline{S}+(1-\nu_l)\,\underline{S} &\iff \\
\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]<\Delta\nu\Delta S, &
\end{aligned}
\tag{A13}
$$

where $\mathbb{E}_h\left[t_{vi}^r(\cdot)\right]\equiv\alpha\nu_h\overline{t}_{vi}^e$ (see the proof of Lemma 3).

It is helpful for the subsequent analysis to derive the following results.

(a) Applying L'Hospital's rule yields

$$
\lim_{\alpha\to0}\mathbb{E}_h\left[t_{vs}^r(\alpha)\right]=\lim_{\alpha\to0}\nu_h\frac{\psi}{\Delta\nu}u^{-1\prime}\left(\frac{\psi}{\alpha\Delta\nu}\right)=+\infty,
$$

where the last equality follows from $\psi>0$, $u^{-1\prime}(\cdot)>0$, and $u^{-1\prime\prime}(\cdot)>0$. Moreover, we obtain that

$$
\lim_{\alpha\to0}\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]=\lim_{\alpha\to0}\nu_h\frac{\psi-\Delta\nu\left[u(\overline{\pi})-u(\underline{\pi})\right]}{\Delta\nu}u^{-1\prime}\left(\frac{\psi+\Delta\nu\left[u(\underline{\pi})-(1-\alpha)\,u(\overline{\pi})\right]}{\alpha\Delta\nu}\right)=+\infty,
$$

where the last equality follows from $\psi>\psi_0$ (by Assumption 1), $u^{-1\prime}(\cdot)>0$, and $u^{-1\prime\prime}(\cdot)>0$.

(b) Combining the conditions $\mathbb{E}_h\left[t_{vs}^c\right]<\Delta\nu\Delta S$ and $\psi<\psi_1$ in the proposition with the results in Lemma 2, we have $\mathbb{E}_h\left[t_{vi}^c\right]<\mathbb{E}_h\left[t_{vs}^c\right]<\Delta\nu\Delta S$.

Given the results in points (a) and (b), the analysis proceeds through the following three steps.

(i) It follows from $\frac{\partial\mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha}<0$ (see Lemma 3), $\lim_{\alpha\to0}\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]=+\infty$ (see point (a)) and $\mathbb{E}_h\left[t_{vi}^c\right]<\Delta\nu\Delta S$ (see point (b)) that there exists a unique threshold $\alpha_1\in(0,1)$ such that condition $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]<\Delta\nu\Delta S$ in (A13) is satisfied if and only if $\alpha>\alpha_1$. In this case, the regulator prefers high effort to low effort under vertical integration.

(ii) It follows from $\frac{\partial\mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha}<0$ (see Lemma 3), $\lim_{\alpha\to0}\mathbb{E}_h\left[t_{vs}^r(\alpha)\right]=+\infty$ (see point (a)) and $\mathbb{E}_h\left[t_{vs}^c\right]<\Delta\nu\Delta S$ (see point (b)) that there exists a unique threshold $\alpha_2\in(0,1)$ such that condition $\mathbb{E}_h\left[t_{vs}^r(\alpha)\right]<\Delta\nu\Delta S$ in (A12) is violated if and only if $\alpha\leq\alpha_2$. In this case, the regulator prefers low effort to high effort under vertical separation.

(iii) It follows from $\frac{\partial\mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha}<0$ (see Lemma 3) and $\mathbb{E}_h\left[t_{vi}^c\right]<\mathbb{E}_h\left[t_{vs}^c\right]$ (see point (b)) that there exists a unique threshold $\alpha_3\in(0,1)$ such that $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]<\mathbb{E}_h\left[t_{vs}^c\right]$ if and only if $\alpha>\alpha_3$. In this case, the regulator prefers vertical integration with $\alpha>\alpha_3$ to vertical separation with $\alpha=1$.

As long as vertical separation emerges, $\alpha=1$ is socially optimal because $\frac{\partial\mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha}<0$. Moreover, this outcome is always achievable for $\mathbb{E}_h\left[t_{vs}^c\right]<\Delta\nu\Delta S$. To see this, recall from Proposition 1 that, when high effort is incentivized at least under vertical separation, i.e.,

$\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$, the firms prefer to remain vertically separated. Given that $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$, the condition $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ in step (iii) is more stringent than the condition $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right] < \Delta\nu\Delta S$ in step (i), which yields $\alpha_3 > \alpha_1$. Note from (A5), (A10) and (A11) that vertical integration is more profitable than vertical separation if and only if high effort is induced under vertical integration but low effort is induced under vertical separation. Combining the results in steps (ii) and (iii), we find that, if $\alpha_3 < \alpha \leq \alpha_2$, the firms prefer to vertically integrate and the regulator provides a lower expected transfer with respect to the best outcome under vertical separation, i.e., $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$. As $\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial \alpha} < 0$, the optimal value for α is $\alpha^* = \alpha_2 \in (0,1)$, where α^* is the unique value for α such that $\mathbb{E}_h\left[t_{vs}^r(\alpha^*)\right] = \Delta\nu\Delta S$. Vertical integration emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vi}^r(\alpha^*)\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]$.

We now show that there exists a threshold ψ^* for the cost of effort ψ, with $\psi_0 < \psi^* < \psi_1$, such that $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ if and only if $\psi < \psi^*$, and therefore the interval $\alpha_3 < \alpha \leq \alpha_2 = \alpha^*$ is nonempty. Recalling from the proofs of Lemmas 2 and 3 that $\mathbb{E}_h\left[t_{vs}^c\right] \equiv \nu_h\overline{t}_{vs}^c$ and $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right] \equiv \alpha\nu_h\overline{t}_{vi}^e$, we find that $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0} = 0 < \mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0} = \nu_h u^{-1}\left(u(\overline{\pi}) - u(\underline{\pi})\right)$, where ψ_0 is defined in Lemma 1. Therefore, there exists a range for ψ such that for $\psi > \psi_0$ it holds $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$. Moreover, taking the derivative of $\mathbb{E}_h\left[t_{vs}^c\right]$ with respect to ψ and evaluating it at $\psi = \psi_0$ yields

$$\left.\frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial \psi}\right|_{\psi=\psi_0} = \frac{\nu_h}{\Delta\nu} u^{-1\prime}\left(u(\overline{\pi}) - u(\underline{\pi})\right). \tag{A14}$$

Taking the derivative of $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]$ with respect to ψ yields after some manipulation

$$\begin{aligned}\frac{\partial \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial \psi} &= \nu_h\left\{\frac{\partial \alpha^*}{\partial \psi}\left[u^{-1}\left(\frac{\psi}{\alpha^*\Delta\nu} + \frac{u(\underline{\pi}) - (1-\alpha^*)u(\overline{\pi})}{\alpha^*}\right) - \overline{\pi}\right]\right. \\ &\left. + \frac{\alpha^* - \frac{\partial \alpha^*}{\partial \psi}\left\{\psi - \Delta\nu\left[u(\overline{\pi}) - u(\underline{\pi})\right]\right\}}{\alpha^*\Delta\nu} u^{-1\prime}\left(\frac{\psi}{\alpha^*\Delta\nu} + \frac{u(\underline{\pi}) - (1-\alpha^*)u(\overline{\pi})}{\alpha^*}\right)\right\}.\end{aligned}$$

Evaluating this expression at $\psi = \psi_0$, we obtain that

$$\left.\frac{\partial \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial \psi}\right|_{\psi=\psi_0} = \frac{\nu_h}{\Delta\nu} u^{-1\prime}\left(u(\overline{\pi})\right). \tag{A15}$$

Recalling $\mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0} = \nu_h u^{-1}\left(u(\overline{\pi}) - u(\underline{\pi})\right)$ and $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0} = 0$ and using (A14) and (A15), a first-order Taylor approximation yields

$$\begin{aligned}\mathbb{E}_h\left[t_{vs}^c\right] &\approx \mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0} + (\psi - \psi_0)\left.\frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial \psi}\right|_{\psi=\psi_0} \\ &= \nu_h u^{-1}\left(u(\overline{\pi}) - u(\underline{\pi})\right) + \frac{\nu_h}{\Delta\nu}(\psi - \psi_0) u^{-1\prime}\left(u(\overline{\pi}) - u(\underline{\pi})\right)\end{aligned}$$

and

$$\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right] \approx \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0} + (\psi - \psi_0)\left.\frac{\partial \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial \psi}\right|_{\psi=\psi_0} = \frac{\nu_h}{\Delta\nu}(\psi - \psi_0) u^{-1\prime}\left(u(\overline{\pi})\right).$$

It holds $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ if and only if

$$\psi < \psi^* \equiv \psi_0 + \Delta\nu \frac{u^{-1}\left(u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right)}{u^{-1\prime}\left(u\left(\overline{\pi}\right)\right) - u^{-1\prime}\left(u\left(\overline{\pi}\right) - u\left(\underline{\pi}\right)\right)}, \tag{A16}$$

where $\psi^* > \psi_0$ follows from $\overline{\pi} > \underline{\pi} \geq 0$, $u^{-1\prime}(\cdot) > 0$, and $u^{-1\prime\prime}(\cdot) > 0$. Note from Lemma 2 that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ implies $\psi^* < \psi_1$. ■

Proof of Proposition 3. Suppose first that $\mathbb{E}_h\left[t_{vi}^c\right] \leq \mathbb{E}_h\left[t_{vs}^c\right]$. The following three cases emerge.

(I) $\mathbb{E}_h\left[t_{vi}^c\right] \leq \mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ and $\psi > \psi^*$. It follows from the proof of Proposition 2 that $\alpha^* = 1$. Vertical separation emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right]$.

(II) $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$. Since condition (A12) is violated, the regulator prefers low effort under vertical separation. However, we know from condition (A13) that the regulator prefers high effort under vertical integration (and therefore it prefers vertical integration to vertical separation) for α high enough. As $\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha} < 0$ (see Lemma 3), we obtain $\alpha^* = 1$. It follows from (A5) and (A11) that vertical integration emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vi}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vi}^c\right]$.

(III) $\mathbb{E}_h\left[t_{vi}^c\right] \geq \Delta\nu\Delta S$. Since conditions (A12) and (A13) are violated, the regulator prefers low effort irrespective of the vertical industry structure. This implies that any probability $\alpha^* \in [0,1]$ of regulatory enforcement can be sustained in equilibrium. It follows from (A5) that the firms are indifferent about the vertical industry structure. Expected social welfare is $\mathbb{E}_l[W] = \nu_l\overline{S} + (1-\nu_l)\underline{S}$.

Now, suppose that $\mathbb{E}_h\left[t_{vi}^c\right] > \mathbb{E}_h\left[t_{vs}^c\right]$. The following two cases emerge.

(IV) $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$. It follows from condition (A12) that the regulator prefers high effort under vertical separation for α high enough. Moreover, under full commitment the regulator prefers vertical separation to vertical integration irrespective of the effort exerted under vertical integration ($\mathbb{E}_h\left[t_{vi}^c\right] > \mathbb{E}_h\left[t_{vs}^c\right]$ and $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$). As $\frac{\partial \mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha} < 0$ and $\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha} < 0$ (see Lemma 3), we find that $\alpha^* = 1$. It follows from (A5) and (A10) that vertical separation emerges in equilibrium, and high effort is provided. Expected social welfare is $\mathbb{E}_h\left[W_{vs}^c\right] = \nu_h\overline{S} + (1-\nu_h)\underline{S} - \mathbb{E}_h\left[t_{vs}^c\right]$.

(V) $\mathbb{E}_h\left[t_{vs}^c\right] \geq \Delta\nu\Delta S$. Then, the outcome in case (III) applies.

Point (i) of the proposition follows from cases (I) and (IV). Point (ii) of the proposition follows from case (II). Point (iii) of the proposition follows from cases (III) and (V). ■

Proof of Remark 1. In the Cournot equilibrium, the payoff of downstream firm $j \in \{1, ..., N\}$ is $\pi = \frac{(1-c)^2}{(1+N)^2}$, where $c \in \{\overline{c}, \underline{c}\}$ is such that $0 \leq \overline{c} < \underline{c} < 1$ and $\Delta c \equiv \underline{c} - \overline{c} > 0$. Assuming that S in (3) represents consumer surplus, we have $S = \frac{(1-c)^2 N^2}{2(1+N)^2}$, where $S \in \left\{\overline{S}, \underline{S}\right\}$ and $\Delta S \equiv \overline{S} - \underline{S} = \frac{(2-\underline{c}-\overline{c})N^2\Delta c}{2(1+N)^2} > 0$. Using the utility function in (6), the results in the remark directly follow from Proposition 2.

We now characterize the nonempty interval for the cost of high effort ψ where regulatory risk is optimal. For $\rho > 0$, Assumption 1 becomes the following.

Assumption 1′ $\psi > \psi_0 \equiv \frac{\Delta\nu}{\rho}\left[e^{-\rho\frac{(1-\underline{c})^2}{(1+N)^2}} - e^{-\rho\frac{(1-\overline{c})^2}{(1+N)^2}}\right]$.

Recalling $\Delta S \equiv \overline{S} - \underline{S} = \frac{(2-\underline{c}-\overline{c})N^2\Delta c}{2(1+N)^2}$ and $\frac{\partial \mathbb{E}_h[t_{vs}^c]}{\partial \psi} > 0$ (see Lemma 2) and using (6), we find that $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ if and only if $\psi < \psi_{vs}^c$, where ψ_{vs}^c satisfies

$$\nu_h \ln\left(1 - \frac{\rho\psi_{vs}^c}{\Delta\nu}\right) + \rho\Delta\nu \frac{\left(2 - \underline{c} - \overline{c}\right) N^2 \Delta c}{2\left(1+N\right)^2} = 0.$$

This yields after some manipulation

$$\psi_{vs}^c \equiv \frac{\Delta\nu}{\rho}\left[1 - e^{-\rho\Delta\nu\frac{(2-\underline{c}-\overline{c})N^2\Delta c}{2\nu_h(1+N)^2}}\right]. \tag{A17}$$

The conditions $\psi > \psi_0$ (by Assumption 1′) and $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ (by supposition in the remark) must be simultaneously satisfied. As $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ if and only if $\psi < \psi_{vs}^c$ (where ψ_{vs}^c is defined by (A17)), this corresponds to $\psi_{vs}^c > \psi_0$. For the sake of convenience, we consider a sufficiently small degree of risk aversion ρ. We find that $\lim_{\rho\to 0}\psi_{vs}^c = \frac{(2-\underline{c}-\overline{c})N^2\Delta c\Delta\nu^2}{2\nu_h(1+N)^2} > \lim_{\rho\to 0}\psi_0 = \frac{(2-\underline{c}-\overline{c})\Delta c\Delta\nu}{(1+N)^2}$ if and only if $\frac{(2-\underline{c}-\overline{c})\left(N^2\Delta\nu - 2\nu_h\right)\Delta c\Delta\nu}{2\nu_h(1+N)^2} > 0$. For $N = 2$, this reduces to $\nu_h > 2\nu_l$, given the assumptions on the parameters of the model. For $N > 2$, the condition $\nu_h > 2\nu_l$ is sufficient but no longer necessary. ■

Proof of Remark 2. Applying the implicit function theorem to (7) yields after some manipulation

$$\frac{\partial\alpha^*}{\partial N} = \frac{\left(2 - \underline{c} - \overline{c}\right) N\Delta c\Delta\nu}{\frac{\partial \mathbb{E}_h[t_{vs}^c]}{\partial\alpha}\left(1+N\right)^3} < 0,$$

where the inequality follows from $\frac{\partial \mathbb{E}_h[t_{vs}^c]}{\partial\alpha} < 0$ (see Lemma 3) and the assumptions on the parameters of the model. Moreover, we obtain that

$$\frac{\partial\alpha^*}{\partial\rho} = -\left[\frac{\rho\psi}{\alpha^*\Delta\nu - \rho\psi} + \ln\left(1 - \frac{\rho\psi}{\alpha^*\Delta\nu}\right)\right]\frac{\alpha^*\nu_h}{\frac{\partial \mathbb{E}_h[t_{vs}^r]}{\partial\alpha}\rho^2} > 0,$$

where the inequality follows from $\frac{\partial \mathbb{E}_h[t_{vs}^r]}{\partial\alpha} < 0$ and the positive sign of the expression in square brackets due to the assumptions on the parameters of the model. ■

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Regulatory risk, vertical integration, and upstream investment Supplementary Appendix

Raffaele Fiocco* Dongyu Guo†

In this Supplementary Appendix we show that our results carry over to non-additively separable preferences. In the spirit of Grossman and Hart (1983), we consider a utility function of the form

$$U(x,e) = \gamma_e u(x) - \psi_e, \tag{S1}$$

where γ_e is a function of effort e, $u(\cdot)$ is an increasing and (weakly) concave function of the payoff $x \geq 0$ (with $u(0) = 0$), and ψ_e denotes the cost of effort, which is zero for low effort and $\psi > 0$ for high effort. Let $\gamma_e = \gamma_h$ with high effort and $\gamma_e = \gamma_l$ with low effort. The probabilities of investment success associated with high and low effort are respectively $\nu_h \in (0,1)$ and $\nu_l \in (0,1)$, with $\Delta\nu \equiv \nu_h - \nu_l > 0$. To ensure interior solutions, we assume that $\frac{\nu_l}{\nu_h} < \frac{\gamma_h}{\gamma_l} < \frac{1-\nu_l}{1-\nu_h}$.[1]

Using (S1), the upstream firm's utility is

$$\Pi_u = \gamma_e u(t) - \psi_e, \tag{S2}$$

where the upstream transfer t is such that $t \geq 0$ by limited liability. This transfer is determined by the regulator according to the investment outcome, i.e., $t \in \{\bar{t}, \underline{t}\}$, where $\bar{t}$ identifies the transfer in case of success and $\underline{t}$ the transfer in case of failure.

The vertically integrated firm's utility is

$$\Pi_{vi} = \gamma_e u(t + \pi) - \psi_e, \tag{S3}$$

where $\pi \geq 0$ is the downstream payoff, which is higher in case of investment success than in case of failure, i.e., $\pi \in \{\overline{\pi}, \underline{\pi}\}$ and $\overline{\pi} > \underline{\pi}$.

The regulator's social welfare function is

$$W = S - t, \tag{S4}$$

where $S > 0$ represents the gross surplus from investment, which is higher in case of investment success than in case of failure, i.e., $S \in \{\overline{S}, \underline{S}\}$ and $\Delta S \equiv \overline{S} - \underline{S} > 0$.

In the following remark, we summarize what happens when the cost of high investment effort is relatively small. The results reflect those of Lemma 1 in the paper.

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[1] As $\nu_h - \nu_l > 0$, this condition is always satisfied for $\gamma_h = \gamma_l$, namely, when $U(\cdot)$ in (S1) is additively separable in money and effort. By continuity, this holds for $\gamma_h \neq \gamma_l$.

Remark 3 *Suppose* $\psi \leq \psi_0 \equiv u(\overline{\pi})(\nu_h\gamma_h - \nu_l\gamma_l) - u(\underline{\pi})[(1-\nu_l)\gamma_l - (1-\nu_h)\gamma_h]$. *Then, the equilibrium probability of regulatory enforcement is* $\alpha^* = 0$. *Vertical integration emerges, and high investment effort is provided at no social cost.*

Proof of Remark 3. We derive the threshold ψ_0. Using (S3), the moral hazard incentive constraint $\mathbb{E}_h[\Pi_{vi}] \geq \mathbb{E}_l[\Pi_{vi}]$ under vertical integration for $\alpha = 0$ (which implies $\overline{t} = \underline{t} = 0$) is given by

$$\nu_h\gamma_h u(\overline{\pi}) + (1-\nu_h)\gamma_h u(\underline{\pi}) - \psi \geq \nu_l\gamma_l u(\overline{\pi}) + (1-\nu_l)\gamma_l u(\underline{\pi}),$$

which is satisfied if and only if $\psi \leq \psi_0$, where ψ_0 is defined in the remark. The rest of the proof directly follows from the proof of Lemma 1 in the paper. ■

For the sake of simplicity, we focus on the case where $\psi_0 > 0$. Throughout the analysis, we impose the following assumption.

Assumption 1'' $\psi > \psi_0 \equiv u(\overline{\pi})(\nu_h\gamma_h - \nu_l\gamma_l) - u(\underline{\pi})[(1-\nu_l)\gamma_l - (1-\nu_h)\gamma_h]$.

In the following remark, we compare the full commitment expected transfers in the two vertical industry structures. The results correspond to those of Lemma 2 in the paper.

Remark 4 *Under firm risk neutrality ($u''(\cdot) = 0$), it holds* $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$. *Under firm risk aversion ($u''(\cdot) < 0$), there exists a threshold ψ_1, with $\psi_1 > \psi_0$, such that* $\mathbb{E}_h[t^c_{vi}] < \mathbb{E}_h[t^c_{vs}]$ *if and only if* $\psi < \psi_1$.

Proof of Remark 4. Using (S2), the moral hazard incentive constraint $\mathbb{E}_h[\Pi_u] \geq \mathbb{E}_l[\Pi_u]$ under vertical separation is given by

$$\nu_h\gamma_h u(\overline{t}) + (1-\nu_h)\gamma_h u(\underline{t}) - \psi \geq \nu_l\gamma_l u(\overline{t}) + (1-\nu_l)\gamma_l u(\underline{t}). \tag{S5}$$

Since upstream transfers reduce social welfare in (S4), the limited liability constraint $\underline{t} \geq 0$ in case of investment failure and the moral hazard incentive constraint (S5) are binding in equilibrium. Hence, under vertical separation, when high effort is incentivized, the full commitment transfers are $\underline{t}^c_{vs} = 0$ in case of investment failure and

$$\overline{t}^c_{vs} = u^{-1}\left(\frac{\psi}{\nu_h\gamma_h - \nu_l\gamma_l}\right) \tag{S6}$$

in case of investment success.

Using (S3), the moral hazard incentive constraint $\mathbb{E}_h[\Pi_{vi}] \geq \mathbb{E}_l[\Pi_{vi}]$ under vertical integration is given by

$$\nu_h\gamma_h u(\overline{t} + \overline{\pi}) + (1-\nu_h)\gamma_h u(\underline{t} + \underline{\pi}) - \psi \geq \nu_l\gamma_l u(\overline{t} + \overline{\pi}) + (1-\nu_l)\gamma_l u(\underline{t} + \underline{\pi}). \tag{S7}$$

As under vertical separation, since upstream transfers reduce social welfare in (S4), the limited liability constraint $\underline{t} \geq 0$ and the moral hazard incentive constraint (S7) are binding in equilibrium. Hence, under vertical integration, when high effort is incentivized, the full commitment transfers are $\underline{t}^c_{vi} = 0$ in case of investment failure and

$$\overline{t}^c_{vi} = u^{-1}\left(\frac{\psi}{\nu_h\gamma_h - \nu_l\gamma_l} + \frac{(1-\nu_l)\gamma_l - (1-\nu_h)\gamma_h}{\nu_h\gamma_h - \nu_l\gamma_l}u(\underline{\pi})\right) - \overline{\pi} \tag{S8}$$

in case of investment success.

Defining $\mathbb{E}_h\left[t_{vs}^c\right] \equiv \nu_h \bar{t}_{vs}^c$ and $\mathbb{E}_h\left[t_{vi}^c\right] \equiv \nu_h \bar{t}_{vi}^c$, where $\bar{t}_{vs}^c$ and $\bar{t}_{vi}^c$ are given by (S6) and (S8) respectively, we find that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ under risk neutrality ($u''(\cdot) = 0$). Now, we turn to the case of risk aversion ($u''(\cdot) < 0$). Differentiating $\mathbb{E}_h\left[t_{vs}^c\right]$ and $\mathbb{E}_h\left[t_{vi}^c\right]$ with respect to ψ yields

$$\frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial \psi} = \frac{\nu_h}{\nu_h\gamma_h - \nu_l\gamma_l} u^{-1\prime}\left(\frac{\psi}{\nu_h\gamma_h - \nu_l\gamma_l}\right)$$

and

$$\frac{\partial \mathbb{E}_h\left[t_{vi}^c\right]}{\partial \psi} = \frac{\nu_h}{\nu_h\gamma_h - \nu_l\gamma_l} u^{-1\prime}\left(\frac{\psi}{\nu_h\gamma_h - \nu_l\gamma_l} + \frac{(1-\nu_l)\gamma_l - (1-\nu_h)\gamma_h}{\nu_h\gamma_h - \nu_l\gamma_l} u\left(\underline{\pi}\right)\right).$$

It follows from $\frac{\partial \mathbb{E}_h\left[t_{vi}^c\right]}{\partial \psi} > \frac{\partial \mathbb{E}_h\left[t_{vs}^c\right]}{\partial \psi} > 0$ (as $u^{-1\prime}(\cdot) > 0$ and $u^{-1\prime\prime}(\cdot) > 0$) and $\mathbb{E}_h\left[t_{vs}^c\right]\big|_{\psi=\psi_0} > \mathbb{E}_h\left[t_{vi}^c\right]\big|_{\psi=\psi_0} = 0$ (where ψ_0 is defined in Remark 3) that there exists a unique (possibly large) threshold ψ_1, with $\psi_1 > \psi_0$, such that $\mathbb{E}_h\left[t_{vi}^c\right] < \mathbb{E}_h\left[t_{vs}^c\right]$ if and only if $\psi < \psi_1$. ■

In the following remark, we formalize the results under full commitment, where the regulatory policy is enforced with certainty. The results reflects those of Proposition 1 in the paper.

Remark 5 *Suppose that the probability of regulatory enforcement is $\alpha = 1$.*

(i) If $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$, vertical separation emerges, and high investment effort is provided.

(ii) If $\mathbb{E}_h\left[t_{vi}^c\right] < \Delta\nu\Delta S \leq \mathbb{E}_h\left[t_{vs}^c\right]$, vertical integration emerges, and high investment effort is provided.

(iii) Otherwise, i.e., if $\min\left\{\mathbb{E}_h\left[t_{vi}^c\right], \mathbb{E}_h\left[t_{vs}^c\right]\right\} \geq \Delta\nu\Delta S$, the vertical industry structure is inconsequential, and low investment effort is provided.

Proof of Remark 5. Using (S2), the vertically separated firms' (expected) aggregate utility $\mathbb{E}_h\left[\Pi_{vs}^c\right]$ from high effort is given by

$$\begin{aligned}\mathbb{E}_h\left[\Pi_{vs}^c\right] &= \nu_h\left[\gamma_h u\left(\bar{t}_{vs}^c\right) + \gamma_h u\left(\bar{\pi}\right)\right] + (1-\nu_h)\left[\gamma_h u\left(\underline{t}_{vs}^c\right) + \gamma_h u\left(\underline{\pi}\right)\right] - \psi \\ &= \frac{\nu_l\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l}\psi + \nu_h\gamma_h u\left(\bar{\pi}\right) + (1-\nu_h)\gamma_h u\left(\underline{\pi}\right), \end{aligned} \tag{S9}$$

where $\bar{t}_{vs}^c$ is given by (S6) and $\underline{t}_{vs}^c = 0$ (see the proof of Remark 4).

Using (S3), the vertically integrated firm's (expected) utility $\mathbb{E}_h\left[\Pi_{vi}^c\right]$ from high effort is given by

$$\begin{aligned}\mathbb{E}_h\left[\Pi_{vi}^c\right] &= \nu_h\gamma_h u\left(\bar{t}_{vi}^c + \bar{\pi}\right) + (1-\nu_h)\gamma_h u\left(\underline{t}_{vi}^c + \underline{\pi}\right) - \psi \\ &= \frac{\nu_l\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l}\psi + \frac{\Delta\nu\gamma_h\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l} u\left(\underline{\pi}\right), \end{aligned} \tag{S10}$$

where $\bar{t}_{vi}^c$ is given by (S8) and $\underline{t}_{vi}^c = 0$ (see the proof of Remark 4).

Now, suppose that the regulator demands low effort. In this case, it suffices to set the transfer at the lowest level compatible with the regulated firm's limited liability irrespective of the investment outcome, i.e., $\bar{t} = \underline{t} = 0$. It follows from Remark 3 and Assumption 1$''$ that low effort is provided in the two vertical industry structures. This yields

$$\mathbb{E}_l\left[\Pi_{vs}^c\right] = \mathbb{E}_l\left[\Pi_{vi}^c\right] = \nu_l\gamma_l u\left(\bar{\pi}\right) + (1-\nu_l)\gamma_l u\left(\underline{\pi}\right). \tag{S11}$$

Using (S9) and (S10), we find that

$$\mathbb{E}_h\left[\Pi_{vs}^c\right] > \mathbb{E}_h\left[\Pi_{vi}^c\right] \iff \left(\nu_h\gamma_h - \nu_l\gamma_l\right) u\left(\overline{\pi}\right) - \left[\left(1-\nu_l\right)\gamma_l - \left(1-\nu_h\right)\gamma_h\right] u\left(\underline{\pi}\right) > 0,$$

where the inequality follows from the assumptions on the parameters of the model. Moreover, using (S10) and (S11) yields

$$\mathbb{E}_h\left[\Pi_{vi}^c\right] > \mathbb{E}_l\left[\Pi_{vs}^c\right] \iff \psi + \left[\left(1-\nu_l\right)\gamma_l - \left(1-\nu_h\right)\gamma_h\right] u\left(\underline{\pi}\right) - \left(\nu_h\gamma_h - \nu_l\gamma_l\right) u\left(\overline{\pi}\right) > 0,$$

where the inequality follows from $\psi > \psi_0$ (by Assumption 1″). The rest of the proof directly follows from the proof of Proposition 1 in the paper. ■

In the following remark, we investigate the impact of the probability α of regulatory enforcement upon the expected transfers in the two vertical industry structures. The results correspond to those of Lemma 3 in the paper.

Remark 6 *It holds* $\frac{\partial \mathbb{E}_h\left[t_{vs}^r\right]}{\partial \alpha} \leq 0$ *and* $\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial \alpha} \leq 0$, *where the strict inequalities follow under firm risk aversion* ($u''(\cdot) < 0$).

Proof of Remark 6. The moral hazard incentive constraint under vertical separation is

$$\alpha\mathbb{E}_h\left[\Pi_u^e\right] + (1-\alpha)\,\mathbb{E}_h\left[\Pi_u^{ne}\right] \geq \alpha\mathbb{E}_l\left[\Pi_u^e\right] + (1-\alpha)\,\mathbb{E}_l\left[\Pi_u^{ne}\right].$$

With probability α, the regulatory policy is enforced and the upstream firm receives expected utility $\mathbb{E}_h\left[\Pi_u^e\right]$ from high effort and $\mathbb{E}_l\left[\Pi_u^e\right]$ from low effort. With complementary probability $1-\alpha$, the regulatory policy is not enforced and a new, sequentially optimal policy is offered by the regulator. This gives the upstream firm expected utility $\mathbb{E}_h\left[\Pi_u^{ne}\right]$ from high effort and $\mathbb{E}_l\left[\Pi_u^{ne}\right]$ from low effort. Using (S2), we have

$$\begin{aligned}&\alpha\left[\nu_h\gamma_h u\left(\overline{t}^e\right) + \left(1-\nu_h\right)\gamma_h u\left(\underline{t}^e\right)\right] + (1-\alpha)\left[\nu_h\gamma_h u\left(\overline{t}^{ne}\right) + \left(1-\nu_h\right)\gamma_h u\left(\underline{t}^{ne}\right)\right] - \psi \geq \\ &\alpha\left[\nu_l\gamma_l u\left(\overline{t}^e\right) + \left(1-\nu_l\right)\gamma_l u\left(\underline{t}^e\right)\right] + (1-\alpha)\left[\nu_l\gamma_l u\left(\overline{t}^{ne}\right) + \left(1-\nu_l\right)\gamma_l u\left(\underline{t}^{ne}\right)\right].\end{aligned} \tag{S12}$$

Since upstream transfers reduce social welfare in (S4), the limited liability constraints $\underline{t}^e \geq 0$ and $\underline{t}^{ne} \geq 0$ in case of investment failure as well as the moral hazard incentive constraint (S12) are binding in equilibrium. With probability α, the regulatory policy is enforced, and the vertically separated upstream firm obtains $\underline{t}_{vs}^e = 0$ in case of investment failure and

$$\overline{t}_{vs}^e = u^{-1}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h - \nu_l\gamma_l\right)}\right) \tag{S13}$$

in case of investment success. With probability $1-\alpha$, the regulatory policy is not enforced, and the new, sequentially optimal policy yields $\underline{t}_{vs}^{ne} = \overline{t}_{vs}^{ne} = 0$.

The moral hazard incentive constraint under vertical integration is

$$\alpha\mathbb{E}_h\left[\Pi_{vi}^e\right] + (1-\alpha)\,\mathbb{E}_h\left[\Pi_{vi}^{ne}\right] \geq \alpha\mathbb{E}_l\left[\Pi_{vi}^e\right] + (1-\alpha)\,\mathbb{E}_l\left[\Pi_{vi}^{ne}\right].$$

With probability α, the regulatory policy is enforced and the upstream firm receives expected utility $\mathbb{E}_h\left[\Pi_{vi}^e\right]$ from high effort and $\mathbb{E}_l\left[\Pi_{vi}^e\right]$ from low effort. With complementary probability $1-\alpha$, the regulatory policy is not enforced and a new, sequentially optimal policy is offered by the regulator. This gives the vertically integrated firm expected utility $\mathbb{E}_h\left[\Pi_{vi}^{ne}\right]$ from high effort and $\mathbb{E}_l\left[\Pi_{vi}^{ne}\right]$ from low effort. Using (S3), we have

$$\begin{aligned}&\alpha\left[\nu_h\gamma_h u\left(\overline{t}^e+\overline{\pi}\right)+\left(1-\nu_h\right)\gamma_h u\left(\underline{t}^e+\underline{\pi}\right)\right]\\&+\left(1-\alpha\right)\left[\nu_h\gamma_h u\left(\overline{t}^{ne}+\overline{\pi}\right)+\left(1-\nu_h\right)\gamma_h u\left(\underline{t}^{ne}+\underline{\pi}\right)\right]-\psi\geq\\&\alpha\left[\nu_l\gamma_l u\left(\overline{t}^e+\overline{\pi}\right)+\left(1-\nu_l\right)\gamma_l u\left(\underline{t}^e+\underline{\pi}\right)\right]\\&+\left(1-\alpha\right)\left[\nu_l\gamma_l u\left(\overline{t}^{ne}+\overline{\pi}\right)+\left(1-\nu_l\right)\gamma_l u\left(\underline{t}^{ne}+\underline{\pi}\right)\right].\end{aligned}\tag{S14}$$

As under vertical separation, since upstream transfers reduce social welfare in (S4), the limited liability constraints $\underline{t}^e\geq 0$ and $\underline{t}^{ne}\geq 0$ as well as the moral hazard incentive constraint (S14) are binding in equilibrium. With probability α, the regulatory policy is enforced, and the vertically integrated firm obtains $\underline{t}_{vi}^e=0$ in case of investment failure and

$$\overline{t}_{vi}^e=u^{-1}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}+\frac{\left(1-\nu_l\right)\gamma_l-\left(1-\nu_h\right)\gamma_h}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}u\left(\underline{\pi}\right)-\frac{1-\alpha}{\alpha}u\left(\overline{\pi}\right)\right)-\overline{\pi}\tag{S15}$$

in case of investment success. With probability $1-\alpha$, the regulatory policy is not enforced, and the new, sequentially optimal policy yields $\underline{t}_{vi}^{ne}=\overline{t}_{vi}^{ne}=0$.

Taking the derivative of $\mathbb{E}_h\left[t_{vs}^r\right]\equiv\alpha\nu_h\overline{t}_{vs}^e$, where $\overline{t}_{vs}^e$ is given by (S13), with respect to α yields

$$\frac{\partial\mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha}=\nu_h\left[u^{-1}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}\right)-\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}u^{-1\prime}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}\right)\right].$$

It holds $\frac{\partial\mathbb{E}_h[t_{vs}^r]}{\partial\alpha}=0$ under risk neutrality ($u''\left(\cdot\right)=0$). To establish the sign of $\frac{\partial\mathbb{E}_h[t_{vs}^r]}{\partial\alpha}$ under risk aversion ($u''\left(\cdot\right)<0$), we investigate how $\frac{\partial\mathbb{E}_h[t_{vs}^r]}{\partial\alpha}$ varies with ψ. We find that $\left.\frac{\partial\mathbb{E}_h[t_{vs}^r]}{\partial\alpha}\right|_{\psi=0}=0$ and

$$\frac{\partial^2\mathbb{E}_h\left[t_{vs}^r\right]}{\partial\alpha\partial\psi}=-\frac{\nu_h\psi}{\alpha^2\left(\nu_h\gamma_h-\nu_l\gamma_l\right)^2}u^{-1\prime\prime}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}\right)<0,$$

where the inequality follows from $\psi>0$ and $u^{-1\prime\prime}\left(\cdot\right)>0$. This implies that $\frac{\partial\mathbb{E}_h[t_{vs}^r]}{\partial\alpha}<0$.

Taking the derivative of $\mathbb{E}_h\left[t_{vi}^r\right]\equiv\alpha\nu_h\overline{t}_{vi}^e$, where $\overline{t}_{vi}^e$ is given by (S15), with respect to α yields

$$\begin{aligned}\frac{\partial\mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha}=\nu_h\Bigg\{&u^{-1}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}+\frac{\left(1-\nu_l\right)\gamma_l-\left(1-\nu_h\right)\gamma_h}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}u\left(\underline{\pi}\right)-\frac{1-\alpha}{\alpha}u\left(\overline{\pi}\right)\right)\\&-\overline{\pi}-\left[\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}+\frac{\left(1-\nu_l\right)\gamma_l-\left(1-\nu_h\right)\gamma_h}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}u\left(\underline{\pi}\right)-\frac{u\left(\overline{\pi}\right)}{\alpha}\right]\\&\times u^{-1\prime}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}+\frac{\left(1-\nu_l\right)\gamma_l-\left(1-\nu_h\right)\gamma_h}{\alpha\left(\nu_h\gamma_h-\nu_l\gamma_l\right)}u\left(\underline{\pi}\right)-\frac{1-\alpha}{\alpha}u\left(\overline{\pi}\right)\right)\Bigg\}.\end{aligned}$$

It holds $\frac{\partial\mathbb{E}_h[t_{vi}^r]}{\partial\alpha}=0$ under risk neutrality ($u''\left(\cdot\right)=0$). To establish the sign of $\frac{\partial\mathbb{E}_h[t_{vi}^r]}{\partial\alpha}$ under risk aversion ($u''\left(\cdot\right)<0$), we investigate how $\frac{\partial\mathbb{E}_h[t_{vi}^r]}{\partial\alpha}$ varies with ψ. We find that $\left.\frac{\partial\mathbb{E}_h[t_{vi}^r]}{\partial\alpha}\right|_{\psi=\psi_0}=0$

and

$$\frac{\partial^2 \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha\partial\psi} = -\nu_h \frac{\psi + \left[\left(1-\nu_l\right)\gamma_l - \left(1-\nu_h\right)\gamma_h\right] u\left(\underline{\pi}\right) - \left(\nu_h\gamma_h - \nu_l\gamma_l\right) u\left(\overline{\pi}\right)}{\alpha^2\left(\nu_h\gamma_h - \nu_l\gamma_l\right)^2}$$
$$\times u^{-1\prime\prime}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h - \nu_l\gamma_l\right)} + \frac{\left(1-\nu_l\right)\gamma_l - \left(1-\nu_h\right)\gamma_h}{\alpha\left(\nu_h\gamma_h - \nu_l\gamma_l\right)} u\left(\underline{\pi}\right) - \frac{1-\alpha}{\alpha} u\left(\overline{\pi}\right)\right) < 0,$$

where the inequality follows from $\psi > \psi_0$ (by Assumption $1''$) and $u^{-1\prime\prime}\left(\cdot\right) > 0$. This implies that $\frac{\partial \mathbb{E}_h\left[t_{vi}^r\right]}{\partial\alpha} < 0$. ■

In the following remark, we show that, when the vertical industry structure is endogenized, some degree of regulatory risk can be socially beneficial. This corroborates the main results of the paper collected in Proposition 2. Note that Proposition 3 in the paper and the associated proof remain unaltered.

Remark 7 *Suppose $\mathbb{E}_h\left[t_{vs}^c\right] < \Delta\nu\Delta S$ and firm risk aversion ($u''\left(\cdot\right) < 0$). Then, there exists a threshold ψ^*, with $\psi_0 < \psi^* < \psi_1$, such that for $\psi < \psi^*$ some degree of regulatory risk is optimal. The equilibrium probability of regulatory enforcement is $\alpha^* \in (0,1)$, where α^* is the unique value for α such that $\mathbb{E}_h\left[t_{vs}^r\left(\alpha^*\right)\right] = \Delta\nu\Delta S$. Vertical integration emerges, and high investment effort is provided.*

Proof of Remark 7. Using (S2), the vertically separated firms' (expected) aggregate utility $\mathbb{E}_h\left[\Pi_{vs}^r\right] \equiv \alpha\mathbb{E}_h\left[\Pi_{vs}^e\right] + \left(1-\alpha\right)\mathbb{E}_h\left[\Pi_{vs}^{ne}\right]$ from high effort is given by

$$\begin{aligned}
\mathbb{E}_h\left[\Pi_{vs}^r\right] &= \alpha\left\{\nu_h\left[\gamma_h u\left(\overline{t}_{vs}^e\right) + \gamma_h u\left(\overline{\pi}\right)\right] + \left(1-\nu_h\right)\left[\gamma_h u\left(\underline{t}_{vs}^e\right) + \gamma_h u\left(\underline{\pi}\right)\right]\right\} \\
&\quad + \left(1-\alpha\right)\left\{\nu_h\left[\gamma_h u\left(\overline{t}_{vs}^{ne}\right) + \gamma_h u\left(\overline{\pi}\right)\right] + \left(1-\nu_h\right)\left[\gamma_h u\left(\underline{t}_{vs}^{ne}\right) + \gamma_h u\left(\underline{\pi}\right)\right]\right\} - \psi \\
&= \frac{\nu_l\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l}\psi + \nu_h\gamma_h u\left(\overline{\pi}\right) + \left(1-\nu_h\right)\gamma_h u\left(\underline{\pi}\right),
\end{aligned}$$

where $\overline{t}_{vs}^e$ is given by (S13) and $\underline{t}_{vs}^e = \underline{t}_{vs}^{ne} = \overline{t}_{vs}^{ne} = 0$ (see the proof of Remark 6).

The vertically integrated firm's (expected) utility $\mathbb{E}_h\left[\Pi_{vi}^r\right] \equiv \alpha\mathbb{E}_h\left[\Pi_{vi}^e\right] + \left(1-\alpha\right)\mathbb{E}_h\left[\Pi_{vi}^{ne}\right]$ from high effort is given by

$$\begin{aligned}
\mathbb{E}_h\left[\Pi_{vi}^r\right] &= \alpha\left[\nu_h\gamma_h u\left(\overline{t}_{vi}^e + \overline{\pi}\right) + \left(1-\nu_h\right)\gamma_h u\left(\underline{t}_{vi}^e + \underline{\pi}\right)\right] \\
&\quad + \left(1-\alpha\right)\left[\nu_h\gamma_h u\left(\overline{t}_{vi}^{ne} + \overline{\pi}\right) + \left(1-\nu_h\right)\gamma_h u\left(\underline{t}_{vi}^{ne} + \underline{\pi}\right)\right] - \psi \\
&= \frac{\nu_l\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l}\psi + \frac{\Delta\nu\gamma_h\gamma_l}{\nu_h\gamma_h - \nu_l\gamma_l} u\left(\underline{\pi}\right),
\end{aligned}$$

where $\overline{t}_{vi}^e$ is given by (S15) and $\underline{t}_{vi}^e = \underline{t}_{vi}^{ne} = \overline{t}_{vi}^{ne} = 0$ (see the proof of Remark 6).

Using $\mathbb{E}_h\left[t_{vs}^r\left(\alpha\right)\right] \equiv \alpha\nu_h\overline{t}_{vs}^e$, where $\overline{t}_{vs}^e$ is given by (S13), and applying L'Hospital's rule yields

$$\lim_{\alpha\to 0} \mathbb{E}_h\left[t_{vs}^r\left(\alpha\right)\right] = \lim_{\alpha\to 0} \frac{\nu_h\psi}{\nu_h\gamma_h - \nu_l\gamma_l} u^{-1\prime}\left(\frac{\psi}{\alpha\left(\nu_h\gamma_h - \nu_l\gamma_l\right)}\right) = +\infty,$$

where the inequality follows from $\psi > 0$, $u^{-1\prime}\left(\cdot\right) > 0$, and $u^{-1\prime\prime}\left(\cdot\right) > 0$.

Using $\mathbb{E}_h\left[t_{vi}^r\left(\alpha\right)\right] \equiv \alpha\nu_h\overline{t}_{vi}^e$, where $\overline{t}_{vi}^e$ is given by (S15), and applying L'Hospital's rule yields after some manipulation

$$\lim_{\alpha\to0}\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]=\lim_{\alpha\to0}\nu_h\left[\frac{\psi}{\nu_h\gamma_h-\nu_l\gamma_l}+\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})-u(\overline{\pi})\right]$$
$$\times u^{-1\prime}\left(\frac{\psi}{\alpha(\nu_h\gamma_h-\nu_l\gamma_l)}+\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\alpha(\nu_h\gamma_h-\nu_l\gamma_l)}u(\underline{\pi})-\frac{1-\alpha}{\alpha}u(\overline{\pi})\right)=+\infty,$$

where the inequality follows from $\psi>\psi_0$ (by Assumption 1″), $u^{-1\prime}(\cdot)>0$, and $u^{-1\prime\prime}(\cdot)>0$. The rest of the proof goes along the same lines as the proof of Proposition 2 in the paper.

Finally, we show that there exists a threshold ψ^* for the cost of effort ψ, with $\psi_0<\psi^*<\psi_1$, such $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]<\mathbb{E}_h\left[t_{vs}^c\right]$ if and only if $\psi<\psi^*$. As $\mathbb{E}_h\left[t_{vi}^r(\alpha)\right]\equiv\alpha\nu_h\overline{t}_{vi}^e$ and $\mathbb{E}_h\left[t_{vs}^c\right]\equiv\nu_h\overline{t}_{vs}^c$ (see the proofs of Remarks 4 and 6), we find that $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0}=0<\mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0}=\nu_h u^{-1}\left(u(\overline{\pi})-\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})\right)$, where ψ_0 is defined in Remark 3. Moreover, taking the derivative of $\mathbb{E}_h\left[t_{vs}^c\right]$ with respect to ψ and evaluating it at $\psi=\psi_0$ yields

$$\left.\frac{\partial\mathbb{E}_h\left[t_{vs}^c\right]}{\partial\psi}\right|_{\psi=\psi_0}=\frac{\nu_h}{\nu_h\gamma_h-\nu_l\gamma_l}u^{-1\prime}\left(u(\overline{\pi})-\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})\right).\tag{S16}$$

Taking the derivative of $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]$ with respect to ψ yields after some manipulation

$$\frac{\partial\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial\psi}=\left[u^{-1}\left(\frac{\psi}{\alpha^*(\nu_h\gamma_h-\nu_l\gamma_l)}+\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\alpha^*(\nu_h\gamma_h-\nu_l\gamma_l)}u(\underline{\pi})-\frac{1-\alpha^*}{\alpha^*}u(\overline{\pi})\right)-\overline{\pi}\right]$$
$$\times\nu_h\frac{\partial\alpha^*}{\partial\psi}+\frac{\alpha^*-\frac{\partial\alpha^*}{\partial\psi}\left\{\psi+\left[(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h\right]u(\underline{\pi})-(\nu_h\gamma_h-\nu_l\gamma_l)u(\overline{\pi})\right\}}{\alpha^*(\nu_h\gamma_h-\nu_l\gamma_l)}$$
$$\times\nu_h u^{-1\prime}\left(\frac{\psi}{\alpha^*(\nu_h\gamma_h-\nu_l\gamma_l)}+\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\alpha^*(\nu_h\gamma_h-\nu_l\gamma_l)}u(\underline{\pi})-\frac{1-\alpha^*}{\alpha^*}u(\overline{\pi})\right).$$

Evaluating this expression at $\psi=\psi_0$, we obtain

$$\left.\frac{\partial\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial\psi}\right|_{\psi=\psi_0}=\frac{\nu_h}{\nu_h\gamma_h-\nu_l\gamma_l}u^{-1\prime}\left(u(\overline{\pi})\right).\tag{S17}$$

Recalling $\mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0}=\nu_h u^{-1}\left(u(\overline{\pi})-\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})\right)$ and $\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0}=0$ and using (S16) and (S17), a first-order Taylor approximation yields

$$\mathbb{E}_h\left[t_{vs}^c\right]\approx\mathbb{E}_h\left[t_{vs}^c\right]|_{\psi=\psi_0}+(\psi-\psi_0)\left.\frac{\partial\mathbb{E}_h\left[t_{vs}^c\right]}{\partial\psi}\right|_{\psi=\psi_0}$$
$$=\nu_h u^{-1}\left(u(\overline{\pi})-\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})\right)$$
$$+\frac{\nu_h}{\nu_h\gamma_h-\nu_l\gamma_l}(\psi-\psi_0)u^{-1\prime}\left(u(\overline{\pi})-\frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u(\underline{\pi})\right)$$

and

$$\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]\approx\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]|_{\psi=\psi_0}+(\psi-\psi_0)\left.\frac{\partial\mathbb{E}_h\left[t_{vi}^r(\alpha^*)\right]}{\partial\psi}\right|_{\psi=\psi_0}$$
$$=\frac{\nu_h}{\nu_h\gamma_h-\nu_l\gamma_l}(\psi-\psi_0)u^{-1\prime}\left(u(\overline{\pi})\right).$$

It holds $\mathbb{E}_h\left[t^r_{vi}\left(\alpha^*\right)\right] < \mathbb{E}_h\left[t^c_{vs}\right]$ if and only if

$$\psi < \psi^* \equiv \psi_0 + \left(\nu_h\gamma_h - \nu_l\gamma_l\right)\frac{u^{-1}\left(u\left(\overline{\pi}\right) - \frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u\left(\underline{\pi}\right)\right)}{u^{-1\prime}\left(u\left(\overline{\pi}\right)\right) - u^{-1\prime}\left(u\left(\overline{\pi}\right) - \frac{(1-\nu_l)\gamma_l-(1-\nu_h)\gamma_h}{\nu_h\gamma_h-\nu_l\gamma_l}u\left(\underline{\pi}\right)\right)},$$

where $\psi^* > \psi_0$ follows from the assumptions on the parameters of the model. We find from Remark 4 that $\mathbb{E}_h\left[t^c_{vi}\right] < \mathbb{E}_h\left[t^r_{vi}\left(\alpha^*\right)\right] < \mathbb{E}_h\left[t^c_{vs}\right]$ implies $\psi^* < \psi_1$. ■

References

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