To spy or not to (fire the) spy: The benefits of acquiring information about rivals' play in Bertrand competition*

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September 23, 2016

Abstract

The present paper explores the impact of planting a spy in a competing firm who discloses operational information about pricing in a Bertrand market game with differentiated products under incomplete information. The results depend upon whether the presence of the spy is common knowledge and whether the identity of the spy has been disclosed. Altogether, spying may benefit both the spying and the spied at firm. Although the spied at firm would prefer not to be spied at if its cost is low, firing the spy, which is an option if the spy's identity has been disclosed, adversely affects beliefs and is never profitable.

KEYWORDS: Industrial espionage, price leadership, collusion, antitrust policy, incomplete information.
JEL CLASSIFICATIONS: L41, D43, D82

1 Introduction

Economic espionage is a common and widely despised activity by governments and firms. Its most common form concerns the illicit appropriation of essential inputs or technology. Prominent historical examples range from stealing the blueprints of the British Cartwright power loom by the American industrialist Francis Cabot Lowell to the smuggling of tea's secrets - plants, seeds, and fermentation techniques - by the Scottish botanist Robert Fortune, which spurred one of the greatest episodes of early globalization, orchestrated by the British East India Company, and the downfall of China's tea monopoly.[1]

Another form of economic espionage - which is the focus of the present paper - concerns the disclosing of operational information about pricing or sales by a mole that has been placed in the rival company.[2] While spying on technology hurts the spied at firm or nation, the disclosure of

*Research support by Korea University (Grant: K1613601) and the National Natural Science Foundation of China (Grant: 71371116) is gratefully acknowledged.

[1]Ben-Atar (2004) offers an inspiring review of the role of economic espionage in the development of the U.S. economy during the 18th and early 19th century. A vivid account of the tea smuggling out of China into British-ruled India is in Rose (2011).

[2]For a detailed review of the different kinds of economic espionage see Nasheri (2005).

operational information may benefit both the company that employs the spy as well as the one that is spied at.

In the present paper we analyze the impact of spying in a Bertrand market game with differentiated products that are substitutes. We first consider a game of complete information assuming the spied at firm is either not aware or aware of the fact that it is spied at. If the spied at firm is unaware, spying has no effect unless firms are not experienced game players; but, if the spied at firm is aware, spying induces a sequential game that benefits both firms, albeit it benefits the spying firm more.

The analysis becomes more complex when firms have private information concerning their unit cost. Then, spying incurs further benefits to the spying firm, whereas the spied at firm benefits from having its private information disclosed if its cost is high and is hurt if its cost is low. This is due to the fact that a high (low) cost is associated with a high (low) price which, when revealed by the spy, induces the rival to respond with a high (low) price. It suggests that if the firm happens to know the identity of the spy, it may wish to fire the spy in the event when its cost is low. However, firing the spy signals information about its cost and induces updating of beliefs to such an extent that unraveling occurs and it never pays to fire the spy.

Throughout our analysis we assume general demand functions that are super-modular in the price vector. In this regard our analysis corresponds to the literature on super-modular oligopoly games and the analysis of second-mover advantages in games in which prices are strategic complements (see, for example, Gal-Or, 1985; Dowrick, 1986; Amir and Stepanova, 2006). While this literature considered games of complete information, in our analysis incomplete information is an essential ingredient.

The plan of the paper is as follows: In *Section 2* we state the model. In *Section 3* we analyze spying in a game of complete information, assuming the spied at firm is either aware or not aware of the presence of the spy. In *Section 4* we introduce incomplete information about firms' unit costs and disentangle the impact of spying by comparing with a hypothetical game in which the spied at firm's private information is revealed but no sequential game is induced. In *Section 5* we explore what happens if the spied at firm happens to know the identity of the spy so that it could fire the spy. We show that, due to the adverse effects of the induced updating of beliefs, firing the spy is never profitable. In *Section 6* we mention antitrust implications and outline some issues for further research.

2 Model

Consider a duopoly with firms 1 and 2 that play a Bertrand market game with differentiated products that are substitutes. Firms have constant unit costs, x_i, that are their private information.

One of the firms, firm 2, has a spy who reports the unit price chosen by firm 1, p_1, before firm 2 chooses its own unit price, p_2. The firm 1 that is spied at is either not aware of the presence of the spy or it is aware and this fact is common knowledge.

Firms' demand functions $Q_i(p_i, p_j)$ are twice continuously differentiable with $\partial_{p_i} Q_i(p_i, p_j) < 0$, $\partial_{p_j} Q_i(p_i, p_j) > 0$, $\partial_{p_i p_j} Q_i(p_i, p_j) \geq 0$, and (for convenience) $\partial_{p_i p_i} Q_i(p_i, p_j) \leq 0$.[3] These properties assure that firms' profit functions, $\pi_i(p_i, p_j, x_i) := (p_i - x_i) Q_i(p_i, p_j)$, are strictly supermodular in the price vector (see, for example, Vives, 2005). By a well-known result due to Topkis (1978), this implies that firms' best reply functions are non-decreasing.[4]

[3] Throughout this paper we write $\partial_x f(x,y)$ for $\partial f(x,y)/\partial x$ and $\partial_{xy} f(x,y)$ for $\partial^2 f(x,y)/\partial x \partial y$.

[4] For convenience we assume that best replies are unique.

Firms' unit costs are *i.i.d.* random variables, drawn from the continuous probability distribution, $F(x)$, with support $[d,c]$, $0 \le d < c$ and with $\bar{x} := E(X)$. The parameters are such that no firm is ever crowded out of the market as firms play a duopoly game.

Our analysis does not assume particular functional forms of demand and probability distribution functions. However, we illustrate some results with an example that assumes linear demand functions: $Q_i(p_i, p_j) := 1 - p_i + sp_j$, with $0 < s < 1$, and $c < 1$, and at some point with some non-linear demand functions.

3 Complete information

As a benchmark suppose both firms have the same unit cost, x, and this fact is common knowledge.

3.1 Firm 1 is not aware of the spy

If firm 1 is not aware of the presence of the spy, the spy can only reduce firm 2's strategic uncertainty. If firms are experienced game players, the spy has no effect.

3.2 Firm 1 is aware of the spy

However, if it is common knowledge that firm 2 has placed a spy in firm 1, the presence of the spy changes the game from a simultaneous to a sequential moves game and makes firm 1 the Stackelberg leader and firm 2 the Stackelberg follower. As is well-known, in a symmetric Bertrand game with substitutes both players are better off than in the simultaneous moves game, yet the Stackelberg follower is even better off than the Stackelberg leader. Therefore:

Proposition 1. *Suppose the presence of the spy is common knowledge and firms have complete information about each others' cost. Both firms benefit from the presence of the spy, although the spying firm 2 benefits more:*

$$\Pi_2^A > \Pi_1^A > \Pi. \tag{1}$$

A proof of the payoff ranking across Stackelberg players and the corresponding simultaneous moves game is in Gal-Or (1985) and Dowrick (1986).[5]

Somewhat paradoxically, the commonly known presence of the spy makes both firms better off, although the firm that has the spy benefits more. The presence of the spy can be viewed as a quasi-collusive scheme because it supports higher equilibrium prices.

4 Incomplete Information

Now suppose each firm has private information concerning its cost. Without the spy, the game is a simultaneous moves game with incomplete information on both sides. When the spy reports the price chosen by firm 1 to firm 2, the uncertainty of firm 2 is removed.

As a benchmark we first solve the simultaneous moves game to which we refer as game G^*. The symmetric Bayesian equilibrium strategies of that game, $p_i^*(x_i) = p^*(x_i), i \in \{1,2\}$, solve the requirements:

$$p^*(x_i) = \arg\max_p (p - x_i) \int_d^c Q_i(p, p^*(x_j)) dF(x_j). \tag{2}$$

[5] As an aside, we mention that if the game is asymmetric and one firm has substantially lower unit cost, that firm has a first-mover advantage. In general, at least one firm has a second-mover advantage but it is not always the case that both firms have a second-mover advantage (see Amir and Stepanova, 2006).

Existence of a monotone equilibrium strategy is assured by the fact that profit functions are strictly supermodular in the price vector and in (p_i, x_i) (see Van Zandt and Vives, 2007, p. 344).

In the case of linear demand the equilibrium prices and expected profits, $\Pi_i^*(x_i)$, are:

$$p_i^*(x_i) = \frac{2+\bar{x}s}{2(2-s)} + \frac{1}{2}x_i \tag{3}$$

$$\Pi_i^*(x_i) := (p^*(x_i) - x_i) \int_d^c Q_i(p^*(x_i), p^*(x_j)) dF(x_j) = (p^*(x_i) - x_i)^2. \tag{4}$$

4.1 Firm 1 is not aware of the spy

Now suppose firm 2 has a spy in firm 1 but firm 1 is not aware of his presence. We refer to the resulting game as game G^N (where N is mnemonic for "not aware"). There, the equilibrium strategy of firm 1 is the same as in the simultaneous moves game, $p_1^N(x_1) = p_1^*(x_1)$, whereas firm 2 observes p_1 and plays its best reply:

$$p_2^N(x_2, p_1) = \arg\max_p (p - x_2) Q_2(p, p_1). \tag{5}$$

The function p_2^N is increasing in x_2 and in p_1.

Proposition 2. *Suppose firm 1 is not aware of the presence of the spy. The firm 2 that uses the spy benefits from spying; the firm that is spied at benefits if its cost is high and is worse off if its cost is low.*

Proof. The proof of the assertion concerning $\Pi_2^N(x_2)$ follows from the fact that more information is better if the rival player is not aware. To prove the assertion concerning $\Pi_1^N(x_1)$, note that, by the fact that $p_2^N(x_2, p_1^*(d)) < p_2^*(x_2) < p_2^N(x_2, p_1^*(c))$, for each x_2:

$$\Pi_1^N(c) - \Pi_1^*(c) = (p_1^*(c) - c) \int_d^c \left(Q_1(p_1^*(c), p_2^N(x_2, p_1^*(c))) - Q_1(p_1^*(c), p_2^*(x_2))\right) dF(x_2) > 0$$

$$\Pi_1^N(d) - \Pi_1^*(d) = (p_1^*(d) - d) \int_d^c \left(Q_1(p_1^*(d), p_2^N(x_2, p_1^*(d))) - Q_1\left(p_1^*(d), p_2^*(x_2)\right)\right) dF(x_2) < 0.$$

Therefore, that payoff difference is negative for low values and positive for high values of x_1. □

In the case of linear demand one finds:[6]

$$p_1^N(x_1) = p_1^*(x_1), \quad p_2^N(x_2, p_1) = \frac{1}{2}(1 + sp_1 + x_2) \tag{6}$$

$$\Pi_2^N(x_2) - \Pi_2^*(x_2) = \frac{Var(X)s^2}{16} > 0 \tag{7}$$

$$\Pi_1^N(x_1) - \Pi_1^*(x_1) = \frac{s^2(x_1 - \bar{x})(2 + \bar{x}s - (2-s)x_1)}{8(2-s)} \gtreqless 0 \iff x_1 \gtreqless \bar{x}. \tag{8}$$

Altogether, spying completely removes the uncertainty of firm 2 about firm 1. This unambiguously benefits firm 2 and that benefit is an increasing function of the variance of the rival's cost.

More surprisingly, the presence of the spy is also beneficial to the firm that is spied at whenever its cost is sufficiently high. This is due to the fact that, if the cost of firm 1 is high, it is driven to set a high price; by informing the rival about its weakness, it induces the rival to also set a high price, which increases the profit of firm 1. The opposite holds true if the cost of firm 1 is sufficiently low; in that case, firm 1 would be better off if the uncertainty of firm 1 were preserved.

[6] Here and elsewhere we use the fact that $E(X^2) \equiv E(X)^2 + Var(X)$).

4.2 The presence of the spy is common knowledge

Now suppose the presence of the spy is common knowledge, although the identity of the spy has not been exposed. We refer to the resulting game as game G^A (where A is mnemonic for "aware"). There, the equilibrium strategies solve the requirements:

$$\begin{aligned} p_2^A(x_2, p_1) &= \arg\max_p (p - x_2)\, Q_2(p, p_1) = p_2^N(x_2, p_1) \\ p_1^A(x_1) &= \arg\max_p (p - x_1) \int_d^c Q_1(p, p_2^A(x_2, p))dF(x_2), \end{aligned}$$

and the equilibrium expected payoffs are:

$$\begin{aligned} \Pi_1^A(x_1) &:= \left(p_1^A(x_1) - x_1\right) \int_d^c Q_1(p_1^A(x_1), p_2^A(x_2, p_1^A(x_1)))dF(x_2) \\ \Pi_2^A(x_2) &:= \int_d^c \left(p_2^A(x_2, p_1^A(x_1)) - x_2\right) Q_2(p_2^A(x_2, p_1^A(x_1)), p_1^A(x_1))dF(x_1). \end{aligned}$$

Compared to the previous game, firm 1 is now able to correctly predict the rival's play which makes it obviously better off. However, it is not clear how this affects firm 2, because it may or may not be advantageous to firm 2 that its rival can correctly predict firm 2's strategy.

Compared to the benchmark game under two-sided uncertainty, there are two effects: 1) firm 2 becomes second mover in a sequential game (strategic effect), and 2) it becomes common knowledge that firm 2 is no longer subject to uncertainty about its rival's cost.

In order to disentangle these two effects, we consider a hypothetical simultaneous moves game, to which we refer as game G^a, where it is common knowledge that firm 2 knows its rival's cost. Therefore, when one compares the equilibrium payoffs of game G^A with that of game G^a, one captures exclusively the effect of moving from a simultaneous moves game to the sequential game.

The equilibrium solution of the game G^a must solve the requirements:

$$\begin{aligned} p_1^a(x_1) &= \arg\max_p (p - x_1) \int_d^c Q_1(p, p_2^a(x_2, x_1))dF(x_2) \\ p_2^a(x_2, x_1) &= \arg\max_p (p - x_2)\, Q_2(p, p_1^a(x_1)), \end{aligned}$$

and the *interim* and *ex ante* equilibrium expected payoffs are:

$$\begin{aligned} \tilde{\Pi}_2^a(x_2, x_1) &:= (p_2^a(x_2, x_1) - x_2) Q_2(p_2^a(x_2, x_1), p_1^a(x_1)) \\ \Pi_2^a(x_2) &:= \int_d^c \tilde{\Pi}_2^a(x_2, x_1)dF(x_1) \\ \Pi_1^a(x_1) &:= (p_1^a(x_1) - x_1) \int_d^c Q_1(p_1^a(x_1), p_2^a(x_2, x_1))dF(x_2). \end{aligned}$$

The following result extends the result on the second-mover advantage in Proposition 1 to incomplete information.

Proposition 3. *In equilibrium both firms are better off in game G^A than in G^a:*

$$\Pi_1^A(x_1) \geq \Pi_1^a(x_1), \quad \Pi_2^A(x_2) \geq \Pi_2^a(x_2). \tag{9}$$

Proof. By an argument similar to Amir and Stepanova (2006, p.14) one has:

$$\begin{aligned}\Pi_1^A(x_1) &= (p_1^A(x_1)-x_1)\int_d^c Q_1\left(p_1^A(x_1),p_2^A(x_2,p_1^A(x_1))\right)dF(x_2)\\ &\geq (p_1^a(x_1)-x_1)\int_d^c Q_1\left(p_1^a(x_1),p_2^a(x_2,x_1)\right)dF(x_2)=\Pi_1^a(x_1)\\ &\geq (p_1^A(x_1)-x_1)\int_d^c Q_1(p_1^A(x_1),p_2^a(x_2,x_1))dF(x_2).\end{aligned}$$

There, the first inequality follows from $p_2^a(x_2,x_1)=p_2^A(x_2,p_1^a(x_1))$ and the definition of p_1^A; the second inequality holds because (p_1^a,p_2^a) is a Bayesian Nash equilibrium. Therefore,

$$\int_d^c Q_1\left(p_1^A(x_1),p_2^A(x_2,p_1^A(x_1))\right)dF(x_2)\geq\int_d^c Q_1\left(p_1^A(x_1),p_2^a(x_2,x_1)\right)dF(x_2),$$

which implies $p_1^A(x_1)\geq p_1^a(x_1)$ (because otherwise $p_2^A(x_2,p_1^A(x_1))<p_2^A(x_2,p_1^a(x_1))=p_2^a(x_2,x_1)$). This, in turn, implies $\Pi_2^A(x_2)\geq\Pi_2^a(x_2)$. □

A priori it is not clear whether firm 2 benefits from having procured the services of a spy. Although firm 2 benefits from observing the rival's price, p_1, it may however be hurt by the fact that firm 1 knows about this and adjusts its price strategy downward in the event if its cost is low and upward if that cost is high. However, the following condition assures that, altogether, firm 2 benefits even if the presence of the spy is common knowledge.

Proposition 4. *In equilibrium, the firm that employs the spy benefits:* $\Pi_2^A(x_2)>\Pi_2^*(x_2)$, *if its interim equilibrium expected payoff function satisfies the conditions:*
(i) $\tilde{\Pi}_2^a(x_2,x_1)$ *is convex in* x_1 *for all* x_2, *and*
(ii) $\tilde{\Pi}_2^a(x_2,\bar{x})\geq\Pi_2^*(x_2)$, *for all* x_2.

Proof. The convexity assumption implies that in the game G^a firm 2 benefits from uncertainty concerning x_1. Combining the two conditions gives:

$$\Pi_2^a(x_2):=E_{X_1}\left(\tilde{\Pi}_2^a(x_2,X_1)\right)\geq\tilde{\Pi}_2^a(x_2,\bar{x})\geq\Pi_2^*(x_2). \tag{10}$$

Using the fact that $\Pi_2^A(x_2)>\Pi_2^a(x_2)$ (by Proposition 3) we conclude:

$$\Pi_2^A(x_2)-\Pi_2^*(x_2)\equiv\Pi_2^A(x_2)-\Pi_2^a(x_2)+\Pi_2^a(x_2)-\Pi_2^*(x_2)>0. \tag{11}$$

□

The conditions stated in Proposition 4 are satisfied if demand is linear. In the Appendix we also provide an example of non-linear demand functions that satisfy these conditions.

In the case of linear demand we find specifically:

$$\begin{aligned}\Pi_2^A(x_2)-\Pi_2^*(x_2) &= \frac{s^3(1-(1-s)\bar{x})\left(8(2-s^2)(1-x_2)+8s(x_2+\bar{x})+s^3(1-4x_2-5\bar{x})+s^4\bar{x}\right)}{16(2-s)^2\left(2-s^2\right)^2}\\ &\quad+\frac{s^2 Var(X)}{16}>0\\ \Pi_1^A(x_1)-\Pi_1^*(x_1) &= \frac{s^2\left(2(1-(1-s)\bar{x})^2-\left(2-s^2\right)\left((2-s)x_1-\bar{x}-1\right)^2\right)}{8(2-s)^2\left(2-s^2\right)}.\end{aligned}$$

In that case, the overall effect of spying on firm 1, $\Delta(x_1) := \Pi_1^A(x_1) - \Pi_1^*(x_1)$, is a quadratic, concave function of x_1 which is positive at $x_1 = c$. If $\Delta(d) > 0$, $\Delta(x_1)$ is positive everywhere. If $\Delta(d) < 0$, there exists a unique $\hat{x} \in (d,c)$ at which $\Delta(\hat{x}) = 0$. Therefore, $\Delta(x_1) \gtreqless 0 \iff x_1 \gtreqless \hat{x}$. Because $\Delta(\bar{x})$ is positive, it follows that $\hat{x} < \bar{x}$.

5 What if the spy has been exposed?

So far we assumed that the spy is never exposed. Now we explore what happens if the spy has been exposed. In that case, firm 1 may be tempted to fire the spy if its cost level is low. We refer to the resulting game as game G^f (where f is mnemonic for "fire"). However, if firm 1 fires the spy, it thus reveals information about its cost, which in turn induces firm 2 to adjust its price. Taking this signaling effect into account, it turns out that it never pays to fire the spy at any level of x_1.

Proposition 5. *Suppose spying is common knowledge and the spy has been exposed. There is no equilibrium in which firm 1 will ever fire the spy.*

Proof. Suppose, *per absurdum*, that there is an equilibrium in which firm 1 fires the spy with positive probability. Then firing must occur in some measurable set $M \subseteq [d,c]$. Let $m = \sup M$. We may assume that $m \in M$ (otherwise one can consider an element in M arbitrarily close to m).

If firm 1 fires the spy at $x_1 = m$, firm 2 learns that $x_1 \in M$. In that case, the equilibrium strategies, denoted by $(p_1^f(x_1), p_2^f(x_2))$, of the subsequent Bertrand game solve the conditions:

$$p_1^f(x_1) = \arg\max_p \int_d^c Q_1(p, p_2^f(x_2))(p - x_1)dF(x_2)$$
$$p_2^f(x_2) = \arg\max_p \int_M Q_2(p, p_1^f(x_1))(p - x_2)dF_M(x_1),$$

where F_M is the conditional distribution of F on M.

If firm 1 does not fire the spy at $x_1 = m$ and sets the price it would choose in the Bayesian game after firing the spy, i.e., $p = p_1^f(m)$, firm 2 optimally responds with the price $p_2 = p_2^A(x_2, p_1^f(m))$ which satisfies:

$$\begin{aligned} p_2^A(x_2, p_1^f(m)) &= \arg\max_p (p - x_2)Q_2(p, p_1^f(m)) \\ &= \arg\max_p \int_M Q_2(p, p_1^f(m))(p - x_2)dF_M(x_1). \end{aligned}$$

By the strict supermodularity of the profit function (which is preserved under integration) and the fact that $p_1^f(x_1)$ is increasing we have $p_2^A(x_2, p_1^f(m)) > p_2^f(x_2)$ for each x_2. Therefore, firm 1 is better off if it does not fire the spy at $x_1 = m$ (or near m), contradicting the existence of such an equilibrium. □

Essentially, if firm 1 fires the spy if its cost is in set $M \subseteq [d,c]$, when firm 2 observes that the spy has been fired, it updates its beliefs and adjusts its price in such a way that the high cost types in set M would always like to reveal their types by not firing the spy. After successive application of this reasoning, complete unraveling occurs.

6 Discussion

The results of the present paper indicate that spying may serve as a quasi-collusive scheme that supports high prices. This suggests that antitrust authorities should keep an eye on spying activities and perhaps probe them as potential antitrust violations.

Our analysis assumes that firms compete in a Bertrand market game. If Bertrand is replaced by Cournot competition it is well-known that, the first-mover is better off than the second-mover who in turn is worse off than in the corresponding simultaneous moves game (see, for example, Gal-Or, 1985; Dowrick, 1986; Amir and Grilo, 1999). In that case it is only the spied at firm that benefits from the presence of a spy.

In our analysis the firm that engages a spy is given exogenously. This is appropriate insofar as spies are engaged more or less at random when an opportunity to build a relationship with a potential spy pops up. However, in the framework of an asymmetric model one may also explain endogenously which firm is likely to be more proactive procuring the services of a spy. There, the firm that has a significant cost advantage prefers to be the first-mover whereas the other firm prefers to be second-mover. This suggests that the firm with the higher cost engages a spy while the firm with the cost advantage is content to be spied at.[7] It remains to be seen whether one can extend this to incomplete information, when firms' unit costs are drawn from different probability distributions that satisfy a sufficiently strong stochastic order.

A Appendix

Here we show that the conditions stated in Proposition 4 are satisfied for the demand functions $Q_i(p_i, p_j) = 1 - p_i + s p_j + \alpha p_i p_j$ with $\alpha \geq 0$ (which includes linear demand as a special case).

Assuming these demand functions we find the following equilibrium prices of the games G^* and G^a:

$$p^*(x_i) = \frac{\gamma(\bar{x}) - \sqrt{\gamma(\bar{x})^2 - 4\alpha(s\bar{x}+2)}}{4\alpha} + \frac{x_i}{2} \tag{A.1}$$

$$p_1^a(x_1) = \frac{1}{4\alpha}\left(\gamma(x_1) - \sqrt{\gamma(x_1)^2 - 8(\alpha+s)\frac{\lambda(x_1)}{\lambda(\bar{x})} + 4s(2-\alpha x_1)}\right) + \frac{x_1}{2} \tag{A.2}$$

$$p_2^a(x_2, x_1) = \frac{1}{4\alpha}\left(\gamma(\bar{x}) - \sqrt{\gamma(\bar{x})^2 - 8(\alpha+s)\frac{\lambda(\bar{x})}{\lambda(x_1)} + 4s(2-\alpha\bar{x})}\right) + \frac{x_2}{2} \tag{A.3}$$

$$\partial_{x_1 x_1} p_1^a(x_1) = \frac{4\alpha(\alpha+s)^2\lambda(\bar{x})}{\Big(\lambda(x_1)\lambda(\bar{x})\big(\lambda(x_1)\lambda(\bar{x}) - 8(\alpha+s)\big)\Big)^{3/2}} \tag{A.4}$$

where $\gamma(x) := 2 - s - \alpha x$, $\lambda(x) := 2 + s - \alpha x$.

Using l'Hôpital's rule one can confirm that, as α goes to zero, one obtains the solutions of p^* and p_1^a, p_2^a that apply in the case of linear demand.

For $\alpha > 0$ the above solutions apply only if α is bounded from above. In order to assure existence of a solution of $p^*(x_i)$ we require that:

$$\alpha < \bar{\alpha} := \frac{1}{c^2}\left(4 + 2c + cs - \sqrt{8\,(2 + 2c + cs + c^2 s)}\right) > 0. \tag{A.5}$$

This parameter restriction also assures that $\partial_{x_1 x_1} p_1^a(x_1) > 0$ for all x_1. Further upper-bound restrictions apply to assure existence of p_1^a, p_2^a.

[7] There is a somewhat related literature on the endogenous timing in oligopoly games in which equilibrium refinements such as risk dominance play a key role (see, for example, Hamilton and Slutsky, 1990; van Damme and Hurkens, 1996; van Damme and Hurkens, 2004).

Assuming that α is sufficiently small to assure that these upper-bound restrictions are satisfied, we find that $\tilde{\Pi}_2^a(x_2,\bar{x}) = \Pi_2^*(x_2)$, for all x_2 which confirms condition (ii) in Proposition 4.

By the envelope property, the total derivative of the *interim* equilibrium expected payoff function $\tilde{\Pi}_2^a$ with respect to x_1 is:

$$\frac{d}{dx_1}\tilde{\Pi}_2^a = (p_2^a - x_2)\,\partial_{p_1} Q_2 \cdot \partial_{x_1} p_1^a. \tag{A.6}$$

Therefore, $\tilde{\Pi}_2^a$ is convex in x_1 if

$$\begin{aligned} 0 < \frac{d^2}{(dx_1)^2}\tilde{\Pi}_2^a = {} & \partial_{x_1} p_2^a \cdot \partial_{p_1} Q_2 \cdot \partial_{x_1} p_1^a \\ & + (p_2^a - x_2)\left(\partial_{p_1 p_1} Q_2 \cdot \partial_{x_1} p_1^a + \partial_{p_1 p_2} Q_2 \cdot \partial_{x_1} p_2^a\right)\partial_{x_1} p_1^a \\ & + (p_2^a - x_2)\,\partial_{p_1} Q_2 \cdot \partial_{x_1 x_1} p_1^a. \end{aligned} \tag{A.7}$$

Given the properties of the assumed demand functions and the solutions of p_1^a, p_2^a, all terms in the first and second lines of (A.7) are positive, and the third line is positive if $\partial_{x_1 x_1} p_1^a \geq 0$, which holds true because the parameter restriction (A.5) implies $\partial_{x_1 x_1} p_1^a \geq 0$. Therefore, the interim equilibrium expected payoff functions is convex in x_1 for all x_2, as asserted.

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