Price commitment vs. flexibility: The role of exchange rate uncertainty and its implications for exchange rate pass-through

Byoung-Ky Chang and Harvey E. Lapan*

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Abstract

This paper investigates the incentives to commit price or retain price flexibility in a model in which exporting firms face different degrees of exchange rate uncertainty. The result shows that introducing exchange rate uncertainty can lead to the endogenous emergence of an unique leader-follower equilibrium; which firm emerges as price leader depends on the substitutability of products, the magnitude of exchange rate uncertainty and the cost structure. Our study may provide one explanation as to why some exporters set price before the realization of the nominal exchange rates ("sticky price"). The results imply exchange rate variability affects exchange rate pass-through.

* Chang: Division Director, International Economic Analysis, SK Securities, Co., Ltd., Seoul, Korea. E-mail: bkchang99@hanmail.net. Lapan: Department of Economics, 283 Heady Hall, Iowa State University, Ames, IA, 50011. Tel: (515) 294-5917; Fax: (515) 294-0221; e-mail: hlapan@iastate.edu.

Address of Corresponding author: Harvey Lapan Department of Economics, 283 Heady Hall, Iowa State University, Ames, IA, 50011. Tel: (515) 294-5917; Fax: (515) 294-0221; e-mail: hlapan@iastate.edu.

I. Introduction

The magnitude of exchange rate pass through is an important issue in the international macroeconomics literature. In this paper we examine a partial equilibrium model of endogenous price-setting behavior which may shed some light on this topic. In general, if duopoly firms have upward-sloping (downward-sloping) reaction functions, each firm will prefer to be a follower (a leader); thus, in a price game, each firm prefers that the other firm is a price leader while it behaves as a price follower. It is well known that in this price game there exist two Nash-equilibria (leader, follower; follower, leader). However, which firm will be the price leader is an open question. Nevertheless, there is a large institutional literature that documents the prevalence of price leader-follower behavior.[1] This study shows that introducing exchange rate uncertainty can lead to the endogenous emergence of an unique leader-follower equilibrium.

The recent literature on price leadership has identified a number of factors that facilitate the emergence and identification of a leader, including a firm's risk attitude, informational advantages, and market shares. Holthausen (1979) developed a model in which the major determinant of the identity of a leader is the firm's attitude towards risk. Eckard (1982) and Rotemberg and Saloner (1990) examined the role of informational advantages in generating price leadership behavior. Deneckere and Kovenock (1992) focused on size, as measured by capacity, as a determinant of leadership. Deneckere, Kovenock and Lee (1992) applied the ideas of Deneckere and Kovenock (1992) by considering a price setting game in which firms have loyal consumer segments, but cannot distinguish them from price sensitive consumers.

While Albaek (1990) and Spencer and Brander (1992) considered a quantity game, rather than a price game, with cost uncertainty and demand uncertainty respectively, their studies are more comparable to this research, even though they differ in some important respects. Albaek (1990) showed that a natural Stackelberg situation exists (does not exist) both when the goods are substitutes and when they are complements if quantities (prices) are the strategic variable. The firm that faces the large variance of cost is willing to be a quantity leader and reveal their cost structure to the rival. Thus, under some conditions the other firm may prefer to be a follower because it can exploit this cost uncertainty. However, Albaek's results rely on the assumption that information sharing is prohibited. In our paper, even if information is public and prices are the strategic variable, a natural Stackelberg situation may arise and hence results differing from Albaek's can be derived. Spencer and Brander (1992), in the quantity game, considered the possibility of endogenous Stackelberg leadership with firm specific marginal cost uncertainty. However, in their paper the emergence of Stackelberg leadership is not completely straightforward or stable. Our results differ as we show, with exchange rate uncertainty, that in the price game the emergence of Stackelberg leadership is completely straightforward.

This paper focuses on exporters from different countries who compete with each other in a local market. Each firm has the opportunity to move (set prices) before uncertainty is resolved, or to defer setting price until exchange rates are known. The risk neutral firm, in choosing its strategy, must choose between the strategic benefit of committing price and the informational benefit of maintaining price flexibility so as to adjust to unanticipated exchange rate movements. Thus, we explore how exchange rate uncertainty and asymmetries among firms may lead to the endogenous emergence of a price leader, or to an equilibrium in which both firms maintain price flexibility. We show that the choice between commitment and flexibility in setting prices depends on the variances and covariance of the exchange rates, as well as upon the substitutability between goods and the profitability of firms. Not surprisingly, as exchange rate uncertainty increases, at least one firm is likely to adopt a flexible strategy as a dominant strategy, thereby leading to a unique Nash equilibrium. Under sufficiently high exchange rate variability, both firms will choose a flexible strategy as a dominant strategy and a unique Nash equilibrium in which neither firm commits its price will emerge. In this environment there will be large exchange rate pass-through, as prices respond to actual exchange rate movements.

This paper, while partial equilibrium in nature, has implications for short-run exchange rate pass-through studies and for macroeconomic models in which price-setting behavior is postulated[2]. In a recent paper Chari, Kehoe and McGrattan (2000) develop a general equilibrium model of staggered contracts in which firms alternately set prices for N periods. They use this model to determine if this price-setting behavior can help explain the persistence of economic disturbances. Betts and Devereux (2000) develop a general equilibrium model with monopolistic competition in which an *exogenous* fraction of firms, which set prices in advance, may price discriminate across international markets. They use their model to study how this price setting behavior affects exchange rate volatility. While our paper treats the exchange rate as exogenous, it endogenizes the price setting behavior, and thus may help shed light on how macroeconomic aggregates (e.g., money supply variability) affect the fraction of firms which set prices.

A more direct implication of this paper is for exchange rate pass-through studies which use disaggregated data in industries. Although there has been much empirical research on exchange rate pass-through, there does not seem to be a literature that considers the role of exchange rate variability. As exchange rate variability changes, short-run exchange rate pass-through may also change as the pricing strategy adopted by firms, and hence the game solution, is affected by the variability. If the firm chooses the role of price leader, exchange rate pass-through (PT) is zero due to this pre-commitment.[3] Thus, the exchange rate PT with price leadership will be less than under a flexible Bertrand model.

This paper is organized as follows. The basic model and game structure are presented in section II. In section III, the Nash-equilibrium, which depends on variances and the covariance of exchange rates, is derived, while section IV reports simulation studies. Section V discusses the implications for short-run exchange rate PT and presents concluding remarks.

II. The model

Consider a heterogeneous duopoly in which firms use price as the strategic variable. There are two firms, one from country *i* and one from country *s*, which export differentiated goods *i* and *s*, respectively, to a third market (the U.S.)[4]. For simplicity, we assume the firms are symmetric except for exchange rates and marginal production costs. The demand function for good (firm) *i* is: $q_i = a - bp_i + cp_s$; where p_i is own price and p_s is rival's price, both in dollars. Goods are assumed to be substitutes (c>0). Each good is produced with constant marginal cost d_i, as measured in the home currency of each firm[5]. Each firm's profit, in home currency units of the producer, is $\Pi_i = (e_i p_i - d_i)(a - bp_i + cp_s)$, where $i \neq s$; and e_i is the exchange rate, defined as units of country *i* currency per dollar. We assume all parameters are positive, that $b > c$ (*i.e.*, own price responsiveness of demand is higher than the cross price responsiveness), and $E[e_i]$ is normalized to one. We abstract from the shut down option and assume both firms always produce positive output. The firms are risk neutral and act to maximize expected profits.

The question we focus on is when firms set their prices. The timing of decisions is as follows. In stage 1, before exchange rates are known, each firm, acting simultaneously with the other firm, can choose either (1) to irrevocably set its price, or (2) to wait to set price until the exchange rates are known. In period 2, after the uncertainty is resolved, the remaining decisions are made. If both firms have set prices in stage 1, no further decisions are made, and sales occur. If only one firm has pre-committed its price, the other firm chooses its (follower) price. If neither firm pre-committed its price, firms (simultaneously) choose their *ex post* (Bertrand) prices.

Our definitions follow those of Spencer and Brander (1992). If both firms pre-commit price before the uncertainty is resolved, the price equilibrium will be of the Bertrand type. We refer to this case as the 'committed Bertrand' regime. If both firms wait to set price until uncertainty is resolved, the price equilibrium also will be of the Bertrand type but with realized exchange rates. We refer to this as the 'flexible Bertrand' regime. If one firm commits its price before exchange rates are revealed, while its rival chooses price after exchange rates are revealed, then sequential rationality implies that the price equilibrium will be of the Stackelberg price leader-follower type. The firms are referred to as the committed leader and the flexible follower, respectively. Four cases may happen because each firm has two options (commit and flexible).

In order to determine which strategy each firm will choose, we must derive and compare the *ex ante* expected profits for each case. In order to do so, it is first necessary to derive the behavioral rules each firm pursues for each of the four cases; for the sake of brevity, we merely sketch how these rules are determined, and summarize them in a table.

The *ex ante* expected profit for each firm, as stated earlier, is given by:

$$E\left(\Pi_i\right) = E\left\{(e_i p_i - d_i)(a - bp_i + cp_s)\right\}; \qquad s \neq i \tag{1}$$

where the *ex ante* expectation is taken over the exchange rates, given the price rules as derived below. The optimal price rule for firm i depends upon that firm's information set - *i.e.,* whether the exchange rate is known when its price is set, and whether firm s sets its price after firm i sets its own price. If firm i sets its price after the exchange rate is known, its optimal pricing rule is[6]:

$$(\partial\Pi_i/\partial p_i) = \{a + (bd_i/e_i) + cp_s - 2bp_i\} = 0 \qquad (2)$$

For this case firm *i*'s optimal price depends upon the *realized* exchange rate for its home currency and (its beliefs about) the price charged by firm *s*. The case in which both firms maintain price flexibility is obtained by simultaneously solving equation (2) and a comparable equation for firm *s*. This *flexible Bertrand* equilibrium is shown as the third row in Table 1.

For the case in which both firm *i* and firm *s* follow a commitment strategy, the FOCs are similar to (2), except exchange rates are not known when prices are set; hence:

$$E(\partial\Pi_i/\partial p_i) = E\left\{e_i\left[a + (bd_i/e_i) + cp_s - 2bp_i\right]\right\} = 0 \qquad (3)$$

Using a symmetric equation for firm *s*, and solving simultaneously, yields the equilibrium strategies when both firms commit their prices. This *committed Bertrand* equilibrium is shown in the first row in Table 1.

The remaining two cases are when one firm commits to its price, while the other maintains its flexibility. To illustrate, assume firm *s* maintains price flexibility, so its best response function is given by (2) (once *i* and *s* are interchanged in the equation). Firm *i*, when it commits its price, does not know the exchange rates or the actual price set by firm *s*, but it does know the *price rule* that firm *s* will use. Maximizing expected profits for this case yields the following FOC for firm *i*:

$$E(\partial\Pi_i/\partial p_i) = E\{(e_i p_i - d_i)(-b + c(\partial p_s/\partial p_i)) + e_i(a - bp_i + cp_s)\} = 0 \quad \text{where:} \qquad (4)$$

$$p_s = \{[a + b(d_s/e_s) + cp_i]/2b\}; \qquad (\partial p_s/\partial p_i) = (c/2b) \qquad (5)$$

Substituting (5) into (4) and simplifying yields the equilibrium price strategies when firm *i* commits its price, while firm *s* maintains price flexibility; this is shown as a Stackelberg leader-follower case in Table 1. Note that the optimal price strategy for the committed firm (the leader) depends upon the covariance between the exchange rate for its home country's currency and the reciprocal of the exchange rate for the country from which the other firm comes. Throughout this paper we maintain the assumption that $E(e_i) = E(e_s) = 1$.

{insert Table 1 here}

Substituting these solutions back into the profit function, and taking expectations, yields each firm's expected profit for each of the four cases. If both firms commit their prices, then expected profits will depend upon only the expected exchange rates (which are normalized to one). However, if at least one firm pursues a flexible strategy, then both firms' expected profits will depend upon the joint distribution of the exchange rates, as well as upon the higher moments of each exchange rate. To illustrate, consider the Stackelberg leader-follower case, where firm *i* commits its price, but firm *s* maintains flexibility. Realized profits for the committed firm (*i*) vary directly with e_i but inversely with e_s (through its impact on p_s). Since p_i depends upon $E(e_i/e_s)$, it follows that the expected profits for the committed firm will depend upon this expectation (and its square). For the flexible firm (*s*), expected profits will depend upon $E(1/e_s)$, as well as $E(e_i/e_s)$, since its *ex post* price varies inversely with the realized exchange rate (e_s).

The expression for expected profits for each firm is quite tedious; to emphasize the role played by exchange rate uncertainty, we define the following terms:

$$R_i \equiv \left(\left(1/e_i\right)-1\right);\; R_i^e \equiv E\left(R_i\right);\quad N_i^e \equiv E\left[\left(e_i/e_s\right)-1\right];\quad S_i^e \equiv E[\left(e_i/e_s^2\right)-1];\qquad i \neq s \tag{6}$$

Given that $E(e_i) = E(e_s) = 1$, note that $R_i^e = N_i^e = S_i^e = 0$ under certainty. Thus, the magnitude of these terms will illustrate how uncertainty influences each firm's optimal strategy.

For notational simplicity, we define these parameters: $f_i \equiv (a/bd_i)$, $d \equiv (c/b)$, and $n_i^2 \equiv (d_s/d_i)$. The parameter d approximates the substitutability between the two goods, while n_i reflects relative costs. It is useful to express equilibrium prices in terms of the "mark-up" over marginal costs; thus, we define: $X_i \equiv ([p_i - d_i]/d_i)$[7]. Using these definitions, equilibrium prices and expected profits for each case are reported in Table 2[8].

{insert Table 2 here}

The results of the Table are read as follows. The first and last rows of the Table show the actual price, and expected profits, for each firm in the case when firms move simultaneously. The case when one firm commits, and the other adopts a flexible price strategy, is shown in the row labeled "Stackelberg Leader-Follower". The first line in this row shows the price, and expected profits, for firm *i*, which commits its price (the leader), whereas the second line shows the actual price, and expected profits, for the flexible follower, firm *s*.[9]

Under certainty, the "two" Bertrand cases are identical, as the Table shows. Comparing the solutions for the leader-follower case to the first and last rows, the standard results under certainty are confirmed: provided the two markets are linked $(d > 0)$, then: (i) both firms charge more in the leader-follower game than in the Bertrand game ($X_i^{L,F} > X_i^{L,L}$ and $X_s^{L,F} > X_s^{L,L}$); and (ii)both firms earn higher profits in the leader-follower game than in the Bertrand game. In the rest of this paper we explore how the introduction of uncertainty alters this result.

III. Nash-equilibrium and price leadership

As is well known, in the price game under certainty neither firm has a dominant strategy; if either firm were to commit to its price, then the other firm would adopt a flexible strategy. Thus, there are two Nash equilibria, with one firm leading and the other following. Further, under symmetry each firm prefers the equilibrium in which it is a follower. However, under exchange rate uncertainty, the best response of one firm to the other firm's decision to "follow" *may* be altered by the potential benefits of deferring action until the exchange rate is known. Consequently, exchange rate uncertainty may help identify which firm emerges as the leader and thus lead to a unique leader-follower Nash equilibrium, or it may even lead to an equilibrium in which both firms choose to "follow". In this section, we study how the Nash equilibrium (or equilibria) is altered by changes in the joint distribution of the exchange rates.

From Table 2, it is clear that if firm *i* chooses "commit", firm *s*'s best response is to be a "flexible follower" $\left(i.e., E\left[P_s^{L,F}\right] > E\left[P_s^{L,L}\right]\right)$. This result, true under certainty, is reinforced by the uncertainty as – given price commitment by the rival firm – delaying action until the exchange rate is known raises expected profits[10]. Thus, the crucial issue is what the firm's best response is when its rival adopts "flexible follower" as a strategy. Under certainty, if firm *s* chooses "flexible follower", firm *i*'s best response is to lead: *i.e.*, $\left([P_i^{L,F}] > [P_i^{F,F}]\right)$. Since exchange rate uncertainty increases the value of waiting, it may alter the firm's best response. If, despite the uncertainty, each firm's best response to "follow" is to lead $\left(\mathrm{E}[P_i^{L,F}] > \mathrm{E}[P_i^{F,F}]\right)$, then there are still two "leader-follower" Nash equilibria. However, if firm *i's* best response to "follow" is to not commit prices $\left(\text{i.e., } \mathrm{E}[P_i^{F,F}] > \mathrm{E}[P_i^{L,F}]\right)$, then firm *i's dominant* strategy is to not commit prices and a unique Nash equilibrium will emerge[11]. Thus, we need to compare $E[P_i^{F,F}]$ to $E[P_i^{L,F}]$ and $E[P_s^{F,F}]$

to $E[P_s^{F,L}]$. As these expressions are tedious, we represent this difference symbolically in the text; Appendix 1 gives the actual expressions.[12] From Table 2, we calculate the following:

$$E[P_i^{F,F}] - E[P_i^{L,F}] = bd_i^2\left\{-A_{0i} + A_{1i}R_i^e + [-A_{2i}N_i^e + A_{3i}\left(S_i^e - 2N_i^e\right) - A_{4i}\left(N_i^e\right)^2 + A_{5i}\left(R_s^e - N_i^e\right)]\right\} \quad \textbf{(7)}$$

where all of the parameters A_{mi} are non-negative, and the impact of uncertainty is reflected in the terms: R_i^e, R_s^e, N_i^e and S_i^e. All terms except the first vanish under certainty and thus, under certainty, or sufficiently small exchange rate volatility, we must have $E[P_i^{L,F}] > E[P_i^{F,F}]$. On the other hand, all terms except A_{1i} are zero when $d = 0$, so that when there is no interaction between the firms, $E\left(P_i^{F,F}\right) > E\left(P_i^{L,F}\right)$. Thus, "flexible follower" is most likely to emerge as a dominant solution when the market linkages are small or the exchange rate variability is large.

For further analysis, we assume the exchange rates follow a bivariate log-normal distribution[13]. Under this distribution, $R_i^e = V_i$, $N_i^e = \left\{(V_s - C)/(1+C)\right\}$, and $S_i^e = \left\{\left[(1+V_s)^3/(1+C)^2\right] - 1\right\}$, where $V_i = Var[e_i]$, $V_s = Var(e_s)$ and $C = Cov[e_i, e_s]$.[14] Substituting these expressions into **(7)** yields:

$$D_i = bd_i^2\left\{-A_{0i} + A_{1i}V_i - A_{2i}\left(\frac{V_s - C}{1+C}\right) + A_{3i}\left(\frac{V_s\left(1+V_s\right)^2 + \left(V_s - C\right)^2}{\left(1+C\right)^2}\right) - A_{4i}\left(\frac{V_s - C}{1+C}\right)^2 + A_{5i}\left(\frac{C\left(1+V_s\right)}{1+C}\right)\right\} \quad (8)$$

where $D_i = \left\{E\left(P_i^{F,F}\right) - E\left(P_i^{L,F}\right)\right\}$. The sign of equation (8) determines whether "follow" is a dominant strategy for firm *i;* a similar expression determines whether "follow" is a dominant strategy for firm *s*. Since demands are symmetric, the two firms will adopt different strategies only if either the variances of their respective home country's currencies differ or if their production costs differ. Intuitively, we might expect the firm with lower costs to emerge as the unique leader as volatility increases, since this firm earns higher profits and thus has the most to lose from a flexible Bertrand solution. Similarly, we might expect that the firm that comes from the country with the more volatile currency would value the flexible strategy more, and thus be the firm that is more likely to have "flexible" as a dominant strategy. However, these "intuitive conjectures" cannot, in most cases, be directly confirmed because equation (8) is nonlinear in V_s, because the parameters (A_{mi}) are nonlinear in costs, and because of the interactions among the variables. Simplification is needed to derive analytic results.

First, consider the case where both firms come from the same country (or currency area), so that $V_i = V_s = C$. Under this condition, equation (8) reduces to:

$$D_i = bd_i^2\left\{-A_{0i} + \left(A_{1i} + A_{3i} + A_{5i}\right)V\right\}; \quad D_s = bd_s^2\left\{-A_{0s} + \left(A_{1s} + A_{3s} + A_{5s}\right)V\right\} \tag{9}$$

Proposition 1. Assume both firms come from the same currency area and that the exchange rate is log-normally distributed with variance *V*. Let firm *i* denote the low cost firm and firm *s* the high cost firm. Then there exist $V_i^* > V_s^* > 0$ such that: (i)for $V < V_s^*$, there are two leader-follower Nash equilibria; (ii)for $V \in \left(V_s^*, V_i^*\right)$ there is a unique leader-follower Nash equilibria with the low cost firm as the price leader; and (iii)for $V > V_i^*$, there is a unique flexible Bertrand solution.

PROOF: See Appendix 2.

This result confirms the intuition that if there is a unique leader-follower equilibrium, the leader is likely to be the low cost firm. However, if exchange rate variances also differ, the non-linearity and interaction among terms in (8) make it impossible to derive analytical results.

To simplify, assume for the rest of the paper that the two firms have the same cost structure $\left(d_i = d_s \rightarrow h_i = 1\right)$, so the parameters do not vary across firms $\left(A_{mi} = A_{ms}, m = 0,...,5\right)$. Also, assume for now that the covariance between the exchange rates is zero. Under these assumptions, equation (8) becomes:

$$D_i = bd^2\left\{-A_{0i} + A_{1i}V_i + V_s\left(A_{3i}\left(1+3V_s+V_s^2\right) - A_{2i} - A_{4i}V_s\right)\right\} \equiv -U_1^i + U_2^i(V_i) + U_3^i(V_s) \qquad (10)$$

Equation (10) consists of three effects. As earlier, the first term (U_1) shows the increase in profits, under certainty, of committing price when the rival firm chooses price flexibility (*i.e.*, $-U_1 = \left(\Pi_i^{L,F} - \Pi_i^{F,F}\right)$ under certainty). The second term $\left(U_2\right)$ shows that the difference in expected profits is linear in the exchange rate variance of the firm's home country currency, while the last term $\left(U_3\right)$ reveals the (strictly convex) effect of the exchange rate variance of the rival firm's home country currency. The fact that $\{E[P_i^{F,F}] - E[P_i^{L,F}]\}$ increases with these variances means that as volatility increases the value of retaining flexibility also increases.

Equation (10) applies to both firms (*i, s*). Note that $U_1^i = U_1^s = U_1$ if costs and demand are the same. We know each firm wishes to follow, given that the other leads. Thus, "*flexible*" is a dominant strategy for firm *i* if, and only if, $[U_2^i(V_i) + U_3^i(V_s)] > U_1$. Similarly, "*flexible*" is a dominant strategy for firm *s* if, and only if, $[U_2^s(V_s) + U_3^s(V_i)] > U_1$. The comparison of these expected values indicates that there are four possible solutions that might emerge.

Proposition 2. Assume exchange rates are log-normally distributed and uncorrelated, and that costs and demand are symmetric; then:

(i) if $Max[U_2^i(V_i) + U_3^i(V_s), U_2^s(V_s) + U_3^s(V_i)] < U_1$, there are two Nash-equilibria (commit, flexible; flexible, commit), the same result as in a standard Bertrand duopoly game.

(ii) if $\left[U_2^s(V_s)+U_3^s(V_i)\right]<U_1<\left[U_2^i(V_i)+U_3^i(V_s)\right]$, then $E[\Pi_i^{F,F}]>E[\Pi_i^{L,F}]$ and $E[\Pi_s^{F,F}]<E[\Pi_s^{F,L}]$. Thus, firm *i* has *flexible* as a dominant strategy, and firm *s's* best response is to be a price leader. A unique Nash-equilibrium (flexible, commit) results.

(iii) if $\left[U_2^s(V_s)+U_3^s(V_i)\right]>U_1>\left[U_2^i(V_i)+U_3^i(V_s)\right]$, then $E[\Pi_i^{F,F}]<E[\Pi_i^{L,F}]$ and $E[\Pi_s^{F,F}]>E[\Pi_s^{F,L}]$. Thus, firm *s* has *flexible* as a dominant strategy, and firm *i's* best response is to be a price leader. A unique Nash-equilibrium (commit, flexible) results.

(iv) if $Min[U_2^i(V_i)+U_3^i(V_s),U_2^s(V_s)+U_3^s(V_i)]>U_1$, both firms have *flexible* as a dominant strategy, and a unique (flexible Bertrand) Nash-equilibrium (flexible, flexible) results.

It is intuitive that increased exchange rate variability in either currency increases the value of deferring action for both firms. Since firms are otherwise alike, the only potential source of asymmetric behavior is if exchange rate variances differ. What is not intuitive is the possibility that increased exchange rate variability in one currency (e.g., country *s*'s currency) *may* have a bigger impact on the firm from the other country (firm *i*). This possibility arises since $E[\Pi_i^{F,F}]-E[\Pi_i^{L,F}]$ is a nonlinear (strictly convex) function of country *s*'s exchange rate variance, while it is a linear function of its own country's exchange rate variance. Due to this nonlinearity firm *i* may be more affected than firm *s* by the variability of country *s*'s exchange rate. Thus, somewhat paradoxically, the firm from the country with the stable exchange rate may emerge as the one that has "flexible" as a dominant strategy, rather than the firm that comes from the country that has high exchange rate variability. We show this case in subsequent simulations.

How large exchange rate variability must be to make *flexible* a dominant strategy depends on the degree of substitutability (d) between the two goods. When d is small, the strategic interaction between the firms is relatively unimportant, and thus the value of "committing", given that the other firm has chosen "flexible", is small. Thus, with small d, "flexible" will emerge as a dominant strategy for both firms at relatively low levels of uncertainty. However, when d is large, the strategic interaction is more important and higher levels of uncertainty are required to allow "flexible" to emerge as a dominant strategy for even one firm.

IV. Simulation and sensitivity

Proposition 2 states that exchange rate volatility may alter the Nash equilibrium that emerges in the price-setting game. However, the complexity of the expression makes it impossible to determine analytically which of the cases mentioned in Proposition 2 are most likely to emerge. To provide a more definitive analysis, we report some simulations in this section. We analyze each of these four cases and discuss how the likelihood each case will occur is affected by the covariance term.

Turning to our simulations, Figure 1, which is drawn under the assumptions d = 0.9, $Var[e_s]$ = 0, and costs and demand are symmetric, shows four regions. The horizontal axis represents the "mark-up" ($X_i^{L,L}$)[15], while the vertical axis represents $Var[e_i]$. In the area above (below) the thick ***ii*** line, $E[\Pi_i^{F,F}]$ is higher (lower) than $E[\Pi_i^{L,F}]$, as the ***ii*** line is the locus such that $E[P_i^{F,F}]$ equals $E[P_i^{L,F}]$. Similarly, in the area above (below) the light ***ss*** line, $E[\Pi_s^{F,F}]$ is higher (lower) than $E[\Pi_s^{F,L}]$. Naturally, a higher variance increases the value of a flexible strategy. Each of these areas corresponds to the four cases outlined in Proposition 2; in particular:

- Area (a): two Nash-equilibria exist, as under certainty; this is the area below both lines.
- Area (b): firm *i*, whose exchange rate is variable, has "flexible" as a dominant strategy yielding the unique NE = (flexible, commit); this is the area above the ***ii*** line and below the ***ss*** line.
- Area (c): firm *s*, whose exchange rate is stable, has "flexible" as a dominant strategy, yielding the unique NE = (commit, flexible); this is the area below the ***ii*** line and above the ***ss*** line.
- Area (d): both firms' dominant strategy is "flexible", yielding the unique NE = (flexible, flexible); this is the area above both lines.

{insert Figure 1 here}

To illustrate, assume $Var\left(e_s\right)=0$, and consider an industry in which goods are close substitutes and the monopoly power is limited $\left\{d=0.9,\ X_i^{L,L}=0.4\right\}$. If $Var[e_i]<0.079$, two NEs exist. If $0.079<Var[e_i]<0.129$, firm *i* will be a price follower and firm *s* will be a price leader, while for $Var[e_i]>0.129$ neither firm commits. However, in a more profitable (higher mark up) industry, which has larger benefits from maintaining one firm as the price leader, we find that larger variances are required to induce a dominant strategy equilibrium, and that area (c), rather than area (b), emerges as the unique leader-follower equilibrium. Thus, somewhat paradoxically, the firm which first emerges as having "flexible" as a dominant strategy is the one whose exchange rate is stable, not the firm that faces the exchange rate variability[16].

Not surprisingly, increased exchange rate volatility increases the profitability of maintaining price flexibility. What Figure 1 shows is that in less profitable (low demand or high cost) industries, the firm that faces the volatile exchange rate has a relatively stronger preference for maintaining flexibility; whereas in more profitable industries it is the firm that faces low (or no) exchange rate volatility that has the relatively stronger preference for maintaining flexibility. Thus, in relatively competitive (low profit) industries the price leader is more likely to come from either the home country or a trading country whose exchange rate varies little, whereas in more profitable industries the price leader is more likely to come from a trading country whose exchange rate variability is high.

Numerical simulations can demonstrate how the areas corresponding to each NE change as factors such as $Var[e_s]$, $Cov[e_i, e_s]$ and d change.[17] As d (the substitutability between goods) decreases, the significance of the strategic interaction diminishes, and hence "flexible" emerges as a dominant strategy at lower variances. Moreover, the reduced interaction between firms means that increases in the variance of country i's currency has a more powerful effect on firms from that country than on other firms. Thus, for low d the likelihood of an equilibrium in region *c* (in which the follower is the firm using the more stable currency) vanishes.

Given d, as the variance of the more stable exchange rate increases, the ***ss*** and ***ii*** lines approach each other.[18] Not surprisingly, the region over which *flexible* is a dominant strategy for both firms increases (area *d*), while other areas (*a, b, c*) shrink. Given the variances, when the covariance between exchange rate movements $\left(Cov[e_i, e_s]\right)$ increases both the ***ss*** and the ***ii*** lines shift downward, increasing the likelihood of a dominant strategy "flexible" Nash equilibrium. Since firms have upward sloping reaction functions in the price game, it is natural that increases in $Var[e_s]$ and/or $Cov[e_i, e_s]$ make a flexible strategy more valuable, and that the smaller difference between the two variances shrinks the leader-follower equilibrium area.

Some general conclusions can be drawn from this analysis. First, asymmetric exchange rate uncertainty can lead to the endogenous emergence of a unique leader-follower equilibrium (areas (b) and (c) in the figures). This equilibrium is most likely to emerge when one exchange rate is fairly stable and the covariance between the exchange rates is relatively low. Note, however, that the price leader *need not* be the firm that faces the lower exchange rate variability (*i.e.*, the follower is not necessarily from the country with higher exchange rate variability). If goods are close substitutes and profit margins are large, then the price leader may be the firm that faces the larger exchange rate variability. Finally, if both exchange rates are highly volatile, or goods are not close substitutes, then a dominant strategy (flexible, flexible) solution emerges.

V. Conclusion

We have studied a price competition game in which exchange rate uncertainty may lead to the emergence of a unique Nash equilibrium. This result occurs because exchange rate uncertainty may cause one, or both, firms to adopt price flexibility as a dominant strategy. Since these firms adjust their prices to realized exchange rate movements, our results might have implications for short-run exchange rate pass-through. The partial equilibrium nature of our model (in which exchange rates are exogenous) may mean the contribution is most applicable for exchange rate pass-through studies that use disaggregated data in industries, rather than for more aggregate studies or general equilibrium models. However, it is possible that the insights from this paper may be applied to some general equilibrium macroeconomic models, such as those in which the share of firms that commit price has heretofore been treated as an exogenous parameter.

The implications of this study for pass-through include helping to identify the types of firms that are likely to adopt flexible pricing strategies, and helping to identify markets in which both (all) firms are likely to adopt flexible pricing as a strategy. For example, we have shown that, *ceteris paribus*, high cost (low profit) firms are more likely to choose price flexibility, so we would expect short run pass-through to be larger for less profitable (perhaps smaller) firms within an industry. On the other hand, very profitable (perhaps larger) firms will be less likely to pass through *unanticipated* exchange rate movements.[19]

Similarly, we have shown that price flexibility is likely to emerge as a dominant strategy for both firms when (both) exchange rates are volatile, when profit margins are small, when goods within the industry are not close substitutes, or when the exchange rate covariance is large. Exchange rate pass-through will be largest in such markets not only because each firm will respond to realized exchange rates, but because – due to the interaction between (or among) firms - the price response of each firm will also be larger. This happens because, in the leader-follower solution, when the follower (e.g., firm *i*) adjusts its price to the realized exchange rate it treats the other firm's price as given, whereas in the flexible Bertrand solution firm *i* incorporates the anticipated price response of the other firm to the realized exchange rate. Since the reaction curves slope upward, both firms adjust price in the same direction, leading to greater price movements for *both* firms than in the leader-follower equilibrium. Thus, although the model structure is the same, the equilibrium exchange rate pass-through depends on which solution prevails (and hence on factors cited above). Finally, note that changes in the (perceived) exchange rate volatility may produce a structural break in the observed pass-through relationship, as the new (game-theoretic) pricing solution may differ from the historic pricing relationships.

Naturally, there are limitations to the analysis. Our results were obtained assuming linear demand functions, constant marginal cost and risk neutrality. Incorporating risk aversion would be likely to increase the desirability of "flexible" as a strategy, and hence increase the frequency of pass-through. While the introduction of nonlinear demands or non-constant costs would change the quantitative results, the basic economic point we are making is unlikely to change. On the other hand, it would be useful to extend the analysis to more than two firms, and perhaps to a dynamic analysis that incorporates the possibility of entry and other dynamic considerations.

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Appendix 1: Definition of Parameters used in Text

Fundamental Parameters:

$a > 0$	Demand intercept
$b > 0$	Absolute value of own price responsiveness of demand $\left(= \left(-\partial q_i / \partial p_i\right)\right)$
$c > 0$	Cross price responsiveness of demand $\left(= \left(\partial q_i / \partial p_s\right)\right)$
$d_i > 0$	Marginal Cost of firm *i*, in local currency units

Constructed Parameters:

$d \equiv (c/b) < 1$	measures the substitutability between goods
$f_i \equiv (a/bd_i)$	measures strength of demand (choke price if no substitute)
$h_i \equiv \sqrt{d_s/d_i}$	measures relative costs of firms
$X_i \equiv ((p_i - d_i)/d_i)$	measures monopoly power (actual value depends on game solution)

Parameter definitions for equation **(7)** of text:

$$A_{0i} \equiv \left(d^4 \left(X_i^{LL}\right)^2 \Big/ 8\left(2-d^2\right)\right) \geq 0$$

$$A_{1i} \equiv \left(\left(2-d^2\right) \Big/ \left(4-d^2\right)\right)^2 > 0$$

$$A_{2i} \equiv \left(d^5 X_i^{LL} h_i^2 \Big/ 4\left(2-d^2\right)\left(4-d^2\right)\right) \geq 0$$

$$A_{3i} \equiv \left(d^2 h_i^4 \Big/ \left(4-d^2\right)^2\right) \geq 0$$

$$A_{4i} \equiv \left(d^2 h_i^4 \Big/ 8\left(2-d^2\right)\right) \geq 0$$

$$A_{5i} \equiv \left(d h_i^2 \left(8-4d^2+d^4\right) \Big/ 2\left(4-d^2\right)^2\right) \geq 0;$$

Appendix 2: Proof of Proposition 1.

From equation (8), assuming $V_i = V_s = C$, we have:

$$D_i = bd_i^2\left(-A_{oi} + V\left[A_{1i} + A_{3i} + A_{5i}\right]\right);\; D_s = bd_s^2\left(-A_{os} + V\left[A_{1s} + A_{3s} + A_{5s}\right]\right) \tag{A1}$$

Define V_i^* s.t. $D_i\left(V_i^*\right) = 0$ and V_s^* s.t. $D_s\left(V_s^*\right) = 0$

Using the definitions for the terms A_{ji} and solving yields:

$$V_i^* = \frac{\left[(a/bd_i)(2+d) + (d\,d_s/d_i) - (2-d^2)\right]^2}{\left[(2-d^2) + (d\,d_s/d_i)^2 + (d\,d_s u/2d_i)\right]} = \frac{\left[(a/b)(2+d) + dd_s - (2-d^2)d_i\right]^2}{\left[(2-d^2)d_i^2 + (d\,d_s)^2 + (d\,d_s d_i u/2)\right]} \tag{A2}$$

where $u \equiv \left(8 - 4d^2 + d^4\right) > 0$. By symmetry:

$$V_s^* = \frac{\left[(a/b)(2+d) + dd_i - (2-d^2)d_s\right]^2}{\left[(2-d^2)d_s^2 + (d\,d_i)^2 + (d\,d_s d_i u/2)\right]} \tag{A3}$$

Let $e \equiv (d_s - d_i) \rightarrow d_s = (e + d_i)$. Substituting into V_i^* and V_s^* and taking the ratio yields:

$$\left[\frac{V_i^*}{V_s^*}\right] = \left[\frac{\left[(a/b)(2+d) + de - (2+d)(1-d)d_i\right]^2}{\left[(a/b)(2+d) - (2-d^2)e - (2+d)(1-d)d_i\right]^2}\right]\left[\frac{\left[ad_i^2 + b_i e d_i + e^2\left(2-d^2\right)^2\right]}{\left[ad_i^2 + b_s e d_i + e^2 d^2\right]}\right] \tag{A4}$$

where $a = \left(\left(2-d^2\right)^2 + d^2 + \frac{du}{2}\right)$; $b_i = \left(2\left(2-d^2\right)^2 + \frac{du}{2}\right) \geq \left(2d^2 + \frac{du}{2}\right) = b_s$ and the inequality is strict if $d < 1$. From (A4) it is readily verified that:

$\left[\frac{V_i^*}{V_s^*}\right] \gtreqless 1$ as $e \gtreqless 0$. But $V_i^* > V_s^*$ implies that $D_i < 0$ at $D_s = 0$. Thus, assuming $d_s > d_i$, for $V < V_s^*$ there are two leader-follower Nash-equilibria; for $V_s^* < V < V_i^*$, there is one Nash leader-follower equilibrium, with the low cost firm being the leader; and for $V > V_i^*$ both firms adopt a flexible price strategy as the unique Nash equililbrium.

	Price
Committed Bertrand $(p_i, p_s \rightarrow e_i, e_s)$	$p_i^{L,L} = \dfrac{2ab + ac + 2b^2 d_i + bcd_s}{4b^2 - c^2} \qquad i \neq s$
Stackelberg leader-follower $(p_i \rightarrow e_i, e_s \rightarrow p_s)$	$p_i^{L,F} = \dfrac{a(2b+c) + (2b^2 - c^2)\, d_i + bcd_s\, E(e_i/e_s)}{2(2b^2 - c^2)};$ $p_s^{L,F} = \dfrac{a + cp_i^{L,F} + b(d_s/e_s)}{2b}$
Flexible Bertrand $(e_i, e_s \rightarrow p_i, p_s)$	$p_i^{F,F} = \dfrac{2ab + ac + \dfrac{2b^2 d_i}{e_i} + \dfrac{bcd_s}{e_s}}{4b^2 - c^2}; \qquad i \neq s$

Table 1. Equilibrium prices for each case

	Mark-up	Expected profit
Committed Bertrand	$X_i^{L,L} = \frac{f_i(2+d)+d\,n_i^2+d^2-2}{4-d^2}$	$E[\Pi_i^{L,L}] = (bd_i^2)(X_i^{L,L})^2$
Stackelberg Leader - firm *i* Follower -firm *s*	$X_i^{L,F} = X_i^{L,L} + s_i^{LF}$ $X_s^{L,F} = X_s^{L,L} + b_{2,s}\,s_i^{L,F} + \frac{R_s}{2}$	$E[\Pi_i^{L,F}] = E[\Pi_i^{L,L}] + bd_i^2\left\{b_{1i}\left(s_i^{LF}\right)^2 + b_{2i}\left(X_i^{LL}N_i^e + N_i^e - R_s^e\right)\right\}$ $E\left[\Pi_s^{L,F}\right] = E\left[\Pi_s^{L,L}\right] + bd_s^2\left\{b_{2,s}s_i^{L,F}\left[2X_s^{L,L} + b_{2,s}s_i^{L,F}\right] + \left(R_s^e/4\right)\right\}$
Flexible Bertrand	$X_i^{F,F} = X_i^{L,L} + \frac{b_{2,i}R_s + R_i}{\left(1+b_{1,i}\right)}$	$E[\Pi_i^{F,F}] = bd_i^2\left\{\left(X_i^{L,L}\right)^2 + \frac{2b_{2,i}\left(1+b_{1,i}\right)X_i^{LL}N_i^e + E\left[e_i\left(b_{2,i}R_s - b_{1,i}R_i\right)^2\right]}{\left(1+b_{1,i}\right)^2}\right\}$

Table 2. Equilibrium price (mark-up) and *ex-ante expected* profits for each case

where: $X_i \equiv \left(\left[p_i - d_i\right]/d_i\right)$; $f_i \equiv \left(a/bd_i\right)$; $d \equiv \left(c/b\right)$; $n_i^2 \equiv \left(d_s/d_i\right)$; $R_i^e \equiv E\left(\left(1/e_i\right)-1\right)$;

$N_i^e \equiv E\left(\left(e_i/e_s\right)-1\right)$; $S_i^e \equiv E\left(\left(e_i/e_s^2\right)-1\right)$; $s \neq i$; $s_i^{LF} \equiv \left[\frac{d^2X_i^{L,L} + d n_i^2 N_i^e}{2(2-d^2)}\right]$; $b_{1i} \equiv \left[\frac{\left(2-d^2\right)}{2}\right] \in \left[\frac{1}{2},1\right]$

$b_{2i} \equiv \left[\frac{dh_i^2}{2}\right] \geq 0$; $E\left[e_i\left(b_{2i}R_s - b_{1i}R_i\right)^2\right] = \left\{\left(b_{2i}^2\right)\left(S_i^e - 2N_i^e\right) - 2b_{1i}b_{2i}\left(R_s^e - N_i^e\right) + b_{1i}^2R_i^e\right\}$

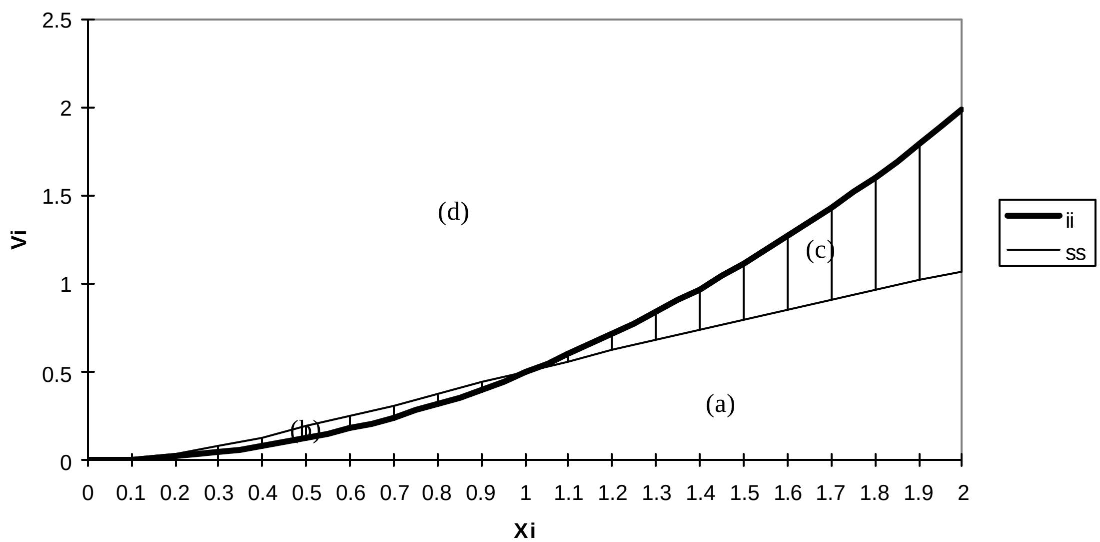

Figure 1. Firms' best regimes; $d = 0.9$, $Var[e_s] = 0$, $n_i = 1$

Notes to Figure:

Area (a) is the region in which there are two Nash equilibrium.

Area (b) is the region in which there is a unique Nash equilibrium with firm *i* the leader.

Area (c) is the region in which there is a unique Nash equilibrium with firm *i* the follower.

Area (d) is the region in which there is a unique Nash equilibrium with both firms choosing flexible follower.

Endnotes

[*] The authors are, respectively, Division Director, International Economic Analysis, SK Securities, Co., Ltd., Seoul, Korea, and Professor of Economics, Iowa State University, Ames, IA, USA.

[1] See Rotemberg & Saloner (1990) and Scherer (1980).

[2] The empirical pass-through literature is voluminous. Some studies have found that pass through differs across source countries (e.g., Knetter, 1989) while others (e.g., Feenstra, 1989; Feinberg, 1989; Knetter, 1993) have found significant differences in pass-through across industries or product categories.

[3] Of course, the expected change of the exchange rate affects prices and hence exchange rate PT.

[4] By setting the variance on one exchange rate to zero, the model could represent one domestic and one foreign firm.

[5] The foreign producers' home market is separated on the technological side and may thus be neglected.

[6] For this case, firm *i* cannot be a price leader with respect to firm *s*.

[7] This "markup" is a standard measure of monopoly power. Clearly, the equilibrium markup is endogenous, and can be shown to be a decreasing function of a firm's own cost and an increasing function of the other firm's cost.

[8] Increases in d reflect greater substitutability between the two goods, which should decrease the equilibrium markup. However, a simple calculation shows that an increase in d, given b, increases demand and hence increases the equilibrium markup. If d and b are both increased so that demand is constant, the equilibrium markup does decline.

[9] The notation $P_i^{L,L}$ shows firm *i*'s profits when both firms commit their price, and $P_i^{F,F}$ shows firm *i*'s profits when both firms are followers. In the Stackelberg case, we adopt the convention that the first superscript refers to the behavior of firm *i*, and the second to firm *s*, so that $P_s^{L,F}$ shows the profits of firm *s* when firm *i* is the leader and firm *s* the follower. Similarly, $P_s^{F,L}$ shows firm *s*'s profits when firm *s* leads and firm *i* follows.

[10] From the second line of row 2 in Table 2, all the terms involving expectations are non-negative, and hence the exchange rate uncertainty reinforces the benefits of being a follower, given the other firm is a leader.

[11] If both firms have flexible as a dominant strategy (as in the symmetric case), then there is a unique Bertrand follower equilibrium. If only one firm has a dominant strategy, there is a unique "leader-follower" equilibrium.

[12] The reason the expressions are so complicated is that they involve expectations of reciprocals of random variables.

[13] We assume a log-normal distribution so that analytical results are possible. However, the use of other distributions such as bivariate normal distribution would not change the main results.

[14] If (x, y) = $(\ln e_i, \ln e_s) \sim N(m_x, m_y, s_x^2, s_y^2, s_{xy})$, $E[e_i] = Exp[m_x + (s_x^2/2)]$ =1, and $E[e_s] = Exp[m_y + (s_y^2/2)]$ =1, then $E[e_j^a e_k^b] = \exp[(s_x^2/2)(a^2 - a) + (s_y^2/2)(b^2 - b) + abs_{xy}]$.

Since: $Var[e_i] = E[e_i^2 - 1] = \exp[s_x^2] - 1$, and $Cov[e_i, e_s] = E[e_i e_s - 1] = \exp[s_{xy}] - 1$, we find:

$$R_i^e = E[R_i] = E[(1/e_i) - 1] = \exp[s_x^2] - 1 = Var[e_i],$$

$N_i^e = E[(e_i/e_s)-1] = \exp[s_y^2 - s_{xy}]-1 = \{(Var[e_s]-Cov[e_i,e_s])/(1+Cov[e_i,e_s])\}$ and

$S_i^e = E[(e_i/e_s^2)-1] = \exp[3s_y^2 - 2s_{xy}]-1 = \{[(1+Var[e_s])^3/(1+Cov[e_i,e_s])^2]-1\}$.

[15] Naturally, the equilibrium mark-up is a decision variable for the firm which depends on the parameters of the model. For example, given d , increases in $f_i \equiv (a/bd_i)$ increase the equilibrium "mark-up". Thus, increases in the demand intercept, and/or decreases in the slope of the demand curve or marginal cost, serve to increase $X_i^{L,L}$.

[16] The technical reason for this result hinges on Jensen's inequality, while the intuitive explanation is more elusive. From firm *i*'s perspective, variability in e_s is isomorphic to variability in firm *s*'s marginal cost. If the goods are close substitutes, it may be relatively more valuable for firm *i* to respond to realized shocks in firm *s*'s marginal cost than to shocks in its own costs.

[17] Details are omitted here to save space; they are available from the corresponding author upon request.

[18] In the discussion, we assume $Var(e_i) \geq Var(e_s)$. Clearly, when $Var(e_i) = Var(e_s)$, the equilibrium is symmetric provided costs (in home currency units) are the same.

[19] Of course, part of the *expected* change in the exchange rate will be "passed-through".