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# State dependent pricing, invoicing currency, and exchange rate pass-through

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**Abstract**

We analyze exchange rate pass-through and volatility of import prices in a dynamic framework where firms are subject to menu costs and decide on price adjustments in response to exchange rate innovations. The exchange rate pass-through and import price volatility then depend on the invoicing currency in combination with functional forms of cost and demand functions. In particular, there is lower pass-through, less frequent price adjustments, and lower price volatility when prices are set in the importer's currency than when prices are set in the exporter's currency.



*Keywords:* Exchange rate pass-through; Nominal rigidities; Invoicing; State dependent pricing; Invoicing currency

*JEL classification:* D40; E30; F31; F40

## 1. Introduction

In a recent speech to the Congress the Federal Reserve chairman, Alan Greenspan, noted that the fall of the dollar during the latter part of 2003 has had little effect on prices of imported goods and services, as "foreign exporters have been willing to absorb some of the price decline measured in their own currencies and the consequent squeeze on profit margins it entails". Abundant empirical research indeed demonstrates that exchange rate pass-through to import prices is less than unity.[1] In particular this seems to be the case for the U.S. where import prices

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[1] See for instance Goldberg and Knetter (1997) and Goldberg and Verboven (2001). Engel and Rogers (1996) and Parsley and Wei (2001) examine pass-through to consumer prices.

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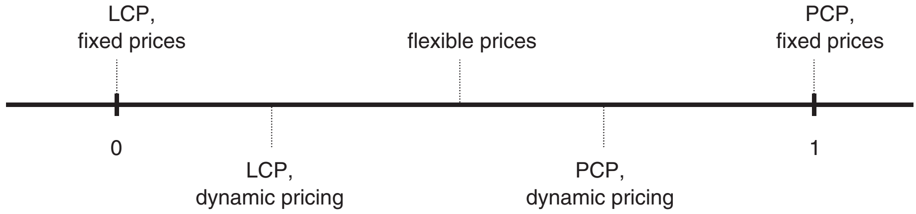


Fig. 1. Degree of pass-through implied by different pricing assumptions.

are to a large extent insulated from movements in the dollar versus the currencies of many of its major trading partners. In spite of extensive theoretical research, the determinants of exchange rate pass-through remain unclear.

Spurred by the dollar appreciation in the late 1970s and early 1980s, a large body of theoretical work analyzed exchange rate pass-through and pricing to market, i.e. failure of import prices to fully respond to changes in exchange rates.[2] These models are characterized by imperfect competition in a flexible price setting. The degree of pass-through is then determined by functional forms of cost and demand functions as well as the form of competition.

Another strand of the literature introduces nominal price stickiness and considers the short run response of import prices to exchange rate fluctuations. When firms do not instantaneously adjust prices in response to fluctuating exchange rates the choice of currency in which to price exports becomes important. The exporting firm can set prices either in its domestic currency (Producer Currency Pricing or PCP) or in the currency of the importer (Local Currency Pricing or LCP), and these models imply that there is either zero (LCP) or complete (PCP) pass-through.[3]

In the present paper, we provide a link between these short run and long run analyses by specifying a dynamic framework with endogenous pricing decisions. More specifically, we consider the pricing strategies of firms that produce in a home country, sell on a foreign market, and can change the price in response to exchange rate fluctuations, while being subject to menu costs. The degree of pass-through is then endogenous and depends on (i) the invoicing convention (LCP or PCP), (ii) the size of menu costs in relation to the costs of using suboptimal prices (since this determines how often firms update prices), and (iii) the frictionless degree of pass-through (since this determines how much prices are changed when firms choose to update prices). Typically, our dynamic setting generates a degree of pass-through between that implied by fixed-price and flexible-price models, as is illustrated in Fig. 1.[4]

Our main finding is that when LCP is favored to PCP, the exporter changes prices less frequently under LCP than under PCP. This results in limited pass-through and a low correlation between exchange rate movements and import prices. While eventually exchange rate pass-through may be determined by factors other than nominal rigidities, our model explains why extensive local currency pricing implies lower volatility of imported goods prices also in the medium run.

[2] Early contributions include Krugman (1987) and Dornbusch (1987).

[3] The sticky-price literature either analyzes the optimal choice of export currency in a partial equilibrium framework such as Baron (1976), Donnefeldt and Zilcha (1991), Friberg (1998) and Bacchetta and van Wincoop (2002), or takes the choice of currency as exogenous and explores the consequences of this choice in general equilibrium macro models such as Obstfeld and Rogoff (2000) and Chari et al. (2002).

[4] In the presence of inflation or other factors that imply asymmetric pricing rules, it is however possible that pass-through under LCP exceeds the flexible-price pass-through. We demonstrate this below.

We further analyze the impact of large versus small innovations in the exchange rate. Since larger fluctuations in the exchange rate raise the opportunity cost of holding prices fixed, firms update prices more frequently. Under LCP we therefore find that pass-through is larger for large exchange rate innovations while for PCP, the degree of pass-through is smaller for large fluctuations. Our model also generates asymmetric responses to appreciations and depreciations, especially in the presence of inflation. Since periods of high inflation imply that firms would adjust prices upward even in the absence of fluctuating exchange rates, under LCP they are more likely to keep prices fixed in the case of a depreciation. Under PCP, given a depreciation, firms are unwilling to allow prices to fall by the full amount and quickly adjust prices upwards. In both cases, a depreciation of the exporters' currency leads to lower pass-through than an appreciation.

Our findings have potential to shed light on a number of issues in open economy macroeconomics. For instance, Obstfeld and Rogoff (2000) argue that the literature assuming LCP and pricing-to-market is hard to reconcile with empirical evidence, and one of their arguments is that although pass-through is estimated to be less than unity, it is higher than zero. According to our analysis, any degree of pass-through in the interval between zero and unity is consistent both with LCP and PCP. This is also the case in Devereux et al. (2004). Although pass-through is implicitly restricted to be either zero or unity for any particular firm in their model, the average pass-through is in the unit interval since firms endogenously choose the invoicing currency. Moreover, the low correlation between exchange rates and import prices under LCP estimated in our model can explain the recent failure of U.S. import prices to change significantly in response to the falling value of the dollar also over longer time horizons.[5] Finally, several empirical studies have examined asymmetric responses to depreciations and appreciations without finding a clear result. We point out that the average pass-through must be identical for depreciations and appreciations in a stationary world, but we demonstrate that the frequency and magnitude of price responses can differ. Such asymmetric responses may result in non-linear relations between pass-through and the sign and magnitude of exchange rate fluctuations. It is therefore important that the econometric model is carefully specified, and we demonstrate that typical regressions can result in biased estimates of the pass-through. In the presence of inflation, prices are not stationary and pass-through may differ for depreciations and appreciations. We demonstrate that pass-through then is higher after appreciations than after depreciation.

In a recent paper, Ran (2004) analyzes pass-through in a framework similar to ours but with quadratic adjustment costs for prices and a constant exchange rate. Assuming linear demand and constant marginal cost, he finds that the degree of pass-through to surprise exchange rate shocks depends on the current price relative to the steady state price, and on the pricing convention. The quadratic adjustment costs induce firms to change prices continuously and always by a small amount, which is not consistent with real-world pricing behavior (Blinder, 1994). Moreover, since the exchange rate process is not explicitly modelled, the scope for an analysis similar to ours is limited.

We now turn to describe the model. Then, in Section 3 we summarize the analysis from the static pass-through literature and discuss how it relates to our dynamic setting. In Section 4 we use artificial data generated by the model to examine how pass-through is affected by the choice of invoicing currency. Finally, Section 5 concludes.

[5] LCP is particularly common in the United States. According to Bekx (1998), 80% of U.S. imports are priced in dollars, while the fraction of imports priced in local currency is around 40% in other large developed countries. For a survey of the currency denomination in international trade, see Hartmann (1998).

## 2. The model

We consider the pricing strategies of an exporting firm that produces in its home country and only sells in a foreign country. Define $p$ and $p^{E}$ as the export price in the foreign currency and in the exporter's currency, respectively. Let $s$ denote the nominal exchange rate (home currency units per foreign currency unit) so that $p^{E}=sp$. The firm's invoicing currency is exogenous. Under LCP, the firm sets the price in the foreign currency, while it sets the price in domestic currency under PCP. Furthermore, let $\bar{p}$ and $\bar{p}^{E}$ denote the average price levels in the foreign and home countries, let $\pi$ and $\pi^{E}$ denote the (constant) inflation rates, and define the normalized prices $\hat{p}^{E}=p^{E}/\bar{p}^{E}$ and $\hat{p}=p/\bar{p}$. The real cost of producing quantity $x$ is $C(x)$, and foreign demand is given by $D(\hat{p})$. The real profit function is then

$$\Pi(q,\hat{p}) = q\hat{p}D(\hat{p}) - C(D(\hat{p}))$$

where $q=s\bar{p}/\bar{p}^{E}$ is the real exchange rate.

We assume that the real exchange rate follows some stationary Markov process. In the beginning of each period, the firm observes the exchange rate and decides whether to keep the price from the previous period or to pay a menu cost $\xi$ to change its price. The firm's problem is then to solve

$$V(q,\hat{p}) = \max\left\{V^{k}(q,\hat{p}), V^{c}(q)\right\}. \tag{1}$$

where $V(q, \hat{p})$ is the firm's value in the beginning of a period if the real exchange rate is $q$ and if the firm's relative price is $\hat{p}$ unless a new price is chosen, $V^{k}$ is the value of keeping the price from the previous period, and $V^{c}$ is the value if a new price is set. Let $\beta$ denote the discount factor, and define an inflation and exchange rate adjustment factor as[6]

$$\zeta' \begin{cases} \frac{1}{1+\pi} & \text{under LCP} \\ \frac{q}{q'(1+\pi^{E})} & \text{under PCP} \end{cases}.$$

The value of keeping the price is then

$$V^{k}(q,\hat{p}) = \Pi(q,\hat{p}) + \beta EV(q',\zeta'\hat{p})$$

while the value of choosing a new optimal price is

$$V^{c}(q) = \max_{\hat{p}} \Pi(q,\hat{p}) - \xi + \beta EV(q',\zeta'\hat{p}).$$

The solution to this problem is characterized by the value functions together with three policy functions, $P(q)$, $\underline{P}(q)$, and $\bar{P}(q)$. The firm will change the price if $\hat{p}$ deviates sufficiently from the optimal price. $\underline{P}(q)$ and $\bar{P}(q)$ denote the lower and upper bound of the firm's region of inaction so that the firm chooses to keep the price as long as $\hat{p}\in[\underline{P}(q), \bar{P}(q)]$. If the price is outside of this region, the firm will choose a new price according to the optimal pricing rule $P(q)=\arg\max_{\hat{p}}\Pi(q,\hat{p})-\xi+\beta EV(q', \zeta'\hat{p})$. The solution algorithm is described in Appendix A.

### 2.1. Functional forms and parameter values

One time period is one quarter and we set $\beta=0.98$. We assume that the cost and demand functions are $C(y)=y^{\alpha}$ and $D(p)=\theta p^{-\mu}$. As a baseline calibration of the demand function we

[6] The normalized foreign-currency price $\hat{p}$ may change even in the absence of active pricing decisions. These changes are captured by $\zeta$.

set $\theta = 20$ and the price-elasticity to $\mu = 4$. In the cost function, we consider three specifications for the convexity, $\alpha = 1.10$, $\alpha = 1.25$, and $\alpha = 1.50$.[7] The firm's cost of adjusting the price is assumed to be the same under LCP and PCP, although one could argue that these costs are different in nature. We choose the adjustment cost $\xi$ so that 25% of firms change prices every quarter under LCP when $\alpha = 1.25$. This frequency of price updates is in line with Bils and Klenow (2004), who report that half of goods display a price that lasts for 5.5 months or less. The resulting menu cost is $\xi = 0.031$ which implies that average adjustment costs are 0.24% of average revenue.[8] In the baseline specification, we ignore inflation and set $\pi^{E} = \pi = 0$, and $\bar{p}^{E} = \bar{p} = 1$.

The log real exchange rate is assumed to follow an AR(1) process,

$$\log(q_{t+1}) = \rho \log(q_t) + \varepsilon_{t+1},$$

where $\varepsilon \sim N(0, \sigma^2)$. Based on estimates in Chari et al. (2002), we set the persistence to $\rho = 0.83$ and the standard deviation to $\sigma = 0.075$.

## 3. Static frameworks

Before analyzing the full dynamic model, we relate our model to the existing literature that examines pass-through in static settings. We ignore inflation in this section and therefore use the notation $s = q$ and $p = \hat{p}$.

### 3.1. Flexible prices

If prices are fully flexible ($\xi = 0$) our model reduces to a static maximization problem as portrayed in Feenstra (1989) and Friberg (1998). The firm chooses the price $p$ to solve

$$\max_{p} spD(p) - C(D(p))$$

Under certainty and letting $s^* \equiv (1/s)$ the solution to this problem can be characterized as the familiar mark-up relation

$$p = s^* C_D \left(1 - \frac{1}{\mu}\right)^{-1}$$

where $\mu$ is the price elasticity of demand. By totally differentiating the above expression and rearranging, we obtain the degree of exchange rate pass-through (the price change in percent due to a one percentage change in the exchange rate) as

$$\varepsilon_{p(s)} = \frac{\mathrm{d}p}{\mathrm{d}s^*} \frac{s^*}{p} = \left[\varepsilon_{\mathrm{MC}(D)} + \varepsilon_{\mathrm{MR}(p)}\right]^{-1} \tag{2}$$

where $\varepsilon_{\mathrm{MC}(D)}$ is the elasticity of marginal cost with respect to output and $\varepsilon_{\mathrm{MR}(p)}$ is the elasticity of marginal revenue with respect to the price. With the functional forms specified in Section 2.1,

[7] If the capital stock is fixed and production is $y = h^{1/\alpha}$, then $1/\alpha$ is the labor share in production and $\alpha = 1.5$ is in line with typical values. If the capital stock can be varied, lower values of $\alpha$ are realistic.

[8] Dutta et al. (1999) found that adjustment costs constitute 0.5% of revenue.

expression (2) implies that $\varepsilon_{p(s)} = [\mu(\alpha-1)+1]^{-1}$. This shows that there is less than full pass-through as long as the marginal cost is increasing. We also see that there is less pass-through if the cost function is more convex or if demand is more convex.[9]

### 3.2. Choice of export currency with fixed prices

In the setting above, the choice of invoicing currency is irrelevant since prices can be optimally adjusted. But if prices must be fixed in advance of the realization of $s$, this is obviously not the case. If firms use PCP, as $s$ changes, so does the import price which causes shifts in demand, and hence profits. If firms use LCP, changes in the exchange rate do not lead to demand shifts but to changes in cash flows from sales. Using the same notation as above, the profit functions corresponding to LCP and PCP are

$$\Pi^{\mathrm{LCP}} = spD(p) - C(D(p)) \tag{3}$$

and

$$\Pi^{\mathrm{PCP}} = p^{\mathrm{E}} D\left(\frac{p^{\mathrm{E}}}{s}\right) - C\left(D\left(\frac{p^{\mathrm{E}}}{s}\right)\right) \tag{4}$$

Note that the profit function under LCP is linear in the exchange rate. So pricing in the importer's currency yields the highest expected profits if the profit function corresponding to PCP is concave in the exchange rate, i.e. if the second derivative of $\Pi^{\mathrm{PCP}}$ with respect to $s$ is negative.[10]

Bacchetta and van Wincoop (in press) and Engel (2005) show that if the cost and demand functions are as specified in Section 2.1, then LCP will be preferred to PCP if $\mu(\alpha-1) > 1$, and PCP will be preferred otherwise. Bacchetta and van Wincoop provide the intuition for this result. PCP implies that prices and hence demand fluctuate. If demand is convex, these fluctuations raise average demand. If marginal cost was constant this would raise profits and would favor PCP over LCP. However, fluctuating demand implies frequent contractions and expansions of output, which raises average costs if the cost schedule is convex. This mechanism favors LCP over PCP, and will dominate as long as costs increase sufficiently quickly when firms expand output.

### 3.3. Pre-set but adjustable prices

Friberg (1998) and Engel (2005) show that the mechanisms generating low pass-through under flexible prices also raise the attractiveness of local currency pricing relative to producer currency pricing when prices are fixed. The intuition is that both limited exchange rate pass-through and LCP allow exporters to limit demand fluctuations by stabilizing local-currency prices. Demand fluctuations raise profits if demand is sufficiently convex relative to the convexity of costs, but reduce profits if costs are relatively convex and producers commit to

[9] According to Friberg (1998), a sufficient condition for pass-through to be less than 100% is that demand is not too convex when marginal costs are constant. As our example demonstrates, with the specific functional forms considered here, increased convexity of demand *reduces* pass-through if costs are convex. It is the interaction term between convexity of demand and costs, $\mu(\alpha-1)$, that determines pass-through.

[10] Our argument is a little simplified since firms typically do not fix the price at the certainty-equivalent level. See Friberg (1998) for a proof.

meet demand. This establishes a link between the flexible-price and fixed-price literatures; when we see little pass-through in the flexible-price literature, we see zero pass-through in the fixed-price literature.

Not surprisingly, the convexity of demand and cost functions have similar effects on pass-through also in our setting with pre-set but adjustable prices. Let $\Pi^*(s)$=max$_p\Pi(s, p)$ denote the current-period profits at the exchange rate $s$ when prices are flexible, and let $L(s, p)=\Pi^*(s)-\Pi(s, p)$ denote the loss of charging the price $p$ rather than the profit-maximizing price. Firms will adjust the price after seeing $s$ if $L(s, p)$ is large relative to the adjustment cost. Bacchetta and van Wincoop (in press) show that[11]

$$E_{t-1}\left[\Pi^{\mathrm{LCP}}\left(s_t,p_{t-1}^*\right)-\Pi^{\mathrm{PCP}}\left(s_t,p_{t-1}^*\right)\right]\begin{cases}<0 & \text{if } \mu(\alpha-1)<1\\ >0 & \text{if } \mu(\alpha-1)>1\end{cases}$$

where $p_{t-1}^*$=arg max$_p\Pi(s_{t-1}, p)$. Since the flexible-price profit $\Pi^*$ is independent of the invoicing currency, we get

$$E_{t-1}\left[L^{\mathrm{LCP}}\left(s_t,p_{t-1}^*\right)-L^{\mathrm{PCP}}\left(s_t,p_{t-1}^*\right)\right]=E_{t-1}\left[\Pi^{\mathrm{PCP}}\left(s_t,p_{t-1}^*\right)-\Pi^{\mathrm{LCP}}\left(s_t,p_{t-1}^*\right)\right].$$

We then see that

$$E_{t-1}\left[L^{\mathrm{LCP}}\left(s_t,p_{t-1}^*\right)-L^{\mathrm{PCP}}\left(s_t,p_{t-1}^*\right)\right]\begin{cases}>0 & \text{if } \mu(\alpha-1)<1\\ <0 & \text{if } \mu(\alpha-1)>1\end{cases},$$

i.e. that the expected loss of not updating the price is lower under LCP than under PCP if the cost function and/or the demand function is sufficiently convex. In deciding upon the frequency with which to update prices, a firm trades off the marginal benefit of more frequent price adjustments to the marginal cost of changing prices more often. Since the adjustment cost is the same under LCP and PCP, firms adjust prices more frequently under LCP than under PCP if $\mu(\alpha-1)<1$, and they adjust prices less frequently under LCP if $\mu(\alpha-1)>1$.

Fig. 2 plots the expected loss under LCP and PCP, using the parameterization from Section 2.1 and assuming that log $s_{t-1}=0$. The figure shows how the incentives to update prices depend on the convexity of the cost function. Under LCP, the loss of holding prices constant falls from 2% of profits when $\alpha=1.10$ to just above 0.5% when $\alpha=1.50$. Under PCP, the loss of holding prices constant increases with $\alpha$. The figure also confirms the theoretical result that the loss under LCP and PCP are approximately equal when $\alpha=1.25$.

To illustrate the intuition behind these results, Fig. 3 plots $\Pi(s_t, p_{t-1}^*)$ for different realizations of $s_t$. Note that profits with fixed prices under PCP do not deviate much from profits under flexible prices when $\alpha$ is low, but the foregone profit under LCP is substantial if the exchange rate fluctuates. When the cost function is very convex, i.e. when $\alpha$ is high, the opposite results hold.

If the cost function is convex as in the right panel in Fig. 3, firms will prefer to follow an LCP strategy and they will change prices infrequently. This behavior then implies low pass-through and increased price stickiness. On the aggregate, it leads to increased volatility of the real exchange rate. This is potentially interesting, as Engel (1999) and Chari et al. (2002) find that the volatility of real exchange rates is mostly due to deviations of the law of one price for tradable goods. Although the results are similar to the static models with fixed prices where the pass-through by construction is zero or unity, the mechanism that yields these results is quite different.

[11] This result holds locally for small variances of the exchange rate.

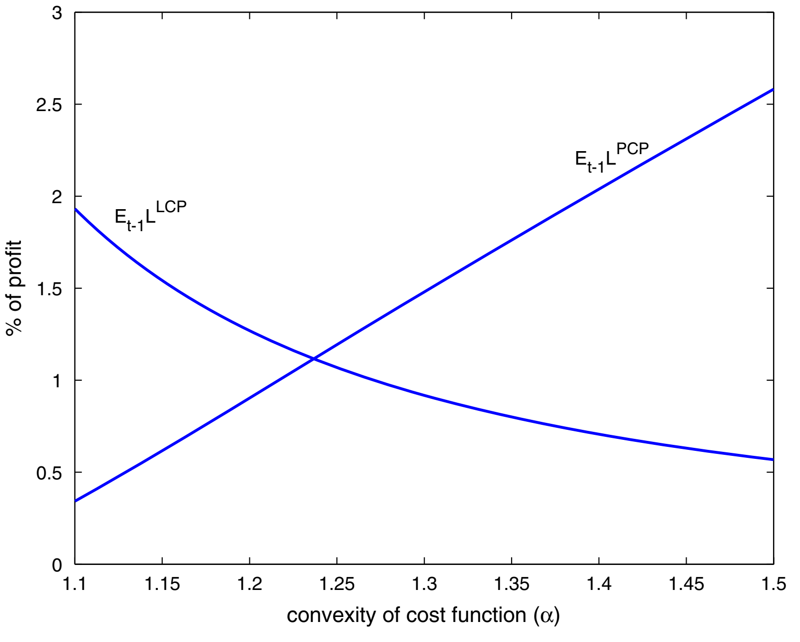


Fig. 2. Expected loss and the convexity of costs. Note: The figure shows the expected loss (relative to profits at $s_t=1$) of not adjusting the price when the price is pre-set at $p=P^*(1)$.

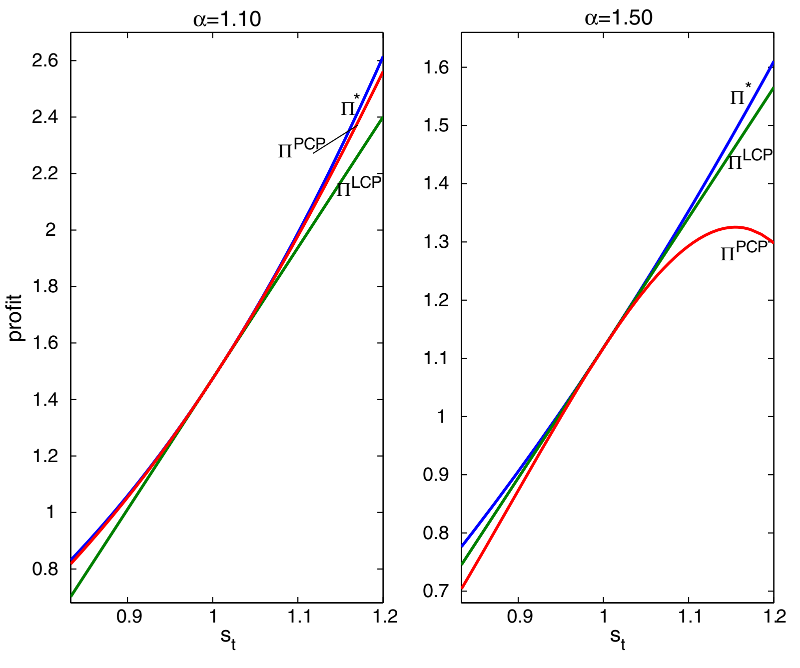


Fig. 3. Loss as a function of realized exchange rate. Note: The figure shows profits as a function of the exchange rate when the price is flexible ($\Pi^*$), and when the price is pre-set at the price that maximizes profits at $s_t=1$ ($\Pi^{LCP}$ and $\Pi^{PCP}$).

Table 1
Benchmark model specification

| Convexity of costs | Low ($\alpha$=1.10) | | | Medium ($\alpha$=1.25) | | | High ($\alpha$=1.50) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flex | LCP | PCP | Flex | LCP | PCP | Flex | LCP | PCP |
| Mean profits | 1.615 | 1.598 | 1.608 | 1.282 | 1.269 | 1.269 | 1.161 | 1.152 | 1.145 |
| Mean price | 1.000 | 1.003 | 1.006 | 1.000 | 0.999 | 1.005 | 1.000 | 1.000 | 1.004 |
| Pass-through | 0.714 | 0.575 | 0.893 | 0.500 | 0.319 | 0.673 | 0.333 | 0.156 | 0.474 |
| Updates | 1.000 | 0.376 | 0.124 | 1.000 | 0.248 | 0.247 | 1.000 | 0.159 | 0.354 |

'Mean price' is $p/\hat{p}^{\text{flex}}$, 'updates' is the fraction of periods when the firm updates its price.

Here we look beyond this first period and examine the incentives for firms to adjust prices, and we let the length of price stickiness be endogenous.

## 4. Simulation results

We use the model to generate artificial data on prices and the exchange rate. To do this, we simulate the history of a firm during 1000 time periods and repeat this simulation 200 times. We discard the first 200 time periods from each simulated series so that assumptions about the initial conditions are irrelevant. The 160,000 remaining observations on prices and the exchange rate are used in our analysis. The artificial data on $p$ and $s$ are used to estimate the degree of pass-through, which is defined as the percentage change in import prices in response to a percentage change in the exchange rate.[12] In Appendix B we argue that pass-through should be estimated with a linear projection of the form

$$y_{t+1} = \hat{\gamma}_0 + \hat{\gamma}_1 x_{t+1} + \varepsilon_{t+1}. \tag{5}$$

where $x$ is the change in the real exchange rate,

$$x_{t+1} = \log \frac{s_{t+1}(1+\pi)}{s_t(1+\pi^{\text{E}})},$$

and $y$ is the change in the real price level,

$$y_{t+1} = \log \frac{p_{t+1}}{p_t(1+\pi)},$$

under the restriction that $\hat{\gamma}_0 = 0$.

### *4.1. The baseline model*

Bacchetta and van Wincoop (in press) demonstrate that PCP will be preferred to LCP in a static model if $\mu(\alpha-1)<1$, and LCP will be preferred if $\mu(\alpha-1)>1$. To examine interesting variations in the model behavior we set the price elasticity of demand to $\mu=4$ and consider different convexities of the cost function. We focus in particular on $\alpha \in \{1.10, 1.25, 1.50\}$. We assume that inflation is zero in both countries in all three specifications.

Table 1 shows some summary statistics of these simulated economies. The first thing to note is that our dynamic model is consistent with the cutoff point in Bacchetta and van Wincoop. When $\mu(\alpha-1)=1$, firms are indifferent between PCP and LCP and average profits are the same.

[12] The model generates data on $\hat{p}$ and $q$. This data is then transformed into $p$ and $s$.

More interesting is the low frequency of price adjustments under LCP when it is favored over PCP ($\alpha = 1.5$). Fig. 4 shows a subsample of the simulated price and exchange rate series and illustrates the remarkable difference in price stickiness that stems from the choice between LCP and PCP. The filled circles indicate that the firm has updated its price under PCP and the filled squares indicate that the firm has updated the price under LCP. As expected, and consistent with the results in Table 1, we see that prices are updated less frequently under LCP. Prices therefore respond slowly to changes in the exchange rate and the pass-through is low.

The long periods of price stickiness and low volatility of the import price, given that firms set prices in the importer's currency, comes from three different sources. The first is trivial, the price importers face is insulated from the small movements in the exchange rate as long as no price adjustments take place. Second, and less trivial, firms change prices infrequently, which leads to long periods without major changes in the import price. The "constructed" zero pass-through under LCP during the period for which prices are contractually fixed, can thus be extended to longer time periods, given that the exchange rate innovation is not too large. Finally, the import price oscillates closer around the average price under LCP. Therefore, LCP implies lower pass-through and less correlation between exchange rates and imported goods prices even when firms can change prices.

Table 1 also shows that the degree of pass-through is low regardless of which invoicing currency that is used if LCP is preferred over PCP, i.e. when $\alpha$ is high. The intuition behind this result is straightforward. The fact that LCP is preferred over PCP demonstrates that it is more important to stabilize the import price than the export price. To stabilize the import price, firms must update prices frequently under PCP, and these price updates insulate import prices from exchange rate fluctuations.

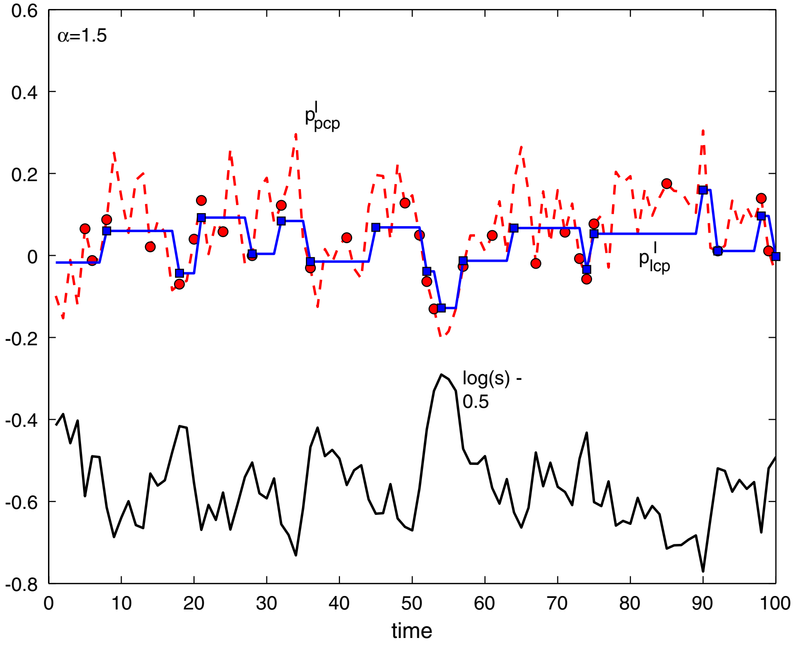


Fig. 4. Price adjustments under LCP and PCP. Note: The figure shows a subsample of the simulation when the LCP and PCP economies are hit by identical exchange rate shocks. The filled squares and circles indicate that the price has been adjusted under LCP and PCP, respectively.

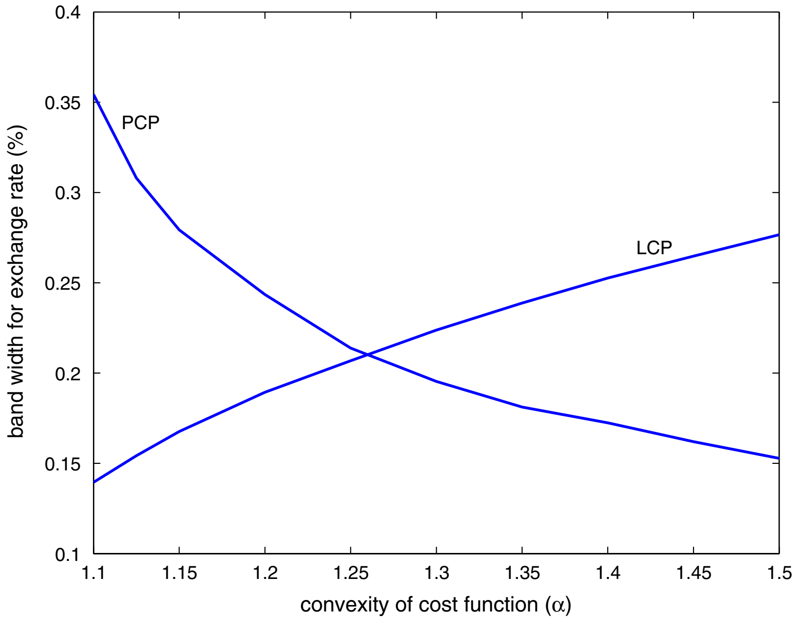


Fig. 5. Size of inaction bands. Note: The figure shows the size of inaction bands for the exchange rate implied by $\underline{\mathrm{P}}(\cdot)$ and $\bar{\mathrm{P}}(\cdot)$ at $s_t = 1$.

Fig. 5 illustrates the mechanisms behind these results. Recall that firms' pricing decisions are described by the policy functions $P(s)$, $\underline{\mathrm{P}}(s)$, and $\bar{\mathrm{P}}(s)$ such that the pre-set price $p$ is updated to $P(s)$ if $p < \underline{\mathrm{P}}(s)$ or $p > \bar{\mathrm{P}}(s)$. A straightforward comparison of these policy functions under LCP and PCP is not meaningful since the dynamics of $p$ depends on the invoicing currency. But we can transform these functions into functions of an exogenous process. Assume that the price is fixed at $\hat{\mathrm{p}}$ and assume that $\hat{\mathrm{p}}$ maximizes the instantaneous profit if the exchange rate is $\hat{\mathrm{s}}$, i.e. $\hat{\mathrm{p}} = P^*(\hat{\mathrm{s}})$. Then transform the rules $\underline{\mathrm{P}}(s)$, and $\bar{\mathrm{P}}(s)$ to rules for the deviation of the exchange rate from $\hat{\mathrm{s}}$, $\underline{\mathrm{S}}(\hat{\mathrm{s}})$, and $\bar{\mathrm{S}}(\hat{\mathrm{s}})$ such that the price is updated if $s/\hat{\mathrm{s}} < \underline{\mathrm{S}}(\hat{\mathrm{s}})$ or $s/\hat{\mathrm{s}} > \bar{\mathrm{S}}(\hat{\mathrm{s}})$. Fig. 5 plots $\bar{\mathrm{S}}(1) - \underline{\mathrm{S}}(1)$, i.e. the width of the inaction bands evaluated at the average exchange rate.

For low values of $\alpha$ the inaction bands are wide under PCP—the exchange rate is allowed to appreciate or depreciate by more than 15% before the price is adjusted when $\alpha = 1.10$. But as the convexity of the cost function increases, the loss of not adjusting the price under PCP increases and the inaction bands narrow. Under LCP, the costs of not adjusting the price are highest when the convexity of the cost function is low relative to the convexity of the demand function. The inaction bands are therefore small, and updates frequent, when $\alpha$ is low. Note also that Figs. 2 and 5 show that the invoicing currency that minimizes the average loss generates the widest inaction band, i.e. that price updates are more frequent if an inferior invoicing currency is used.

Table 1 also shows that average prices are slightly higher under PCP than under LCP, by about 0.5% on average. This has already been noted in the static price literature (Baron, 1976), where the optimal price–quantity combination under PCP is influenced by the exporter's risk aversion.[13]

[13] In that literature, the failure of what is frequently called the separation theorem to hold under PCP, relies on the fact that the exporter is not able to perfectly hedge the demand risk by buying forward contracts in her own currency. To limit demand fluctuations a risk averse exporter sets a slightly higher price. If a perfect hedge was possible, the optimal price would not be influenced by the risk aversion and the separation theorem would hold.

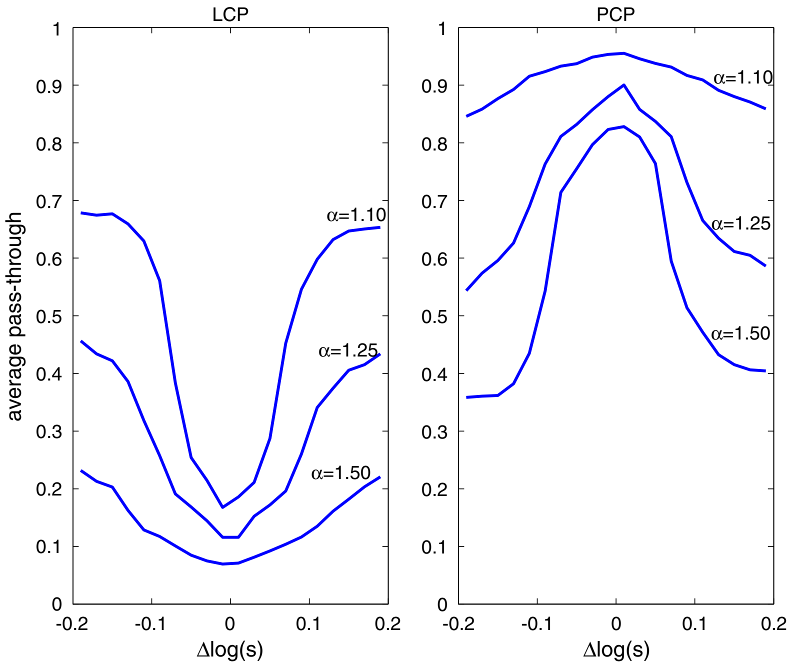


Fig. 6. Pass-through and shock size. Note: The figure plots the average pass-through, $-\Delta\log(p)/\Delta\log(s)$, for different exchange rate shocks.

By setting a price higher than the certainty equivalent price, a risk averse exporter can reduce demand fluctuations (and hence fluctuations in profits). In our framework, even risk neutral exporters set a slightly higher price under PCP since a large depreciation of the exchange rate would lead to substantially increased demand which is costly to meet if costs are convex.

### *4.2. The magnitude of exchange rate fluctuations*

Does increased exchange rate volatility lead to a higher or lower pass-through? As pointed out in a recent paper by Pollard and Coughlin (2003), this should depend on if goods are priced in the exporter's or the importer's currency. Regardless of invoicing currency, larger swings in the exchange rate imply greater incentives to adjust prices.[14] Pass-through is unity under PCP if firms do not update prices, and pass-through falls as the updating frequency increases. Larger exchange rate fluctuations therefore reduce pass-through. The mechanism is the opposite under LCP. The import price is fixed as long as firms do not update prices, but pass-through increases with the updating frequency. Pass-through is then higher for large shocks. Pollard and Coughlin examined 19 U.S. industries and found that larger exchange rate innovations on average implied larger pass-through coefficients, but with some variation between industries. Given that U.S. imports are usually denominated in dollars, their findings are consistent with the theory discussed above.

Our model nicely generates the results anticipated by Pollard and Coughlin. Fig. 6 plots the average simulated exchange rate pass-through elasticity as a function of shock size under PCP

[14] Devereux and Siu (2004) and Burstein (in press) similarly note that large monetary policy shocks can have small output effects since many firms choose to adjust prices in response to these large shocks.

Table 2
Asymmetric responses to appreciations and depreciations

| Convexity of costs | Low ($\alpha = 1.10$) | | | Medium ($\alpha = 1.10$) | | | High ($\alpha = 1.50$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flex | LCP | PCP | Flex | LCP | PCP | Flex | LCP | PCP |
| $\Delta s < 0\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.581 | 0.892 | 0.500 | 0.321 | 0.670 | 0.333 | 0.157 | 0.468 |
| Updates | 1.000 | 0.356 | 0.118 | 1.000 | 0.255 | 0.236 | 1.000 | 0.161 | 0.331 |
| $\lvert\Delta p\rvert$ | 0.045 | 0.087 | 0.048 | 0.031 | 0.066 | 0.073 | 0.021 | 0.051 | 0.085 |
| $\lvert\Delta s\rvert$ | 0.063 | 0.105 | 0.113 | 0.063 | 0.110 | 0.111 | 0.063 | 0.113 | 0.107 |
| $\Delta s > 0\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.568 | 0.894 | 0.500 | 0.317 | 0.675 | 0.333 | 0.154 | 0.480 |
| Updates | 1.000 | 0.395 | 0.129 | 1.000 | 0.242 | 0.259 | 1.000 | 0.157 | 0.378 |
| $\lvert\Delta p\rvert$ | 0.045 | 0.078 | 0.044 | 0.031 | 0.069 | 0.066 | 0.021 | 0.052 | 0.075 |
| $\lvert\Delta s\rvert$ | 0.063 | 0.100 | 0.109 | 0.063 | 0.108 | 0.108 | 0.063 | 0.110 | 0.102 |
| $\Delta s < -10\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.678 | 0.873 | 0.500 | 0.386 | 0.605 | 0.333 | 0.187 | 0.373 |
| Updates | 1.000 | 0.910 | 0.320 | 1.000 | 0.719 | 0.660 | 1.000 | 0.443 | 0.873 |
| $\lvert\Delta p\rvert$ | 0.098 | 0.102 | 0.051 | 0.069 | 0.072 | 0.080 | 0.046 | 0.055 | 0.098 |
| $\lvert\Delta s\rvert$ | 0.138 | 0.140 | 0.152 | 0.138 | 0.144 | 0.145 | 0.138 | 0.151 | 0.141 |
| $\Delta s > 10\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.636 | 0.878 | 0.500 | 0.377 | 0.617 | 0.333 | 0.181 | 0.413 |
| Updates | 1.000 | 0.888 | 0.340 | 1.000 | 0.661 | 0.698 | 1.000 | 0.423 | 0.877 |
| $\lvert\Delta p\rvert$ | 0.098 | 0.097 | 0.047 | 0.069 | 0.076 | 0.074 | 0.046 | 0.056 | 0.091 |
| $\lvert\Delta s\rvert$ | 0.137 | 0.140 | 0.148 | 0.137 | 0.144 | 0.142 | 0.137 | 0.149 | 0.140 |

'Updates' is the fraction of periods when the firm updates its price, and $|\Delta p|$ and $|\Delta s|$ are the absolute values of the average price change (in exporter's currency if PCP) and exchange rate change for firms that update their price.

and LCP. The estimated elasticity is decreasing in shock size under PCP, while the opposite pattern holds for LCP. The mechanism generating these patterns is the one described above. The willingness to pay the fixed cost of updating prices is higher when shocks are large since the pre-set price then deviates substantially from the optimal instantaneous price. Table 2 confirms that the fraction of firms that update prices is higher for large shocks than for small shocks, regardless of the direction of the shock or invoicing currency. Moreover, the difference in updating frequency between local currency pricing and producer currency pricing is greater when shocks are large. Since firms find it optimal to choose the invoicing strategy that minimizes adjustments (since these are costly) this indicates that the gains from an optimal choice are larger the more volatile the exchange rate is.[15]

### 4.3. Asymmetric pass-through under appreciations and depreciations

Both theoretical and empirical studies have analyzed asymmetric responses to exchange rate fluctuations. The theoretical literature has identified two main predictions.[16] The first theory,

[15] Note however that the optimal choice in our model does not depend on the volatility of the exchange rate.

[16] The price response to exchange rate fluctuations is similar to the price response to variations in marginal costs. Empirical studies, in particular Borenstein et al. (1997) and Peltzman (2000), have found that price responses to cost shocks are asymmetric. Theoretically, Devereux and Siu (2004) and Ellingsen et al. (2004) show that the incentive to raise prices in response to increases in marginal costs typically is greater than the incentive to reduce prices in response to falls in marginal costs.

pointed out by Knetter (1994), notes that firms operating under capacity constraints, which limit potential sales, do not benefit from low prices. Hence, a depreciation of the exporter's currency might result in a lower pass-through than an appreciation, for which the capacity constraint is not binding. On the other hand, Froot and Klemperer (1989), Marston (1990), and Krugman (1987) argue that firms competing strategically for market shares may have the opposite result on pass-through. Low prices are then the means by which firms compete, so an appreciation of the exporter's currency will result in firms adjusting by reducing the markup, while during a depreciation they will maintain the markup and allow prices to fall. While the empirical literature on asymmetries is extensive, it has found mixed support for these competing theories of asymmetric responses.[17]

Note, however, that price reductions must on average be as large as price increases in a stationary setting without inflation. Both appreciations and depreciations will therefore result in similar average pass-through. The estimated pass-through conditional on appreciations and depreciations reported in Table 2 are consequently similar.[18] But the way in which firms respond to appreciations and depreciations may still be asymmetric. If, for example, the loss of having a too low price relative to the loss of having a too high price is large, we would expect firms to frequently raise prices by a small amount and to infrequently reduce prices by a large amount.

Table 2 shows that our framework generates such asymmetries. Under PCP, firms adjust prices more frequently in response to depreciations than to appreciations, but the price changes (conditional on changing) are larger under appreciations. This is consistent with the asymmetries displayed in Fig. 3. In particular, under PCP a depreciation typically implies that the pre-set price is inefficiently low and consequently that demand will be high if the price is not adjusted. If the cost function is relatively convex, the loss of not adjusting the price is larger after depreciations ($\Delta s > 0$) than after appreciations.

### 4.4. Inflation and asymmetric pass-through

According to the Ss-pricing literature, prices should respond asymmetrically to cost and demand shocks when firms expect future inflation to be positive.[19] More specifically, firms should be more reluctant to reduce prices than to raise prices, because they would have raised prices in the absence of shocks. The results in Table 3 are based on a model specification where we set the quarterly inflation rate to 2% in both countries. The asymmetries induced by inflation are substantial, and the asymmetries reported in Table 2 for the baseline model are swept away by this more powerful mechanism.

From Table 3 we see that the price response to exchange rate fluctuations is asymmetric in the presence of inflation—there is higher pass-through in response to appreciations than in response to depreciations. Since firms know that they will need to raise prices in the future, the incentive to reduce prices in response to depreciations is low under LCP, and pass-through is consequently low. On the contrary, firms are quick to raise prices in response to appreciations since the underlying inflation also pushes prices up.

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[17] Perhaps the binding quantity constraint explanation has been given the most support, although this is far from evident. For a nice survey of the empirical literature, see Pollard and Coughlin (2003).

[18] The small asymmetries are a result of asymmetric responses discussed below, which generate nonlinearities that are not captured by the regressions.

[19] Adjustment costs need not only be actual menu costs, but can also include e.g. customer relations costs. Arguably, these costs may be low if firms passively update prices with inflation. In the extreme case when firms costlessly can index prices to inflation, the analysis reduces to that without inflation.

Table 3
Price responses under inflation, $\pi = \pi^{E} = 2\%$

| Convexity of costs | Low ($\alpha = 1.10$) | | | Medium ($\alpha = 1.25$) | | | High ($\alpha = 1.50$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flex | LCP | PCP | Flex | LCP | PCP | Flex | LCP | PCP |
| Mean profits | 1.615 | 1.598 | 1.603 | 1.282 | 1.267 | 1.268 | 1.161 | 1.148 | 1.144 |
| Mean price | 1.000 | 1.003 | 1.001 | 1.000 | 1.000 | 1.004 | 1.000 | 1.001 | 1.009 |
| Full sample | | | | | | | | | |
| Pass-through | 0.714 | 0.622 | 0.761 | 0.500 | 0.382 | 0.652 | 0.333 | 0.269 | 0.472 |
| Updates | 1.000 | 0.405 | 0.282 | 1.000 | 0.323 | 0.306 | 1.000 | 0.289 | 0.387 |
| $\Delta s < -10\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.738 | 0.863 | 0.500 | 0.503 | 0.745 | 0.333 | 0.381 | 0.480 |
| Updates | 1.000 | 0.984 | 0.002 | 1.000 | 0.946 | 0.193 | 1.000 | 0.882 | 0.640 |
| $\Delta s > 10\%$ | | | | | | | | | |
| Pass-through | 0.714 | 0.627 | 0.690 | 0.500 | 0.302 | 0.537 | 0.333 | 0.172 | 0.370 |
| Updates | 1.000 | 0.768 | 0.789 | 1.000 | 0.291 | 0.892 | 1.000 | 0.072 | 0.958 |

Contrary to the typical pattern displayed in Fig. 1, Table 3 shows that pass-through in response to appreciations can be higher under LCP than under flexible prices. The intuition is clear; when there are adjustment costs, firms raise prices more than what is motivated by today's exchange rate shock due to the upward trend in prices. But there is no such need to compensate for future inflation when prices can be adjusted costlessly.

Under PCP, a depreciation of the exporter's currency implies that the import price falls, and an appreciation implies that the import price rises if the firm does not react. Since inflation drives the profit-maximizing import price up over time, the loss of not adjusting the export price is more costly after depreciations than after appreciations. We therefore see more adjustments after depreciations than after appreciations. These frequent price updates after depreciations reduce pass-through under PCP.

Note that inflation leads to larger pass-through in response to appreciations than depreciations both under LCP and under PCP. The presence of inflation thus generates the same asymmetric pass-through for both invoicing currencies, although the underlying mechanisms are almost the opposite.

## 5. Concluding remarks

This paper has used a dynamic framework to analyze exchange rate pass-through and import price volatility. By simulating the response of an individual firm to an explicitly modelled stochastic exchange rate, we have examined how the choice of invoicing currency affects consumer prices over longer time periods. When firms adjust pre-set prices in response to exchange rate fluctuations, pass-through approaches the flexible price pass-through from different directions. Pass-through is unity under producer currency pricing if prices are fixed, and falls as price updates become more frequent. The mechanism is reversed under local currency pricing where there is zero pass-through when prices are fixed and higher pass-through when updates are more frequent. We demonstrate that the invoicing currency that minimizes the frequency of price updates also maximizes average profits. If firms choose the optimal invoicing currency, our model therefore predicts that pass-through is high under PCP and low under LCP just as in models with fixed prices. But if the invoicing currency is determined by factors outside the model, this need not be the case. Prices will then be updated frequently and pass-through will be closer to the flexible-price pass-through which is determined by properties of the cost and demand functions.

We have also analyzed if larger fluctuations in the exchange rate lead to higher pass-through than small fluctuations, as well as if there are asymmetric responses in price adjustments depending on if the currency appreciates or depreciates. For large exchange rate innovations, there is a high opportunity cost of not adjusting prices, which results in more frequent price updates. Under PCP, this leads to a lower pass-through than for small exchange rate innovations, while under LCP the more frequent price updating leads to a higher pass-through. Finally, prices respond asymmetrically to appreciations and depreciations of the exporter's currency. In the baseline specification with no inflation, this asymmetry is in general small. But in the presence of inflation in the importing country, prices respond more to appreciations than to depreciations of the exporter's currency.

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## Appendix A. Solution Algorithm

Note that $P(q) \in [\underline{P}(q), \bar{P}(q)]$, and that

$$V^k(q, P(q)) = V^c(q) + \xi$$

(often referred to as the value matching condition), and

$$V^k\left(q, \underline{P}(q)\right) = V^k\left(q, \bar{P}(q)\right) = V^c(q).$$

We use the following algorithm to solve the firm's recursive problem.

1. Choose evaluation nodes $q$ for the exchange rate and $e$ for the exchange rate shocks.
2. Set $\xi = 0$ and solve the problem without menu costs. Use the solution as an initial guess for $V^c(q)$ and $P(q)$. Also initially guess that $\underline{P}(q) = \bar{P}(q) = P(q)$. Define $\underline{\zeta}(q) = V_p^k(q, \underline{P}(q))$ and $\bar{\zeta}(q) = V_p^k(q, \bar{P}(q))$, and guess that $\underline{\zeta}(q) \equiv \bar{\zeta}(q) \equiv 0$.
3. Find polynomial approximations of the functions $V^c$, $P$, $\underline{P}$, $\bar{P}$, and linear-spline approximations of $\underline{\zeta}$ and $\bar{\zeta}$.
4. Update the value functions and policy functions at all nodes $q_i \in q$. Use some maximization algorithm to find $p_i^* = P(q)$. To evaluate $EV(q', p')$, we use Gaussian quadrature and evaluate $V(q', p')$ at all nodes $q' = q_i + e$. To evaluate $V(q', p')$, we proceed as follows:
   (a) Evaluate $V^c(q')$, $P(q')$, $\underline{P}(q')$, $\bar{P}(q')$, $\underline{\zeta}(q)$, and $\underline{\zeta}(q)$ using the approximations from step 3.
   (b) If $p' \notin [\underline{P}(q'), \bar{P}(q')]$ then $V(q', p') = V^c(q')$.
   (c) If $p' \in [\underline{P}(q'), P(q')]$ then $V(q', p')$ is approximated by a cubic spline through $V^c(q')$ and $V^c(q') + \xi$ with slope $\underline{\zeta}(q')$ at $\underline{P}(q')$ and slope zero at $P(q')$.

(d) If $p' \in [P(q'), \bar{P}(q')]$, $V(q', p')$ is approximated by a cubic spline through $V^c(q')+\xi$ and $V^c(q')$ with slope zero at $P(q')$ and slope $\bar{\zeta}(q')$ at $\bar{P}(q')$.

5. Check if the value functions and policy functions have converged. If not, repeat from 3.

## Appendix B. Estimating Pass-Through

In the empirical literature, pass-through is typically estimated in a regression like

$$\Delta \log p_{t+1} = \gamma_0 + \gamma_1 \Delta \log s_{t+1} + \varepsilon_{t+1} \tag{B.1}$$

or

$$\log p_t = \gamma_0 + \gamma_1 \log s_t + \varepsilon_t \tag{B.2}$$

where $\gamma_1$ is the pass-through coefficient. The constant terms in (B.1) and (B.2) typically capture trends in price levels and exchange rates, for example due to inflation. We are typically interested in how a firm's price responds to unanticipated or unusual exchange rate fluctuations. It may therefore be necessary to remove price level and exchange rate trends from the data. Consider defining

$$x_{t+1} = \log \frac{s_{t+1}(1+\pi)}{s_t(1+\pi^{\mathrm{E}})}$$

and

$$y_{t+1} = \log \frac{p_{t+1}}{p_t(1+\pi)},$$

and regressing

$$y_{t+1} = \hat{\gamma}_0 + \hat{\gamma}_1 x_{t+1} + \varepsilon_{t+1}. \tag{B.3}$$

As long as $\hat{\gamma}_0=0$, the estimated pass-through in (B.3) will be identical to that estimated in (B.1). But as we demonstrate below, $\hat{\gamma}_0$ will not always equal zero. Estimating the pass-through from (B.1) can then result in a severe bias. We therefore argue that pass-through should be estimated from (B.3) under the restriction that $\hat{\gamma}_0=0$, which is the method used in this paper.[20]

When estimating pass-through for the full sample, forcing the constant to equal zero is not important. When conditioning on the direction and size of exchange rate fluctuations, however, the consequences of allowing for a constant term can be dramatic and undesired. To illustrate this problem, Fig. B1 displays a hypothetical but realistic relation between prices and the exchange rate where firms only change prices in response to large exchange rate fluctuations. Clearly, there is little or no pass-through in response to small exchange rate fluctuations, and the combined pass-through in points A, B, and C is smaller than the pass-through in points A and B. But if one conditions on large appreciations (points A and B) and allows for a constant term, the estimated pass-through will be small. If also point C is included in a regression the estimated pass-through will be much higher. Such regressions are misleading since they capture additional price changes on the margin in response to additional appreciations on the margin. To find the true pass-through–the price response to the total appreciation–one has to force the regression through the origin.

This turns out to be an important problem also in our simulated data when we condition on exchange rate fluctuations being large. Pass-through is estimated to be much higher when we

[20] The empirical literature typically allows for constant terms.

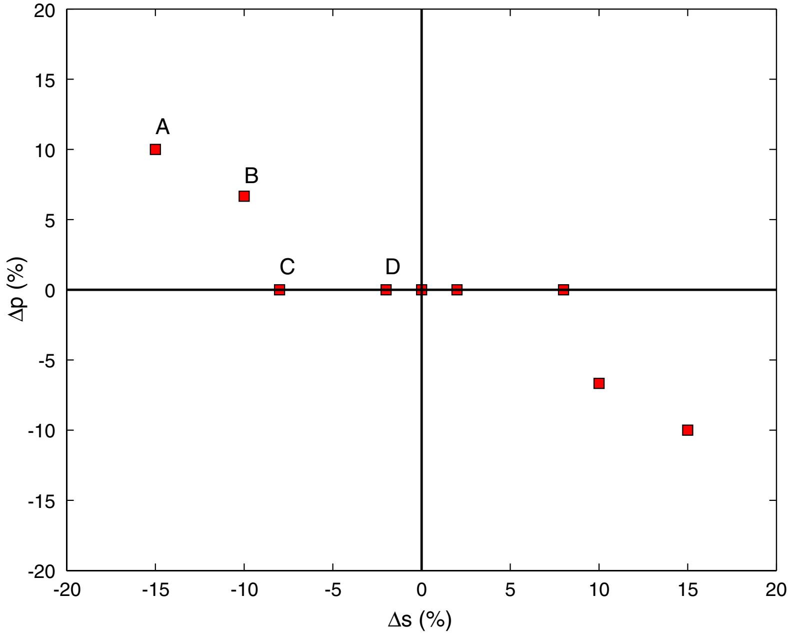


Fig. B1. Example.

allow for constant terms. This is explained by a large number of observations similar to point C in Fig. B1, i.e. firms that do not change prices in response to exchange rate changes around 10%. Table 2 shows that the estimated pass-through is 0.19 conditional on appreciations larger than 10%. When including a constant term, the estimate increases to 0.37.

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