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State Dependent Pricing and Exchange Rate Pass-Through*

Martin Flodén and Fredrik Wilander**

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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 pricing convention in combination with functional forms of cost and demand functions. In particular, there is lower pass-through, less frequent price adjustments, lower price volatility, and slightly lower average prices when prices are set in the importer's currency than when prices are set in the exporter's currency. The degree of pass-through also depends on the magnitude of exchange rate innovations. Large exchange rate innovations raise pass-through if prices are set in the importer's currency but reduce pass-through if prices are set in the exporter's currency. Finally, the presence of inflation can generate a substantial asymmetry in price adjustments. This asymmetry could lead to pitfalls when empirically estimating pass-through, and we present some potential resolutions to this estimation problem.

Keywords: Exchange rate pass-through; Nominal rigidities; Invoicing; State dependent pricing
JEL Classification: D40, E30, F31, F40

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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 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 1970's and early 1980's, 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 consider 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 become 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 are allowed to change the export 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 Figure 1.[4]

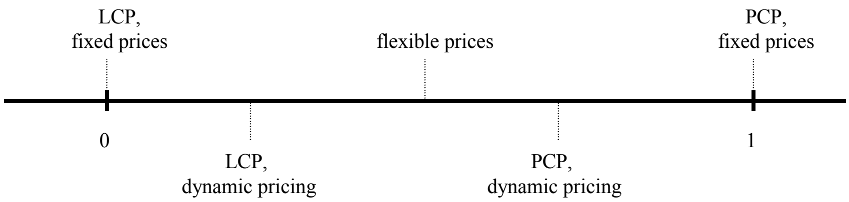
[1] See for instance Goldberg and Knetter (1997) or Goldberg and Verboven (2001). See also Engel and Rogers (1996) and Parsley and Wei (2001) for pass-through to consumer prices.

[2] See for example Krugman (1987) and Dornbusch (1987).

[3] The models in the sticky price framework either analyze the optimal choice of export currency in a partial equilibrium framework such as Baron (1976), Donnenfeldt and Zilcha (1991), Friberg (1998) and Bacchetta and van Wincoop (2002), or takes the choice of currency as exogenous and explore the consequenses of this choice in general equilibrium macro models such as Obstfeld and Rogoff (2000) and Chari, Kehoe and McGrattan (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.

Figure 1: Degree of Pass-Through Implied by Different Pricing Assumptions



Our main finding is that when LCP is favored to PCP, the exporter changes prices less frequently under LCP than 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.

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 get the result 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 price responses to appreciations and depreciations, especially in the presence of inflation in the importing country. 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 in their model, pass-through is implicitly restricted to be either zero or unity for any particular firm, the average pass-through is in the unit interval since firms endogenously choose the invoicing convention. 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 our model predicts different pass-through coefficients depending on the sign of the exchange rate innovation. This issue has received a lot of attention in empirical studies, with no clear cut answer. We will return to asym-

[5] A majority of U.S. imports are priced in dollars.

metric exchange rate pass-through, as well as to some methodological issues in estimating it, below.

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 present the results from the baseline model specification, and in Section 5 we introduce inflation. Finally, Section 6 concludes.

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. Under PCP, the firm sets the export price p^E denoted in terms of the home currency while it sets the import price p denoted in the foreign currency under LCP. Let s denote the nominal exchange rate (home currency units per foreign currency unit), and note that $p^E = sp$. Furthermore, let $\bar{p}^E$ and $\bar{p}$ denote the average price levels in the home and foreign countries, let π^E and π 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 ξ 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 β denote the discount factor, and define an inflation and exchange rate adjustment factor as

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

The value of keeping the price is then

$$V^k(q,\hat{p}) = \Pi(q,\hat{p}) + \beta \mathrm{E}V\left(q',\zeta'\hat{p}\right)$$

while the value of choosing a new optimal price is

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

The solution to this problem is characterized by the value functions together with three policy functions, $P(q)$, $\underline{P}(q)$, and $\overline{P}(q)$. The firm will change the price if $\hat{p}$ deviates sufficiently from the optimal price. $\underline{P}(q)$ and $\overline{P}(q)$ 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 $\hat{p} \in \left[\underline{P}(q), \overline{P}(q)\right]$. If the price is outside of this region, the firm will choose a new price according to the optimal pricing rule $P(q) = \arg\max_{\hat{p}} \Pi(q,\hat{p}) - \xi + \beta EV\left(q',\zeta'\hat{p}\right)$. The solution algorithm is described in the appendix.

2.1 Functional Forms and Parameter Values

One time period is one quarter and we set $\beta = 0.98$. In the baseline specification, 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 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 $\alpha = 1.50$.[6] The firm's cost of adjusting the price is assumed to be the same both under LCP and PPP, although one could argue that these costs are different in nature. We choose the adjustment cost ξ so that a 25 percent 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 last for 5.5 months or less. The resulting menu cost is $\xi = 0.031$ which implies that average adjustments costs are 0.24 percent of average revenue.[7] 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 $\varepsilon \sim N\left(0,\sigma^2\right)$. 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 Previous Static Models

Before analyzing the full dynamic model, we briefly 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 $p = \hat{p}$.

[6] 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 α are realistic.

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

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 $s^* \equiv \frac{1}{s}$ 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 μ 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

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

where $\varepsilon_{MC(D)}$ is the elasticity of marginal cost with respect to output and $\varepsilon_{MR(p)}$ is the elasticity of marginal revenue with respect to the price. With the functional forms specified in Section (2.1), 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 non-decreasing. We also see that there is less pass-through if the cost function is more convex or if demand is more convex.[8]

3.2 Static Choice of Export Currency with Sticky Prices

In the setting above, the choice of invoicing currency is irrelevant since prices can be optimally adjusted. But if prices must be set in advance of the realization of s, this is obviously not the case. Consider a static version of our model and assume that ξ is very high so that prices are not adjusted in response to exchange rate fluctuations. If firms use PCP, as s changes, so does the import price which causes variability in demand, and hence profits. If firms choose LCP, fluctuating exchange rates do not lead to demand volatility but volatility in cash flows from sales. Using the same notation as above, the profit functions corresponding to LCP and PCP are

$$\Pi_I = spD(p) - C(D(p)) \tag{3}$$

and

$$\Pi_E = p^E D(\frac{p^E}{s}) - C(D(\frac{p^E}{s})). \tag{4}$$

Note that the profit function corresponding to LCP (Π_I) is linear in the exchange rate. It then follows that if the profit function corresponding to PCP is concave in the exchange

[8] According to Friberg (1998), a sufficient condition for pass-through to be less than 100 percent is that demand is not too convex. 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.

rate, then pricing in the importer's currency yields the highest expected profits.[9] Pricing in the importer's currency will therefore yield higher profits than pricing in the exporter's currency if the second derivative of Π_E with respect to s is negative.

Bacchetta and van Wincoop (2003) and Engel (2003) 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 fluctuates. 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 imply constant 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 quick when firms expand output.

3.3 Connections between Sticky and Flexible Prices and Our Dynamic Model

Friberg (1998) and Engel (2003) demonstrate that the assumptions on cost and demand functions that generate a low exchange rate pass-through in the flexible price literature also lead to LCP being favored over PCP in the sticky-price framework. The intuition, pointed out by Friberg (1998), is that both limited exchange rate pass-through and LCP allow exporters to limit demand fluctuations. Demand fluctuations, which lead to contractions and expansions in output (if producers commit to meet demand) are costly with sufficiently convex cost schedules. Such fluctuations are, however, beneficial if marginal cost is constant and demand is convex. This establishes a link between the two literatures; when we see little pass-through in the flexible-price literature, we see zero pass-through in the sticky-price literature.

Our framework approaches the question of LCP versus PCP and the relation to exchange rate pass-through from a different perspective. To see this, consider again the shape of the profit functions under different strategies. For most functional forms of C and D, PCP induces a concave relationship between profits and exchange rate movements. LCP, as noted before, implies a linear relationship. However, if prices costlessly could be adjusted in response to exchange rate changes, one would be at least weakly better off than when prices are fixed, so that the profit function corresponding to an optimally chosen price must be convex in s.

[9] 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.

Figure 2: Difference between Profits with Fixed and Flexible Price

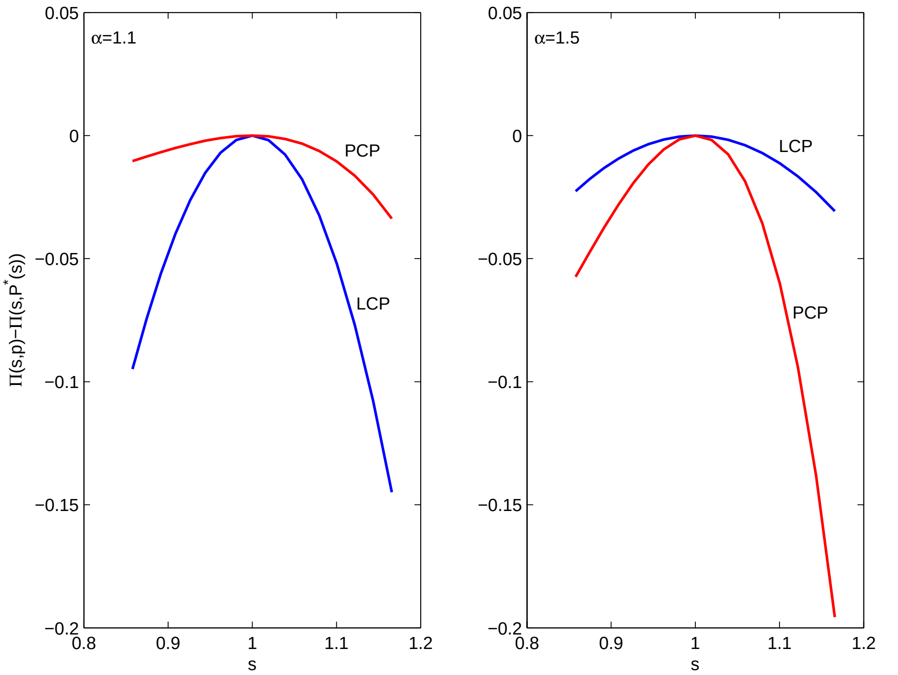


Figure 2 shows profits as a function of the exchange rate in a static model with pre-set prices relative to profits with flexible prices. More precisely, we assume that demand is $D = p^{-\mu}$, costs are $C(D) = D^{\alpha}$, the price p is fixed at the certainty-equivalent optimal price, and the price elasticity is $\mu = 4$. We then plot $\Pi(s, p) - \Pi(s, P^*(s))$, where $P^*(s)$ is the optimal flexible price given the real exchange rate s.

The figure provides much of the intuition for the results in the dynamic setting analyzed below. Note in particular that the PCP curve is relatively flat when α is low, and that the LCP curve is relatively flat when α is high. That is, profits with fixed prices under PCP do not deviate much from profits under flexible prices when α is low. But the foregone profit under LCP can be substantial if the exchange rate fluctuates. When the cost function is very convex, i.e. when α is high, the opposite results holds. In deciding upon the frequency with which to change prices, a firm trades off the marginal benefit of more frequent price adjustments to the marginal cost of changing price more often. If the cost function is convex as in the right panel in Figure 2, firms will prefer to follow a LCP strategy and they will only 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 Chari et al. (2002) find evidence that the volatility of real exchange rates is mostly due to deviations of the law of one price for tradeable goods. Although the results are similar to the static models with pre-set prices where the pass-through by construction is zero or unity, the mechanism that yields these results is quite different. Here we look beyond this first period and examine the incentives for firms to adjust prices, and the length of price stickiness is endogenous.

4 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 is 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.[10] In the appendix 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,

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

and y is the change in the real price level,

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

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

4.1 The Baseline Model

Bacchetta & van Wincoop (2003) 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 three different parameterizations of the cost function, $\alpha^A = 1.1$, $\alpha^B = 1.25$, and $\alpha^C = 1.5$. We assume that inflation is zero in both countries in all three specifications.

Table 1. Benchmark Model Specification

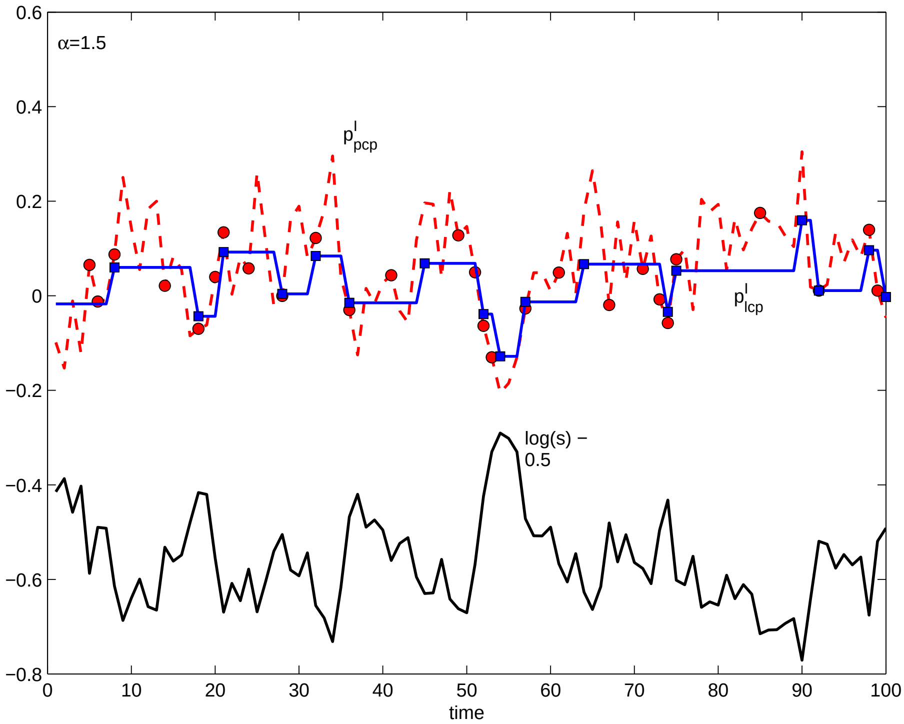
α	1.1			1.25			1.5		
	Flex	LCP	PCP	Flex	LCP	PCP	Flex	LCP	PCP
Mean profits	1.615	1.598	1.608	1.282	1.269	1.269	1.161	1.152	1.145
Mean price	1.000	1.003	1.006	1.000	0.999	1.005	1.000	1.000	1.004
Pass-through	0.714	0.575	0.893	0.500	0.319	0.673	0.333	0.156	0.474
Updates	1.000	0.376	0.124	1.000	0.248	0.247	1.000	0.159	0.354

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

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

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. More interesting is the low frequency of price adjustments under LCP when it is favored over PCP ($\alpha = 1.5$). Figure 3 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 that the pass-through is low.

Figure 3. Price Adjustments under LCP and PCP



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 pricing convention that is used if LCP is preferred over PCP, i.e. when α 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.

Finally we can note that average prices are slightly higher under PCP than 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.[11] By setting a price higher than the certainty equivalent price, a risk averse exporter can lower 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. If firms use PCP, larger swings in the exchange rate imply greater incentives to adjust prices. This should lead to more firms responding to an innovation and lower pass-through. Under LCP, on the other hand, pass-through is higher when more firms change prices. 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, this result is consistent with their discussion.

[11] 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 slighlty 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.

Figure 4: Pass Through under LCP, $\alpha = 1.5$

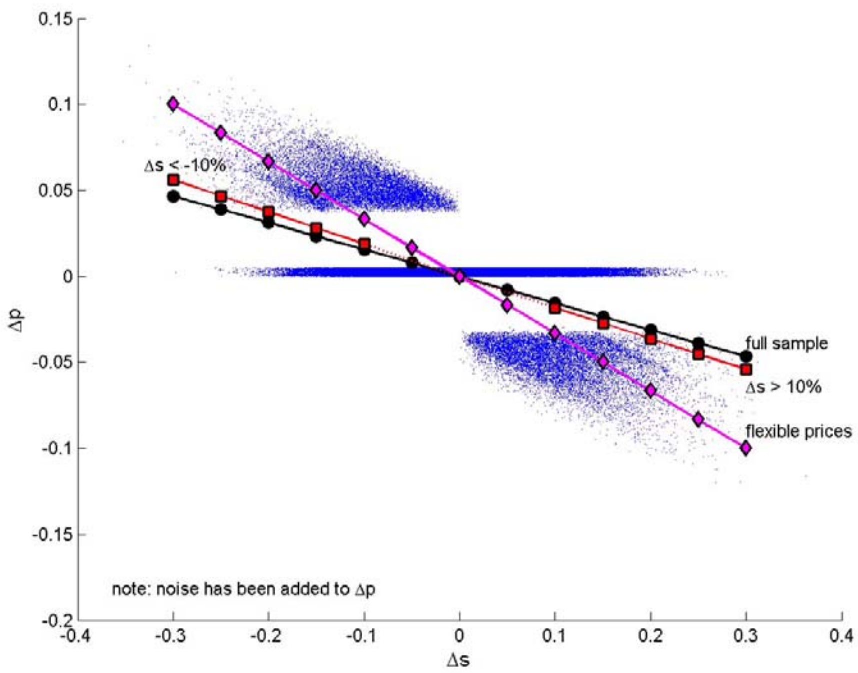
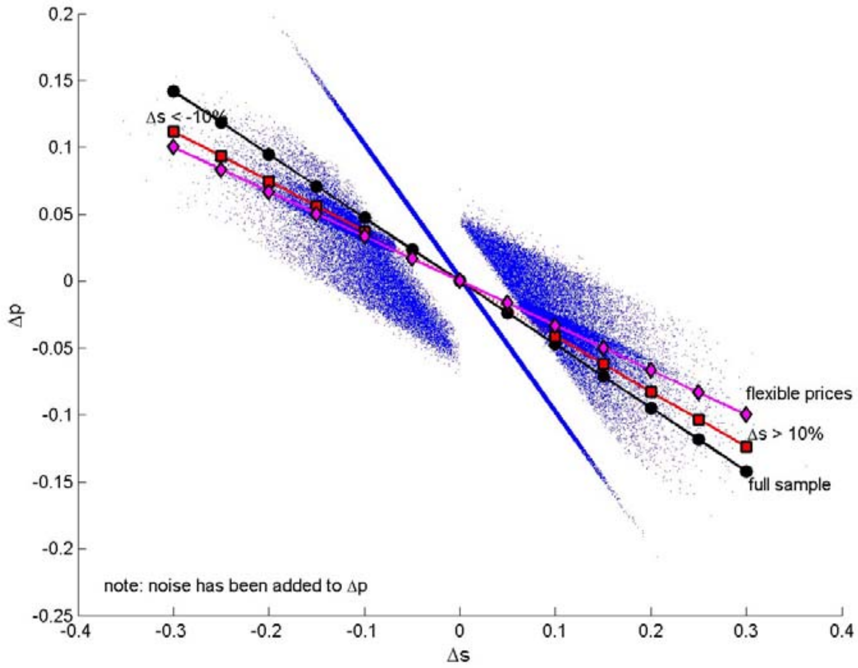


Table 2 and Figures 4 and 5 show that our model nicely generates the results anticipated by Pollard and Coughlin – larger shocks lead to increased pass-through under LCP, and vice versa under PCP. Figure 4 plots the exchange rate and price fluctuations generated by the simulations under LCP together with least squares regression lines through the data points.[12] The flexible-price line shows how firms react when there are no menu costs, the full-sample line shows the regression results based on all observed data points, while the $\Delta s < -10\%$ and $\Delta s > 10\%$ lines show the regression results when conditioning on large exchange rate changes. The slopes of the lines equal (the negative of) the estimated pass-through. As expected, the figure shows that pass-through is higher when we condition on large exchange rate fluctuations. Since for $|\Delta s| > 10\%$ the exchange rate innovation almost always lead to an updated price, the horizontal thick line representing firms that do not adjust becomes thinner and thinner as $|\Delta s|$ becomes larger. These observations then exert less influence when fitting the regression line through the data points, which results in a steeper slope coefficient.

Figure 5 shows simulated exchange rate and price changes under PCP, again assuming that $\alpha = 1.5$. Now the slope of the line representing firms that do not adjust is -1. Under PCP, there is full pass-through if firms keep prices fixed. Also here we see that the line representing no adjustment gets thinner as Δs gets larger. In this case more firms adjusting leads to lower pass-through, which reduces the slope of the regression line for large changes.

[12] Some noise has been added to the simulated price changes in the graph so that the number of identical and overlapping data points is reduced.

Figure 5: Pass-Through under PCP, $\alpha = 1.5$



4.3 Asymmetric Pass-Through under Appreciations and Depreciations

Both theoretical and empirical papers have analyzed asymmetric responses to exchange rate fluctuations In the theoretical literature, two main predictions can be outlined. The first theory, pointed out by Knetter (1994), states that if firms operate under capacity constraints, which limit potential sales, it is not worthwhile to have 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, if firms compete strategically for market shares, quite the opposite may result.[13] Now low prices are 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 this is vast, it has found mixed support for these competing theories of asymmetric responses.[14]

Table 2 shows that the baseline model generates asymmetric pass-through depending on

[13] The connection between market share objectives and exchange rate pass-through has been analyzed in papers such as Froot and Klemperer (1989) Marston (1990) as well as Krugman (1987).

[14] Previous empirical papers have found very different results. Some have found evidence of clear asymmetries, while others have not. However, when asymmetries have been found, no clear cut direction has generally been distinguishable. Perhaps the binding quantity constraint explanation have been given the most support, although this is far from evident. For a nice survey of the empirical literature, see Pollard and Coughlin (2003).

the sign of Δs, although the asymmetry is small.[15] In the absence of inflation, the pricing convention determines the direction of the asymmetry. Under LCP, exchange rate pass-through is higher under appreciations than depreciations. To understand this, note that the profit function under LCP, equation (3), implies that the optimal price is

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

Fluctuations in the exchange rate, s, thus affect the firm's optimal price in the same way as fluctuations in marginal cost affect the price. Our model is therefore consistent with that firms are more prone to raise price in response to a rise in marginal costs than they are willing to lower price in response to a decline in marginal costs. Many empirical studies have confirmed what seem to be a "stylized fact", that firms' price responses to cost shocks are asymmetric. Borenstein et al. (1997) examine retail gasoline prices and finds evidence that gasoline prices react more to increases in crude oil prices than they do to decreases. Peltzman's (2000) study confirms this asymmetry both for producer and consumer products. While the proposed explanations for this phenomenon are many, in our pure baseline model without strategic interaction, inflation, inventory systems etc, many of these explanations are implausible. However, in a recent paper, Ellingsen et al. (2004) show that under very mild conditions on functional forms of cost and demand (essentially all cases except both constant demand and constant marginal cost), the firm's incentive to raise price in response to an increase in marginal cost is greater than the incentive to reduce the price in response to a fall in marginal costs. They show that this result holds also in a dynamic setting with menu costs.[16] Given that we from the first order condition above can note that changes in exchange rates under LCP are equivalent to changes in marginal costs, our results are basically a replication of the asymmetry found in Ellingsen et al.

[15] The general pattern displayed in Table 2 are robust to alternative values for the convexity of demand, μ. We find that the asymmetries are larger when μ is high, i.e. when the markup is low.

[16] Burstein (2002) discuss a similar mechanism, and Devereux and Siu (2004) demonstrate that general equilibrium effects reinforce the asymmetry.

Table 2: Asymmetric Responses to Appreciations and Depreciations

α	1.1			1.25			1.5		
	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

Note: '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.

This clean result does not carry over to the case of PCP. Exchange rate fluctuations then affect demand in the importing country, so the equivalence of changes in s and changes in marginal cost is no longer true. Under PCP, pass-through is higher under depreciations than appreciations. To get some intuition for this result, recall that the solution to the firm's dynamic problem can be characterized by the value functions together with three policy functions – the lower and upper bound of the firm's region of inaction, $\underline{P}(q)$, and $\overline{P}(q)$, and the optimal updating price $P(q)$. The firm will change the price if last period's price $\hat{p}$ is outside the region of inaction, i.e. if it deviates sufficiently from the optimal price. Recall that a depreciation of the exporter's currency raises demand under PCP, and if the cost function is very convex, as in the right-hand plot in Figure 1, profits fall sharply in s. Firms will therefore be reluctant to have a price that is too low. This results in an asymmetric band of inaction where $\underline{P}(q)$ is close to $P(q)$, so that firms change prices more frequently after depreciations than after appreciations. Under PCP, this mechanism tends to reduce the pass-through for depreciations. But since the optimal price is closer to the lower bound, given that firms change the price, Δp is on average larger for firms that reduce prices in response to appreciations than for firms that raise prices in response to depreciations. This mechanism tends to reduce pass-through under appreciations. The second effect dominates, especially for large fluctuations in the exchange rate since most firms then update prices regardless of the sign of Δs. Under PCP we therefore have lower pass-through for appreciations than depreciations.

5 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. 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 two percent 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 response of prices 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. Figures 6 and 7 provide insights to the mechanisms that generate these results. Figure 6 shows the estimated pass-through under LCP and inflation. Since firms know that they will need to raise prices in the future, the incentive to reduce prices in response to depreciations is low. On the contrary, firms are quick to raise prices in response to appreciations since many of them would have raised prices anyway. Contrary to the typical pattern displayed in Figure 1, 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.

Table 3: $\pi^I = \pi^E = 2\%$

α	1.1			1.25			1.5		
	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

Note: $\bar{\pi}$ is the average profit, p.t. is the degree of pass through, and Δp is the fraction of periods when the firm changes its price.

Under PCP, a depreciation of the exporter's currency implies that the import price falls if firms do not react. Therefore, we see more adjustments to a depreciation than to an appreciation. If the exchange rate strengthens, it is not so costly to have a price slightly too high, as inflation will erode it. However, in response to a depreciation it is not optimal to allow prices to fall by the full amount, so firms adjust prices upwards. As can be seen from Figures 6 and 7, inflation leads to larger pass-through in response to appreciations than depreciations under both pricing conventions. The presence of inflation thus generates the same asymmetric pass-through under both pricing conventions, although the underlying mechanisms are almost the opposite.

Figure 6: Price Adjustments under LCP and Inflation, $\alpha = 1.5$

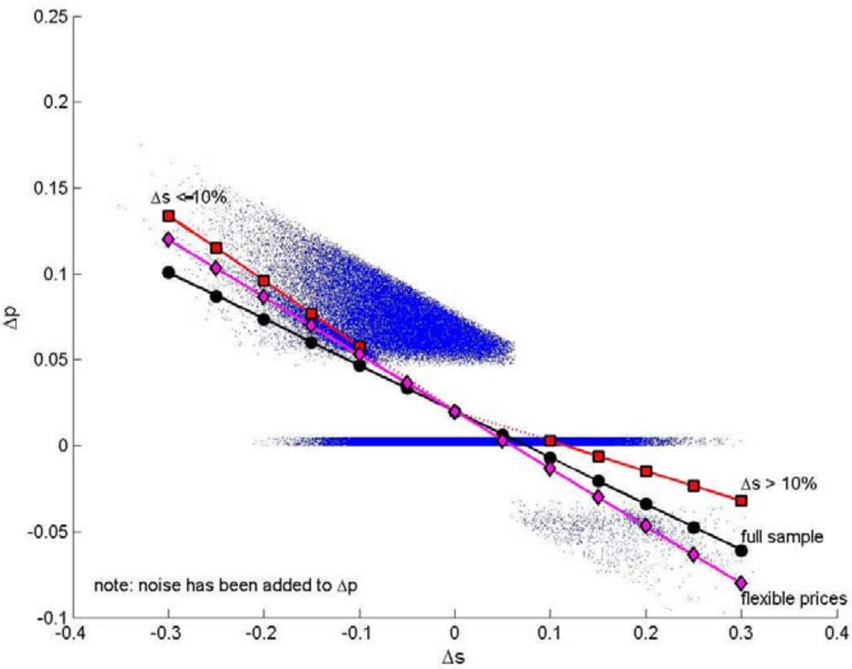
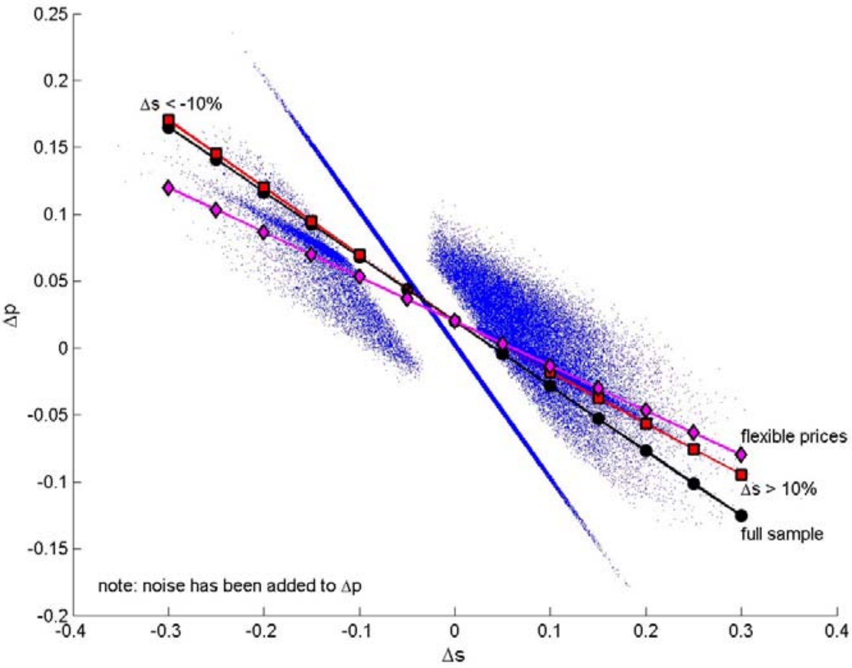


Figure 7: Price Adjustments under PCP and Inflation, $\alpha = 1.5$



6 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. Our results indicate that extending the analysis beyond the time for which prices are contractually fixed, thereby allowing firms to adjust prices, implies a pass-through that approaches the flexible price pass-through from different directions. Producer currency pricing generally generates a pass-through coefficient higher than the flexible price pass-through which in turn typically is higher than the pass-through under local currency pricing. Moreover, when analyzing how import prices evolve over time, we concluded that local currency pricing can lead to long periods without adjustments to exchange rate innovations, which results in low correlations between nominal exchange rates and import prices. Import prices also fluctuate much closer around its mean and are on average slightly lower than under producer currency pricing.

We have also analyzed if larger fluctuations in the exchange rate leads 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 a 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.

Appendix A Solution Algorithm

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

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

and

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

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 $\underline{P}(q) = \overline{P}(q) = P(q)$. Define $\underline{\zeta}(q) = V_p^k\left(q, \underline{P}(q)\right)$ and $\overline{\zeta}(q) = V_p^k\left(q, \overline{P}(q)\right)$, and guess that $\underline{\zeta}(q) \equiv \overline{\zeta}(q) \equiv 0$.
3. Find polynomial approximations of the functions V^c, P, $\underline{P}$, $\overline{P}$, and linear-spline approximations of $\underline{\zeta}$ and $\overline{\zeta}$.
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 $\mathrm{E}V(q', p')$, 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 $V^c(q'), P(q'), \underline{P}(q'), \overline{P}(q'), \underline{\zeta}(q)$, and $\overline{\zeta}(q)$ using the approximations from step 3.
   (b) If $p' \notin \left[\underline{P}(q'), \overline{P}(q')\right]$ then $V(q', p') = V^c(q')$.
   (c) If $p' \in \left[\underline{P}(q'), P(q')\right]$ 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 $p' \in \left[P(q'), \overline{P}(q')\right]$, $V(q', p')$ is approximated by a cubic spline through $V^c(q') + \xi$ and $V^c(q')$ with slope zero at $P(q')$ and slope $\overline{\zeta}(q')$ at $\overline{P}(q')$.
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.

$$\Delta \ln p_{t+1} = \gamma_0 + \gamma_1 \Delta \ln s_{t+1} + \varepsilon_{t+1} \tag{B.6}$$

or

$$\ln p_t = \gamma_0 + \gamma_1 \ln s_t + \varepsilon_t \tag{B.7}$$

where γ_1 is the pass-through coefficient. A coefficient of unity would implicate full pass-through and a coefficient less than unity would indicate less than full pass-through. The constant terms in (B.6) and (B.7) 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. Therefore it may be necessary to remove price level and exchange rate trends from the data. Consider defining

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

and

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

and regressing

$$y_{t+1} = \hat{\gamma}_0 + \hat{\gamma}_1 x_{t+1} + \varepsilon_{t+1}. \tag{B.8}$$

As long as $\hat{\gamma}_0 = 0$, the estimated pass-through in (B.8) will be identical to that estimated in (B.6). To see this, note that (B.8) in combination with $\hat{\gamma}_0 = 0$ implies that

$$\Delta \ln p_{t+1} - \ln(1+\pi) = \hat{\gamma}_1 \Delta \ln s_{t+1} + \hat{\gamma}_1 \ln \frac{1+\pi}{1+\pi^E}$$

so that (B.6) results in

$$\gamma_0 = (1+\gamma_1)\ln(1+\pi) - \gamma_1 \ln\left(1+\pi^E\right)$$

and

$$\gamma_1 = \hat{\gamma}_1.$$

Although we typically want to restrict the constant term to equal zero when we have controlled for trend inflation and trend exchange rate movements, $\hat{\gamma}_0$ will not always equal zero. In those special cases, as we demonstrate in Section 4.1.1 below, estimating the pass-through from (B.6) can result in a severe bias. Hence we argue that pass-through should be estimated from (B.8) under the restriction that $\hat{\gamma}_0 = 0$,which will be the method used in this paper.

An example that can perhaps clarify our point is when one condition on large exchange rate movements, as well as the direction of the asymmetry.When estimating pass-through for the full sample, forcing the constant to equal zero is not important. When conditioning on the size of exchange rate fluctuations, however, the consequences of allowing for a constant term can be dramatic and undesired, and this is particularly the case when conditioning on depreciations and appreciations separately.[17] To illustrate this problem, Figure 5 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.

Figure A1

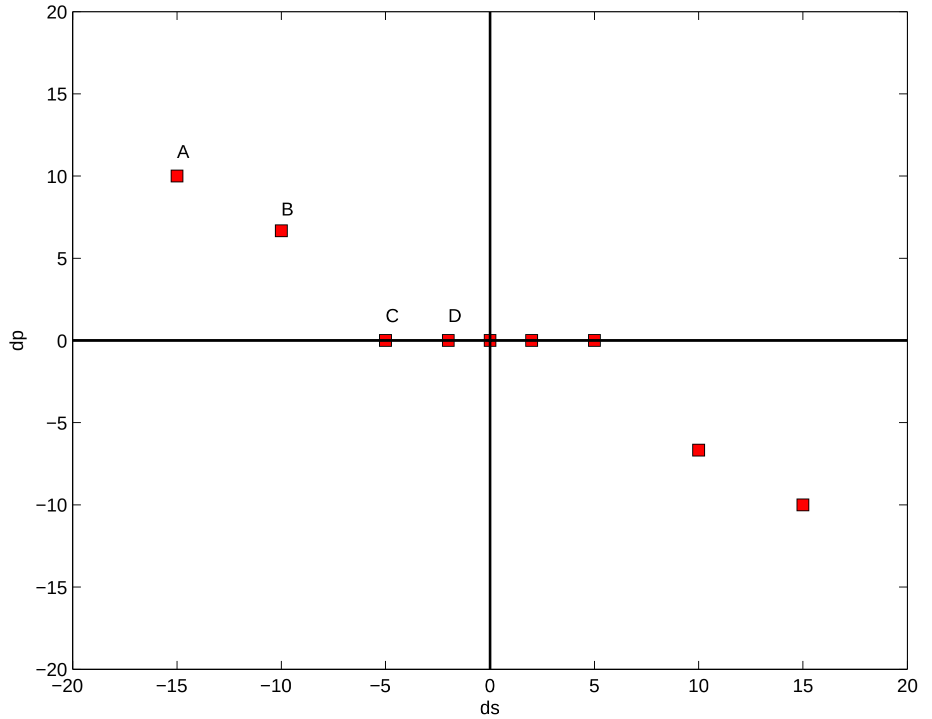
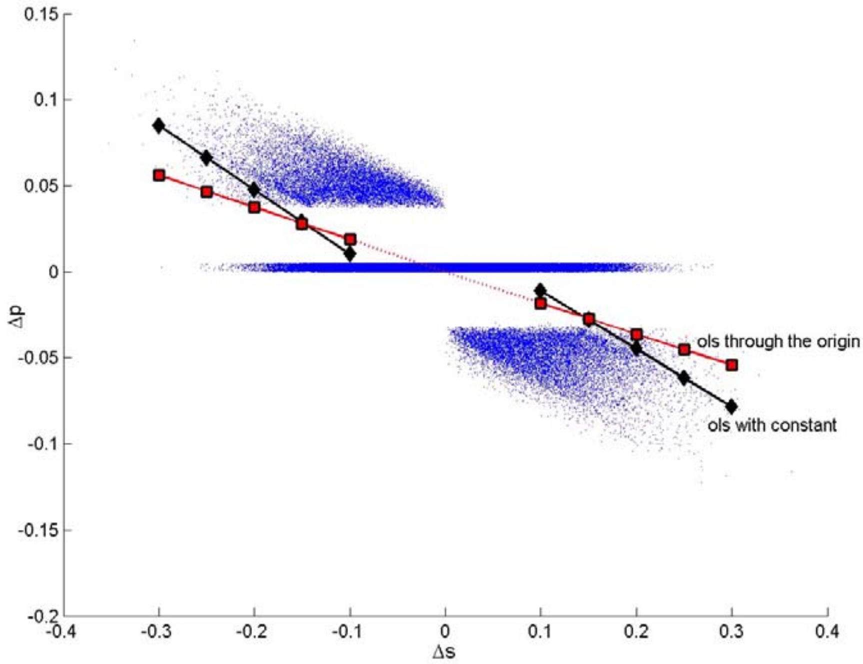


Figure A2 shows that this is an important problem also in our simulated data. Pass-through is estimated to be much higher when we allow for constant terms. This is explained by a large number of observations similar to point C in Figure A1, i.e. firms that do not change prices in response to exchange rate changes around 10 percent. Table 2 shows that the estimated pass-through is 0.19 conditional on appreciations larger than 10 percent. When allowing for a constant term, the estimate increases to 0.37.

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

Figure A2. Pass-Through under LCP, $\alpha = 1.5$



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