Asymmetries and Non-Linearities in Exchange Rate Pass-Through*

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Abstract

While exchange rate pass-through into import prices is often assumed to be symmetric to appreciations and depreciations, we show that foreign currency appreciations pass through faster than foreign currency depreciations into product-level BLS import prices. This asymmetry is not the result of asymmetric price stickiness or selective exit, but it is more pronounced among differentiated goods closer to the consumer, rather than intermediate or capital goods. Using sectoral data on U.S. trade values, we also compute the implied import quantity responses, showing that imports respond little in the short run and that foreign depreciations lead to larger import responses than appreciations.

JEL classifications: E31, F14, F31, L11

Keywords: Trade Prices, Pass-through, Asymmetries

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1 Introduction

Exchange rates play a key role in the global transmission of shocks via trade linkages. Exploring how exchange rate changes pass through into product-level import prices helps to understand both inflation at an aggregate level and the nature of firm supply and demand at a micro level. Theoretical and empirical analyses typically assume exchange rate appreciations and depreciations pass through symmetrically. Likewise, the literature typically assumes that large and small exchange rate changes pass through at the same rate. Evidence of asymmetries and/or non-linearities have important implications for how central banks set monetary policy rules.

We show that foreign currency appreciations pass through more quickly and completely than foreign currency depreciations using product-level microdata of U.S. import prices at the dock. In particular, this asymmetry toward faster pass-through of appreciations is more evident among differentiated goods closer to the consumer. Theoretically, this could reflect differences in pricing power, the shape of consumer demand, or the cost structure faced by firms. On the other hand, it could also represent asymmetric price stickiness or selective exit.

We address the former by analyzing what Gopinath et al. (2010) term medium-run pass-through (MRPT), or pass-through conditional on a price change. This eliminates the direct implications of sticky prices, and we show that the asymmetry persists. Indeed, we actually find that an exchange rate depreciation raises the probability of a price change, while a appreciation slightly lowers it, though the difference is not statistically significant.

Selective exit would also lead to the asymmetry in exchange rate pass-through that we observe. Foreign currency appreciations are a negative shock for foreign exporters: they must either pass through the appreciation into a higher dollar price and face lower demand or adjust their markups and earn a lower profit. Either way, the appreciation may be sufficient to induce them to exit the U.S. market, and the lack of a recorded price would bias pass-through of appreciations towards zero. We show that, focusing on those exits most likely to be endogenous, foreign currency appreciations do not significantly raise the probability of exit more than foreign currency depreciations. Strikingly, both raise the probability of exit, which suggests that exchange rate changes may be resulting from volatility in the foreign market and that volatility is what is inducing product exit.

It may be the case that larger exchange rate changes have different effects than smaller exchange rate changes. By adding higher order terms to our estimating equation, we look for the potential of nonlinearities in pass-through. We find no evidence, however, that larger exchange rate changes pass through at different speeds than smaller exchange rate changes.

The asymmetries we find could also be exhibited in trade quantities. Although we do not have data on trade quantities, we can estimate responses of trade value to exchange rate shocks using sectoral data. We find significant asymmetries. In response to a foreign currency appreciation, the value of imports actually rises in the short run before ending up near zero. On the other hand, in response to a foreign currency depreciation, import value falls a bit in the short run before ending up near zero. This is a puzzling asymmetry previously identified in Lewis (2017), but with well-identified trade price elasticities in hand, we can go one step further and compute the implied trade quantity response. Both appreciations and depreciations have near-zero import quantity responses in the short run, while foreign currency depreciations have a stronger response than appreciations after six quarters.

We evaluate the potential for standard models of exchange rate pass-through to match the asymmetries we identify. Incorporating sticky prices (whether Calvo-style or menu cost) and strategic complementarities into a standard model do not generate large enough asymmetries. We therefore add capacity constraints, in the form of convex adjustment costs to increasing the quantity produced, to result in lower pass-through for producer currency depreciations relative to appreciations in the short run. While in principle these costs can generate larger asymmetries, in practice the models are incapable of simultaneously matching standard price facts like the frequency and size of price changes while still generating the asymmetric pass-through. In the data, price changes are infrequent and large in absolute magnitude, while convex adjustment costs work to create smaller price adjustments.

This paper contributes to a vast literature on understanding exchange rate pass-through to aggregate and product-level prices.[1] The empirical literature has found a wide variation in the estimates of exchange rate pass-through across countries, goods, and time periods. However, the literature has converged on a number of stylized facts. For the United States, studies find that pass-through is incomplete and low. In the aggregate data, the long-run pass-through estimate is around 0.4 (Campa and Goldberg 2005); in the product-level data, the estimate is similar (Gopinath and Itskhoki 2010). Empirical studies also show that exchange rate pass-through in the U.S. has been declining since at least the 1980s (Marazzi et al. 2005).

The recent empirical evidence on non-linearities or asymmetries in exchange rate pass-through is limited, especially for the case of the United States.[2] Older studies focused on asymmetry find mixed results with no clear evidence on whether appreciations or depreciations are associated with higher pass-through. Mann (1986) used aggregate U.S. data and found that exchange rate pass-through was higher, but slower, in a period of dollar depreciation than one of dollar appreciation. However, the difference was not statistically significant. Kadiyali (1997) and Goldberg (1995) focused on a single industry and found the opposite result. Other industry studies found that the direction of asymmetry depended on the industry, e.g Mahdavi (2002) and Olivei (2002).

Pollard and Coughlin (2004) is one study that considers both asymmetries and non-linearities in

[1] Burstein and Gopinath (2014) provide an excellent overview.

[2] Other fields have considered asymmetric pass-through, however. For example, Batista Politi and Mattos (2011) finds evidence that value added tax increases as passed through more than decreases in Brazil, while Benedek et al. (2015) finds no evidence for asymmetric pass-through in a sample of 17 Euro-area countries. (Benzarti et al. 2017) does, however, find evidence that prices rise faster than they fall for changes in VAT among a sample of European countries.

exchange rate pass-through into U.S. import prices. They use industry-level exchange rate changes and find no clear direction of asymmetry across industries, as in the previous literature. They do find that non-linearities exist such that larger exchange rate fluctuations are generally associated with higher exchange-rate pass-through, even when taking asymmetries into account. Razafindrabe (2017) finds evidence of asymmetry using a small sample of individual French import prices, but that this asymmetry is largely due to nominal rigidities.[3]

The paper proceeds as follows: Section 2 provides a description of the BLS microdata. Our empirical results on asymmetries in pass-through is presenting in section 3, which is followed by a proposal for a model capable of explaining our results in section 4. Section 5 concludes.

2 Data

We use monthly product-level price data from the BLS International Price Program (IPP) Research Database spanning 1994-2014 (Kim et al. 2015). The BLS collects pricing information from U.S. importers in order to produce a monthly import price index. Importers are sampled based on a probability proportionate to size sampling strategy at the reporter/item level.[4]

Importers are asked to report transaction prices whenever possible. However, they may instead report list or estimated prices. These reported prices are then adjusted and converted into U.S. dollar prices, if needed. For the purpose of index construction, the BLS does not differentiate between intrafirm and arms-length transactions, other than to note which items are traded between related parties. We exclude these from our study, since intrafirm prices are shown to have different properties (Neiman 2010). We also exclude estimated, imputed, services, and petroleum prices, as well as prices from exporting countries with exchange rate regimes fixed to the dollar.[5]

Aside from prices, we observe information about the U.S. importer, country of origin, invoicing currency, trade status, a classification coding, and the reason for the product being dropped from the sample. The product exit codes allow us to differentiate between products that exit due to sample rotation and products that exit due to other reasons. In order to examine selection, we consider product exits due to the exporter going out of business or the item no longer being traded.

In addition, we add data on monthly foreign CPIs and exchange rates from the IMF International Financial Statistics. When time dummies are not available, we also use a monthly non-fuel commodity price index from the IMF.

Of particular interest here is the distribution of exchange rate changes. Making use of bilateral exchange rates allows us to observe much larger exchange rate appreciations and depreciations than

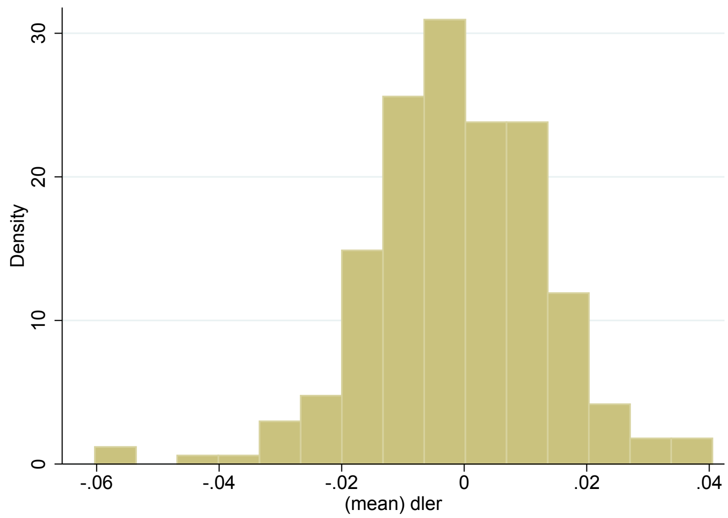
[3]The French import price data do not distinguish the country of origin and thus preclude the use of bilateral exchange rates when estimating pass-through.

[4]See Kim et al. (2013) for more details about the sampling strategy.

[5]Countries with dollar pegs are identified using Shambaugh's Exchange rate Regime Classification dataset that he generously provides on his website. For the missing countries, data is supplemented with information found in internet searches.

could be analyzed with aggregate multilateral import price pass-through regressions. A large sample of appreciations and depreciations in the same time period helps us identify asymmetries. In our sample, the distribution of bilateral exchange rate changes used in our study are shown in Figure 1.

Figure 1: Histogram of log exchange rate changes



3 Asymmetries and Non-Linearities in U.S. Microdata

To look for asymmetric pass-through in U.S. import prices, we augment a standard pass-through regression to separately account for pass-through of foreign currency appreciations and depreciations. First, define the bilateral exchange rate $e_{j,t}$ as the U.S. dollar per foreign currency of country i at time t (that is, an increase in e is a foreign currency appreciation). Then, let:

$$\Delta e^{+}_{j,t} \begin{cases} \Delta e & \text{if } \Delta e > 0 \\ 0 & \text{otherwise,} \end{cases}$$

and similarly,

$$\Delta e^{-}_{j,t} \begin{cases} \Delta e & \text{if } \Delta e < 0 \\ 0 & \text{otherwise.} \end{cases}$$

This forms the core of our estimating equation of the nominal price $p_{i,j,t}$ for product i in country j at time t at a monthly frequency:

$$\Delta p_{i,j,t} = \sum_{k=0}^{18} \{\beta_k^+ \Delta e^+_{j,t-k} + \beta_k^- \Delta e^-_{j,t-k}\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t}, \tag{1}$$

where $P_{j,t}$ is the foreign CPI in country j, $\boldsymbol{\alpha_t}$ are a set of monthly time dummies, and $\boldsymbol{s}_j$ are a set of country/sector dummies.[6] The time dummies control for all U.S. and global characteristics. That is, identification of pass-through comes from relative exchange rate movements between the U.S. and its trading partners, rather than multilateral changes in the dollar or domestic conditions within the U.S. Estimation in differences removes product-specific level effects, and sectoral dummies control for trends in these prices.

The straightforward impulse response at horizon h of a price to a bilateral change in the exchange rate is simply $\sum_{k=0}^{h} \beta_k^+$ for dollar depreciations and $\sum_{k=0}^{h} \beta_k^-$ for dollar appreciations.[7] Of particular interest is the point estimate and statistical significance of the difference in impulse responses at each horizon, $\sum_{k=0}^{h} \left[\beta_k^+ - \beta_k^-\right]$, shown in the right panel of Figure 2.[8]

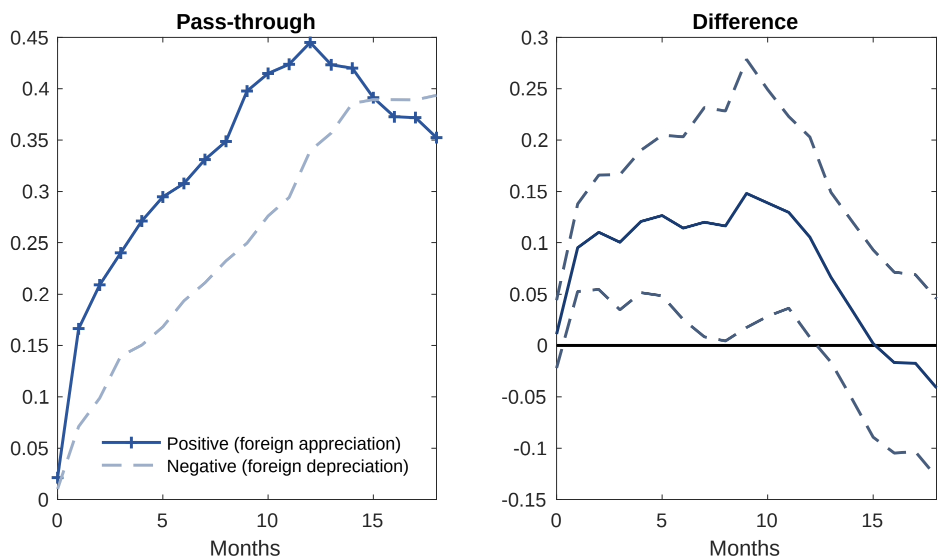


Figure 2: Pass-through for foreign currency depreciations (-) and appreciations (+)

[6] Sectors are identified according to BLS's classification system. Primary strata are BLS designated sectors that roughly correspond with 2- or 4-digit HS codes.

[7] Kilian and Vigfusson (2011) demonstrate that the asymmetric impulse responses depend on the past-history and size of shocks and propose a bootstrap algorithm to generate average impulse response point estimates. The impulse responses presented here can be considered valid for large exchange rate shocks or shocks occurring in isolation.

[8] Statistical significance is computed via Wald statistics of the linear combination of the coefficients; 95% confidence bands are shown.

In the short-run (about the first 15 months), foreign currency appreciations pass-through significantly more than depreciations. Statistically speaking, this difference lasts about 12 months. At its peak, the difference in pass-through is roughly 0.15 percentage points, or about one-third of the 0.4 pass-through elasticity observed by the end of 18 months.

Many foreign exporters do not, however, have the kind of pricing power required to price-to-market like this. We therefore next limit our analysis to goods with which firms can exhibit some pricing power. More specifically, we focus on differentiated goods, as emphasized in the literature. Differentiated goods are identified in our data using Rauch (1999) classification. The impulse responses to exchange rate changes at each horizon for differentiated goods is plotted in the left panel of Figure 3. The right panel shows the difference in impulse responses to appreciations versus depreciations.

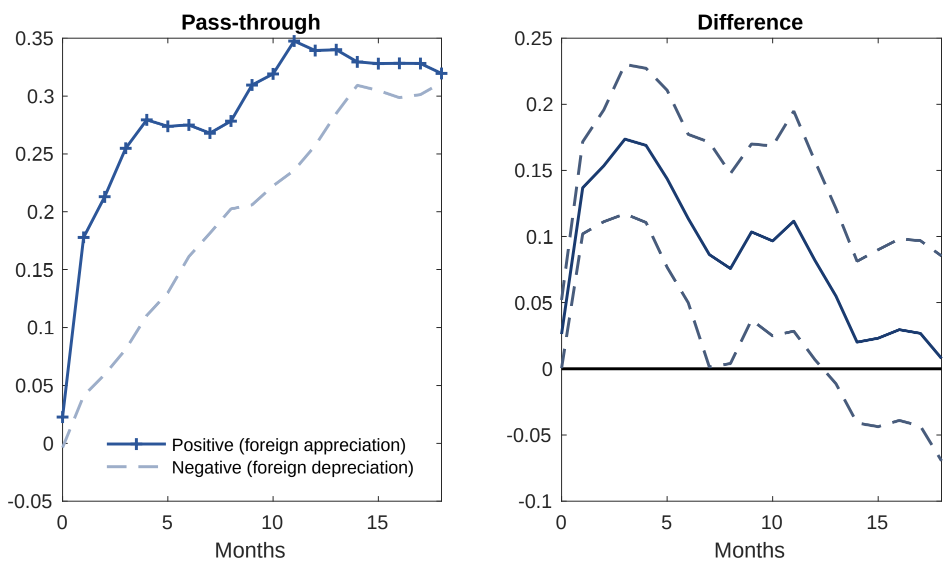


Figure 3: Pass-through for foreign currency depreciations (-) and appreciations (+) using Rauch (1999) differentiated goods

Here, the asymmetry is more pronounced in the short run, peaking at a nearly 0.17 difference in the first few months. Still, the difference among all differentiated goods becomes economically small and statistically insignificant before the end of 18 months, at around 12 months.

3.1 Asymmetries by sector

To analyze whether the asymmetry in pass-through found for the whole sample is driven by certain types of goods, we split our sample into groups by 1-digit end-use categories. These categories provide economically meaningful distinctions between types of goods.

Figures 4 and 5 make clear that the economic and statistical significance of the overall asymmetry is being driven by automotive products and consumer goods rather than intermediate goods and capital goods. Combined with the more significant asymmetries for Rauch (1999) differentiated goods, this suggests that pricing power is an important element to understand the nature of the asymmetries. The fact that the asymmetry seems to exist largely in the short-run suggests that price stickiness may be playing a role in the asymmetry. We examine this possibility in the next section.

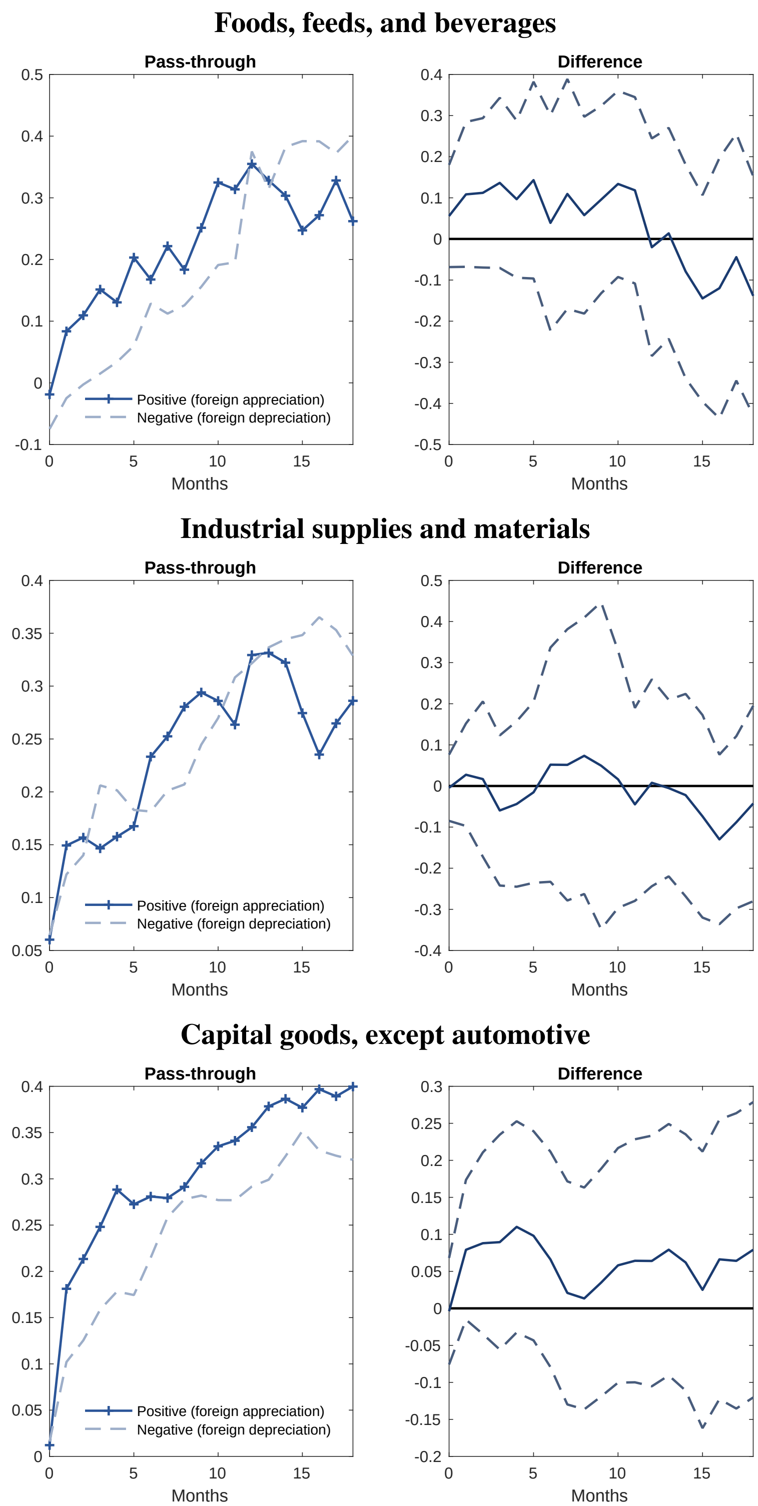


Figure 4: Pass-through for dollar appreciations (-) and depreciations (+) for end-use categories 0, 1, and 2

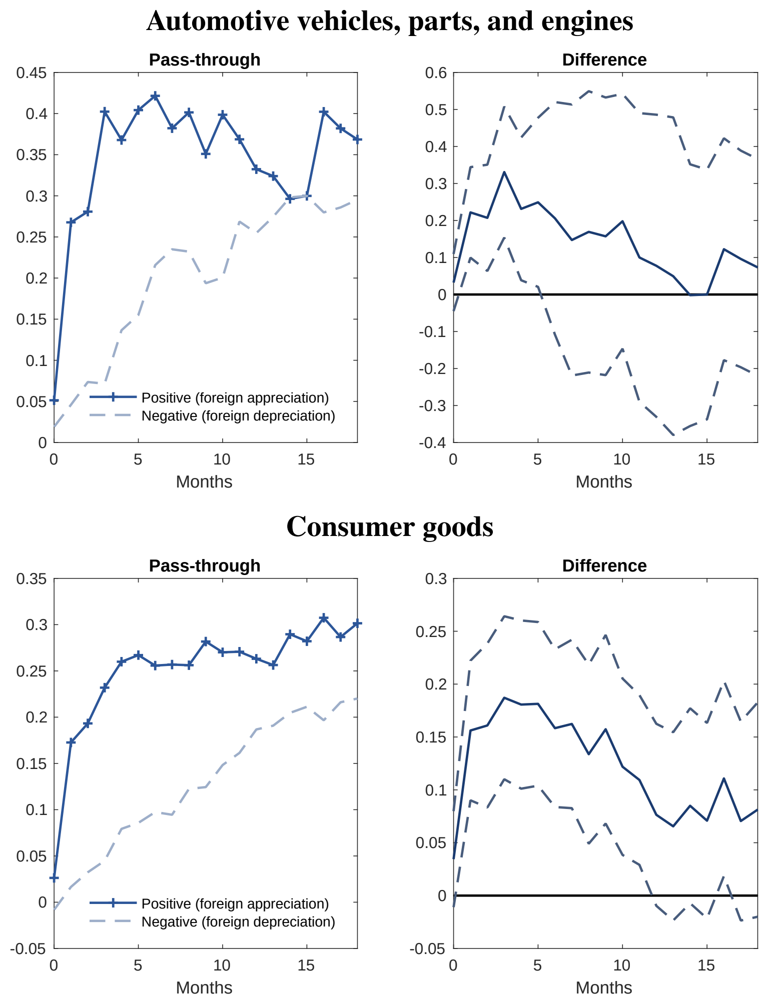


Figure 5: Pass-through for foreign currency depreciations (-) and appreciations (+) for end-use categories 3 and 4

3.2 Medium-run pass-through

As documented by Gopinath and Rigobon (2008), U.S. import prices are fairly sticky and set in dollars. Therefore, pass-through will be reduced in the short-run simply because they remain fixed in dollar terms. We consider whether price stickiness is driving the documented asymmetries by exploiting the data's ability to capture pass-through conditional on a price change, which Gopinath et al. (2010) define as medium run pass-through (MRPT).[9]

[9] Gopinath et al. (2010) define MRPT as a weighted average of desired short-run pass-through, which they then show is equivalent to the MRPT regression coefficient.

Table 1: Pass-through conditional on a price change

	Depreciation	Appreciation	Difference	N	R^2
All goods	0.228***	0.247***	0.019	133,928	0.076
Differentiated (stricter def)	0.172***	0.315***	0.143***	38,370	0.119
Differentiated (looser def)	0.183***	0.269***	0.085**	57,958	0.116
By end-use:					
0. Foods, feeds, bev.	0.128***	0.167***	0.039	23,826	0.028
1. Industrial supplies	0.370***	0.178**	-0.192***	47,256	0.072
2. Capital goods ex auto	0.265***	0.220***	-0.045	12,344	0.196
3. Automotive products	0.116	0.408***	0.292*	1,085	0.218
4. Consumer goods	0.098***	0.239**	0.141*	11,392	0.150

We estimate the following:

$$\Delta p_{i,j,c} = \beta^{+}\Delta e^{+}_{j,c} + \beta^{-}\Delta e^{-}_{j,c} + \gamma\Delta P_{j,c} + \Delta Z_c + \boldsymbol{s_j} + \varepsilon_{i,j,c} \tag{2}$$

where subscript c denotes the cumulative change between time t and the last price change $t-k$ for good i from country j. Time dummies are fairly unnatural in this setting, so we include other explanatory variables Z, such as the U.S. CPI, U.S. GDP, and a measure of global non-oil commodity prices. Country/sector fixed effects s_j are still included.

Table 1 shows that even conditional on a price change, foreign currency appreciations have 0.09 to 0.14 higher pass-through than depreciations among differentiated goods. As seen in the results by end-use categories, this asymmetry is being driven by higher pass-through for consumer goods and automotives. In contrast, MRPT for industrial supplies goes in the opposite direction, where depreciations pass-through more completely than appreciations.

Note that the difference in pass-through rates for appreciations versus depreciations is negligible when considering all goods. However, given the results for differentiated goods, the direct effects of price stickiness are unlikely to be the only drivers of asymmetric pass-through. That said, firms may still choose to adjust their prices more often in response to a foreign currency appreciation versus a depreciation.

3.3 Probability of price adjustment

While numerous characteristics of firm price-setting behavior suggest that firms change their prices for largely idiosyncratic reasons, aggregate shocks can still play an important role. We consider whether foreign currency appreciations relative to depreciations make firms more likely to change their prices by considering a straightforward linear probability model:

$$prob(\Delta p_{i,j,t} \neq 0) = \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t} \tag{3}$$

Figure 6 shows how following a foreign currency depreciation, firms become more likely to change their price. We find that 18 months after a 1 percent depreciation, a firm is about 0.7 percent more likely to change their price. By contrast, appreciations slightly lower the probability of changing the price. The difference (the positive response probability minus the negative response probability), shown to the right, is negative and economically meaningful, but not statistically significant. Nonetheless, considering that pass-through is faster for foreign currency appreciations, there is little evidence that this is coming through earlier price changes than would otherwise have occurred absent an appreciation.

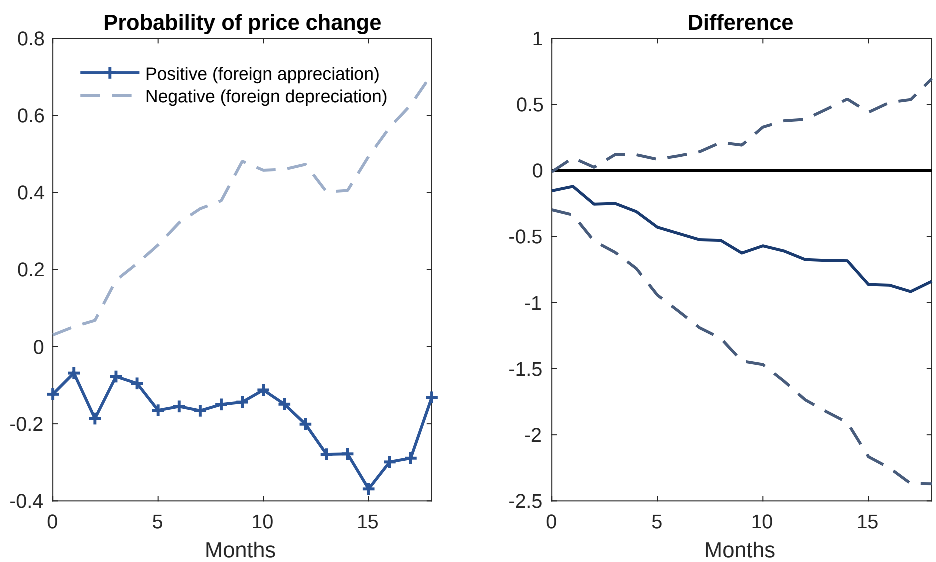


Figure 6: Percent probability of changing price for foreign currency depreciations (-) and appreciations (+) using Rauch (1999) differentiated goods

3.4 Selection bias and exit

More complete pass-through from dollar depreciations might be driven by selective exit: foreign currency depreciations are adverse shocks for foreign exporters, and if they exit because of the depreciation, this could bias the estimates of pass-through towards finding more complete pass-through for appreciations relative to depreciations.

To examine the scope for this, we estimate a similar linear probability model as that for price change, but replacing the left hand side with the probability of exit:

$$prob(exit_{i,j,t}) = \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t}. \tag{4}$$

As discussed by Gagnon et al. (2014), products exit the BLS sample routinely for reasons unrelated to aggregate economic conditions. Fortunately, the BLS tracks the reason for the product leaving the sample, and we use those product exits that are likely to be endogenous.[10]

Figure 7 shows that the probability of exit following an exchange rate appreciation is very similar to that of a depreciation, and that their difference is not statistically significant. Of some interest is that any exchange rate change actually raises the probability of exit. Potentially, this could reflect exchange rate movements representing volatility in the foreign market. While selection might still play a role in biasing the pass-through estimates, it does not appear to be a primary factor in explaining the asymmetries found earlier.

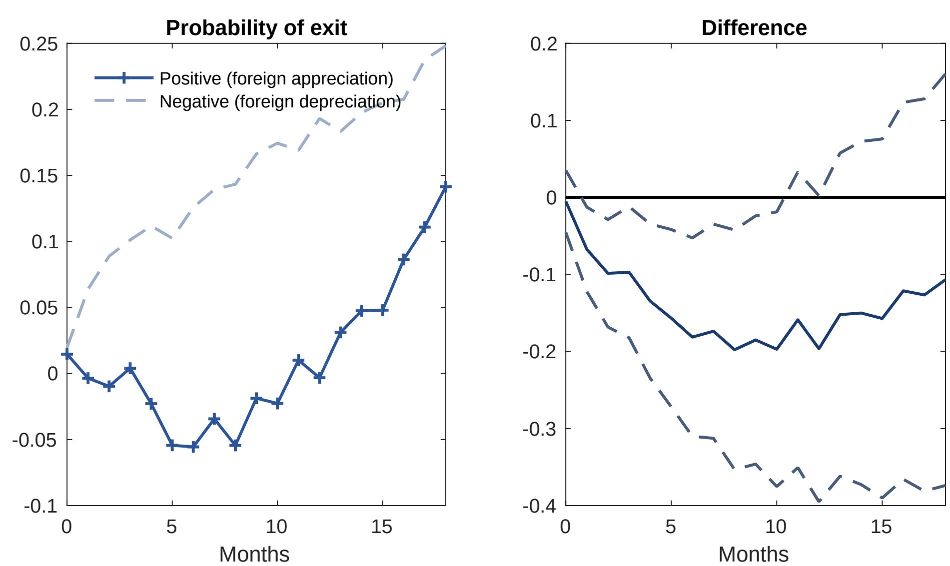


Figure 7: Percent probability of endogenous exit for foreign currency depreciations (-) and appreciations (+) using Rauch (1999) differentiated goods

3.5 Non-linearities

Finally, we consider the potential for non-linear pass-through. Ritz (2015) emphasizes how many theoretical explanations of asymmetric pass-through also imply non-linear pass-through. To look

[10] We exclude product exits related to sample rotation or reporter refusal.

for non-linearities, we add square and cubic terms to our asymmetric pass-through regression:

$$\Delta p_{i,j,t} = \sum_{k=0}^{h} \{\beta_k^+ (\Delta e^+)_{j,t-k} + \gamma_k^+ (\Delta e^+)^2_{j,t-k} + \delta_k^+ (\Delta e^+)^3_{j,t-k}\} \tag{5}$$

$$+ \sum_{k=0}^{h} \{\beta_k^- (\Delta e^-)_{j,t-k} + \gamma_k^- (\Delta e^-)^2_{j,t-k} + \delta_k^- (\Delta e^-)^3_{j,t-k} \tag{6}$$

$$+ \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_t} + \varepsilon_{i,j,t} \tag{7}$$

Cubic terms are potentially important in that the non-linearity may not be symmetric, and the cubic term would potentially better capture that asymmetry.

Consider two different cases of foreign currency depreciations, a small shock at the 10th percentile of the distribution of depreciation and a large shock at the 90th percentile. Figure 8 plots the pass-through of each shock. Clearly, their pass-through rates are nearly identical from an economic standpoint, suggesting that pass-through is not significantly non-linear.

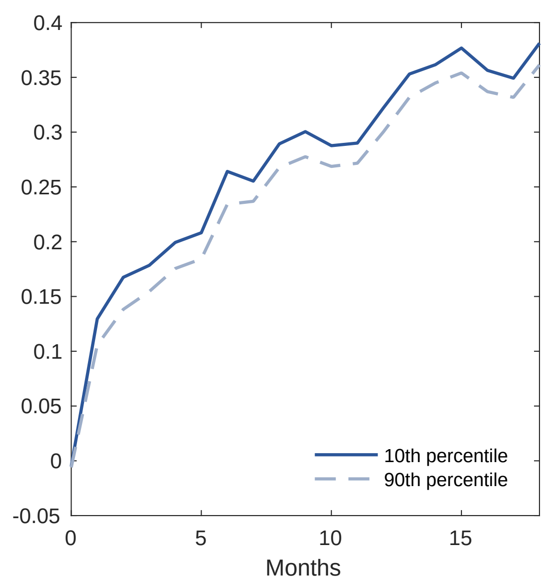


Figure 8: Pass-through of 10th percentile and 90th percentile exchange rate depreciations using Rauch (1999) differentiated goods

4 Trade values and quantities

Given asymmetries in the speed of pass-through, the next question is whether these asymmetries affect the response of trade quantities as well. Unfortunately, the product-level BLS data contains no information about quantities. Instead, we use publicly available sector-level data on the universe of U.S. imports obtained from the USITC over the same sample period, 1994-2014. We can then run an analogous regression to estimate the response of nominal trade value to foreign currency appreciations and depreciations, taking the form of:

$$\Delta pq_{i,j,t} = \sum_{k=0}^{6} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t}, \tag{8}$$

Here, we use nominal trade values at a quarterly frequency, to reduce some of the noise from capturing trade at higher frequencies. We use the same basic controls as in the baseline pass-through regression: the foreign CPI P, sector-time dummies, and country dummies. Crucially, the sector-time dummies capture global and U.S.-specific demand. To be comparable to our preferred exchange rate pass-through estimates, we focus only on those SITC4 categories that Rauch classifies as differentiated.[11]

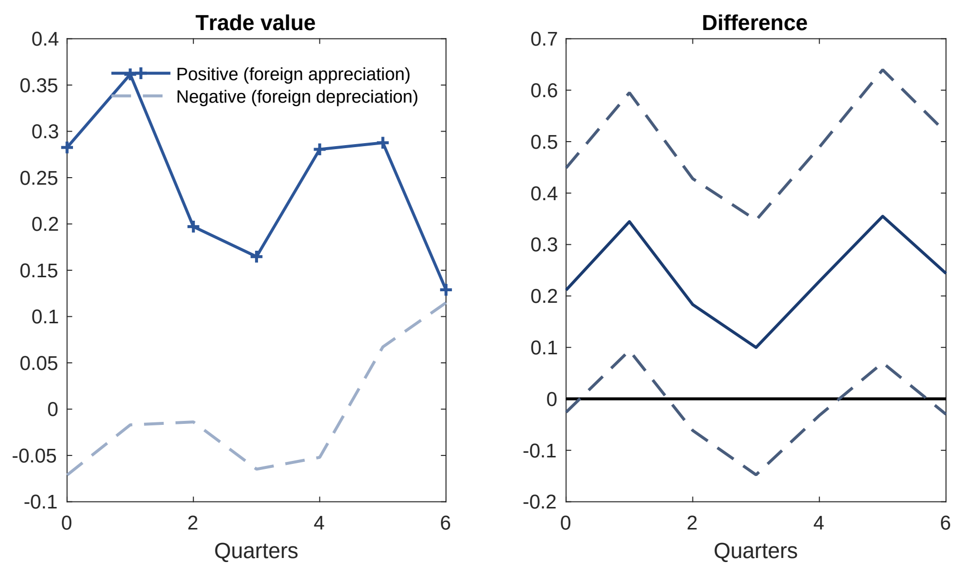


Figure 9: Import value responses for foreign currency depreciations (-) and appreciations (+) using Rauch (1999) differentiated goods

Figure 9 shows the implied responses of import value to exchange rate changes. In response to a 1% foreign currency appreciation, the import value (measured in USD) actually rises by 0.3% immediately. Over time, the import value falls to near zero. By contrast, in response to a 1% foreign currency depreciation, the import value falls slightly and rises slowly, but remains economically

[11]The trade value responses across all goods are very similar and available upon request.

(and statistically) around zero.[12] This pattern is consistent, for example, with a near-unitary demand elasticity (Cobb-Douglas preferences). Of course, a unitary demand elasticity is inconsistent with a model of monopolistic competition and the elasticities generally required to replicate trade price facts, though this could be dealt with by carefully nesting demand within an exporting country as having a separate elasticity from that between countries. As shown in the right panel of Figure 9, the magnitude of these two responses is economically and sometimes statistically significantly different from zero.

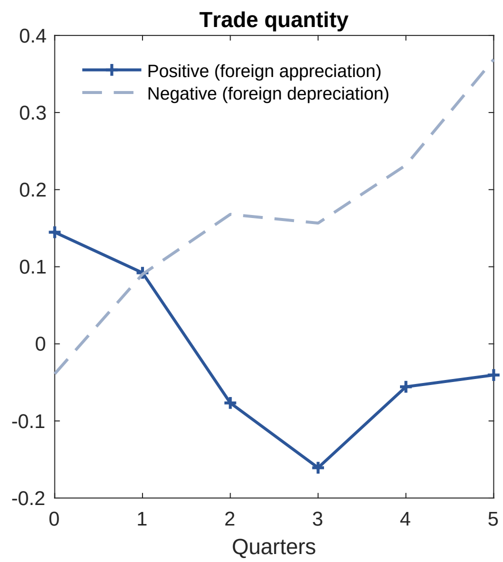


Figure 10: Implied import quantity responses for foreign currency depreciations (-) and appreciations (+) using Rauch (1999) differentiated goods

We can take this a step further by combining the exchange rate responses of trade values in equation (8) with those of trade prices in equation (1). The result is the implied trade quantity response, shown in Figure 10. For both appreciations and depreciations, the quantity response is near-zero immediately after the exchange rate shock. But after 5 quarters, a foreign currency appreciation barely lowers imports (a 1% foreign currency appreciation leads to a smaller than 0.1% reduction in real imports) while a foreign currency depreciation leads to a more significant increase in real imports (a 1% foreign currency depreciation leads to a nearly 0.4% increase in real imports). Thus, while pass-through exhibits short-run asymmetry, the implied trade quantity response exhibits long-run asymmetry.

The combination of trade price and trade quantity responses suggests that supply-side considerations will be incapable of explaining both responses. We proceed in the next section to examine

[12] A foreign currency appreciation is statistically significantly higher than zero at the 95% until 6 quarters, while a foreign currency depreciation is never statistically distinguishable from a zero response

the potential for standard models of trade prices to explain these patterns.

5 Model

In this section, we outline a standard model of trade prices with one added element to generate short-run asymmetries in pass through. The model's key ingredients include (1) strategic complementarities that reduce pass-through in both the short and long-run, (2) a capacity constraint that, in principle, leads to temporarily lower pass-through for depreciations of the producer currency relative to appreciations, and (3) sticky prices that further slow the price adjustment process, in combination with (1), and (2).

As has been well documented, standard CES demand with firm i setting price p_i while taking the sectoral price P and demand C as given will generate complete pass-through with no asymmetries, as optimal prices are simply a constant markup over marginal cost mc_i based on the demand elasticity θ over marginal cost: $p_i = \frac{\theta}{\theta-1} mc_i$. Thus, we specify a model in a non-CES setting.

Instead, we use a demand system within the class of Kimball (1995) aggregators to model strategic complementarities in price setting. One such aggregator by Klenow and Willis (2006) has been used frequently in the international literature.[13] With this demand system, pricing is still a markup over the marginal cost, but the demand elasticity itself depends on the firm's price relative to its competitors:

$$p = \frac{\tilde{\theta}}{\tilde{\theta}-1} mc, \tag{9}$$

$$\tilde{\theta} = \frac{\theta}{1-\varepsilon \ln\left(\frac{p}{P}\right)}. \tag{10}$$

The "super-elasticity" of demand ε (the elasticity of the demand elasticity θ) controls the degree to which the firm wants to keep its price close to the sectoral average.

[13] See for example Gopinath et al. (2010), Gopinath and Itskhoki (2010), and (Lewis 2017).

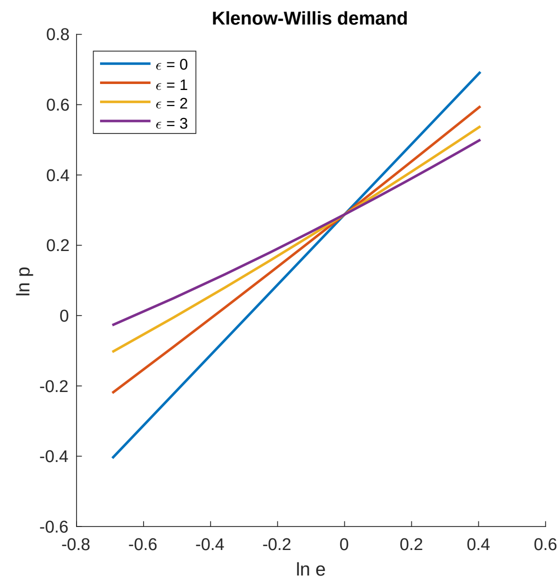


Figure 11: Optimal log prices under Klenow-Willis (2006) demand

Gopinath and Itskhoki (2010) demonstrated that this demand system, in combination with imported intermediates, is capable of reproducing the low pass-through rates we observe even in the long-run. That said, it does not generate asymmetric pass-through. While technically not log-linear, it generates essentially symmetric optimal prices. Figure 11 shows optimal prices ($\ln p_i$) for a given exchange rate ($\ln e$), where a higher e corresponds to a local currency appreciation. The blue line is the CES case, and complete pass-through is a slope of 1. Raising the super-elasticity ε forces prices to stay closer to the sectoral average, pivoting the optimal price through the zero exchange rate change axis (since the firm's competitors will not be subject to the exchange rate). However, optimal prices are still very nearly log-linear, and thus pass-through is essentially symmetric to increases and decreases in the log-log space we estimate in the data.

Therefore, a model that only features strategic complementarities can not fully explain the characteristics of our data. We add convex adjustment costs to increasing output in the model to generate asymmetries. Convex adjustment costs could involve both costs to increase physical production (e.g. expanding a factory, finding new workers, etc), but could also represent costs involved with finding new buyers.[14]

[14]Drozd and Nosal (2012) illustrate how a model with costs to acquire new customers could reconcile a short-run trade elasticity being smaller in magnitude than a long-run trade elasticity. In earlier work, Froot and Klemperer (1989) emphasize that the nature of pass-through depends on whether an exchange rate change is thought to be temporary or permanent when sales depend on market shares. However, we show in the appendix that exchange rate appreciations and depreciations are similarly persistent. Auer and Schoenle (2016) also emphasize the importance of a firm's market share in its pass-through, but they argue that it is hump-shaped, with the lowest pass-through representing firms between those

More specifically, the model consists of exporting firms competing monopolistically in partial equilibrium, taking sectoral prices, demand, wages, and the exchange rate as given. In addition to aggregate conditions, each firm has an idiosyncratic productivity shock that dominates their pricing decisions, consistent with price changes being only modestly explained by aggregate conditions.

In the first sticky price formulation, firms face Calvo-style sticky prices: with probability α, they are allowed to change their price, maximizing their expected discounted value:

$$V^A(p,a,e) = \max_{p'} \Pi(p',a,e) + \beta E\left[\alpha V^A(p',a',e') + (1-\alpha)V^N(p',a',e')\right], \tag{11}$$

where p is the firm's price choice, a is the firm's productivity, e is the exchange rate defined as the destination currency in units of the exporter's currency, and Π is the flow profit of the firm. V^A is the value of the firm if it is allowed to adjust its price, and V^N is the value if the firm cannot.

Flow profit has two key elements:

$$\Pi(p',a,e) = \frac{p'q(p')}{e} - \frac{\bar{c}}{a}q(p') - \mathbb{I}[q(p') > q(p)]\phi\bar{c}(q(p') - q(p))^2$$

First, $q(p)$ is a Klenow and Willis (2006) demand curve, which as previously discussed, induces firms to price closer to the sectoral price $\bar{P}$. This generates incomplete pass-through even in the long run. This demand takes the form:

$$q(p) = \left(1 - \varepsilon \ln \frac{p}{\bar{P}}\right)^{\frac{\theta}{\varepsilon}},$$

In our first parameterization, we examine the potential for these convex adjustment costs to generate the pattern of asymmetric pass-through we find empirically. Table 2 shows a proof-of-concept calibration for the Calvo model. Many parameters are standard: the elasticity of substitution $\theta = 4$, the super-elasticity of demand $\varepsilon = 3$. Exchange rates are highly persistent ($\rho_e = 0.99$) with modest volatility ($\sigma_e = 0.03$). Here, we effectively shut down idiosyncratic productivity shocks by setting $\sigma_a = 0.001$. Prices are fairly flexible, as $\alpha = 0.5$ implies that firms can change their price on average every other month. We set the convex adjustment cost $\phi = 10$ to generate a roughly 0.1 difference in pass-through.

Figure 12 shows the results. A foreign appreciation passes through more quickly than a depreciation, and as shown in the right panel, the difference peaks at about 0.1 after 1 month before declining to near-zero. Pass-through peaks at about 0.45. Thus in principle, convex adjustment costs are capable of generating asymmetry in pass-through that is strikingly similar to what we observe.

with no market share and complete monopoly power, and they find evidence for it with the same U.S. import price data used in this paper.

Table 2: Parameterization (Calvo)

Parameter	Value	Description
θ	4	Elasticity of substitution
ε	3	Super-elasticity
α	0.5	Probability of price change
ϕ	10	Convex adjustment cost
β	$0.94^{\frac{1}{12}}$	Discount factor
ρ_a	0.96	AR(1) coefficient for productivity
σ_a	0.001	Standard deviation of productivity
ρ_e	0.99	AR(1) coefficient for exchange rates
σ_e	0.025	Standard deviation for exchange rates

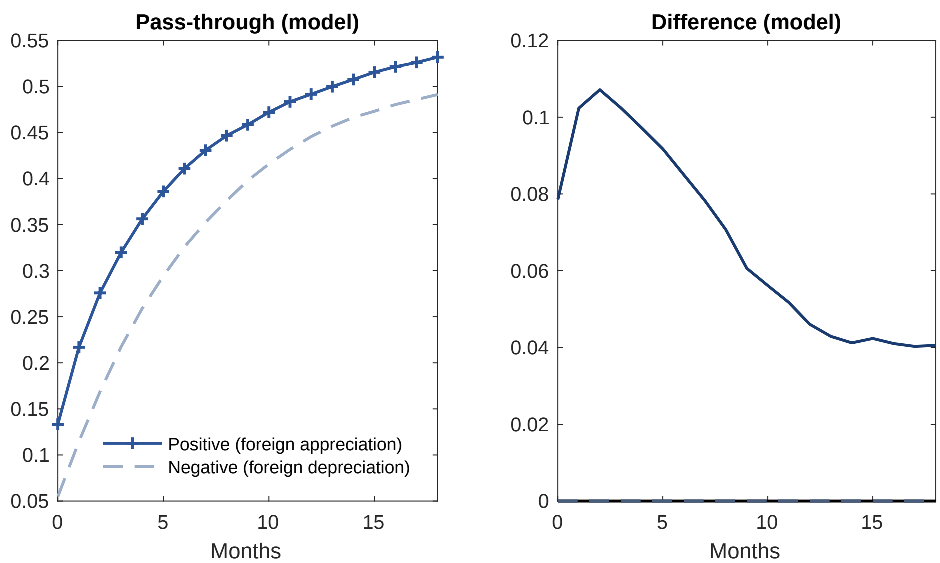


Figure 12: Pass-through in the benchmark model for foreign currency depreciations (-) and appreciations (+)

While this Calvo model is capable of nicely matching the pattern of pass-through, it fails to match other pricing facts. The median absolute price change is 0.75%, far from the 8% median in the data (Gopinath and Rigobon 2008). As previously noted, the frequency of price change is also too frequent.

So instead we turn to a menu cost model generally capable of matching trade price facts. Here, the value of a firm adjusting its price becomes:

$$V^A(p,a,e) = \max_{p'} \Pi(p',a,e) - \kappa + \beta E\left[V(p',a',e')\right], \tag{12}$$

where $V(p,a,e) = max\{V^A(p,a,e), V^N(p,a,e)\}$ and κ is the menu cost paid by firms to change their price, and where

$$V^N(p,a,e) = \Pi(p,a,e) + \beta E\big[V(p,a',e')\big], \tag{13}$$

is the value of not adjusting the price.

Here, we use numerical optimization and indirect inference to calibrate four parameters in the model to four moments of the data. Each moment is primarily controlled by one parameter. The long-run pass through (pass-through at 18 months) is targeted to be 0.4, and it is largely controlled by the super-elasticity of demand ε. The frequency of price changes is targeted to be 9%, largely controlled by the menu cost κ. The median absolute size of price changes is targeted to be 8%, and it the standard deviation of the idiosyncratic productivity shock σ_a can achieve this. Finally, the maximum difference in pass-through between foreign appreciations and depreciations is targeted to be 0.1, and the convex adjustment cost ϕ attempts to capture this. The other parameters in the model are the same as in Table 2.

[To be added]

6 Conclusion

In this paper, we demonstrate that U.S. import prices at the product level pass-through foreign currency appreciations faster and more completely than depreciations. We show that this asymmetry persists even conditional on a price change, and it is unlikely to be the result of selective exit. The asymmetry is more pronounced among those goods closer to the consumer, such as automotives and consumer goods, and more pronounced among those goods Rauch (1999) classifies as differentiated. On the other hand, we find little evidence for non-linearities in price setting. Economically, pass-through of large exchange rate shocks is very similar to pass-through of smaller ones.

By using sectoral data on trade values, we calculate the implied trade quantity response and find a different kind of asymmetry. In the short run, both foreign currency appreciations and depreciations have little effect on import quantities. However, in the long run, foreign currency depreciations lead to a larger increase in imports, while appreciations lead to a smaller decrease in imports. This suggests that in addition to potential supply factors, demand itself may not be symmetric.

Modeling the trade price asymmetry is difficult alongside other price facts. While convex adjustment costs can generate clean short-run pass-through asymmetries, they work at odds with sticky prices. Sticky prices have infrequent, large price changes, while convex adjustment costs encourage small reductions in prices. Thus in a model properly calibrated to match the frequency and size of price changes, it is difficult to generate the magnitude of asymmetry we observe.

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A Exchange rate persistence

One potential source of asymmetry is if firms believe that foreign appreciations are more or less persistent than depreciations. While exchange rates in general are seen as difficult to distinguish from a random walk, here we directly test the persistence of appreciations and depreciations separately.

To do this, we estimate the response of bilateral log exchange rate $e_{i,t}$ at horizon h using a local projection method:

$$e_{j,t+h} - e_{j,t-1} = \beta^{+}(\Delta e^{+})_{j,t} + \beta^{-}(\Delta e^{-})_{j,t} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} \tag{14}$$

This includes the foreign CPI $P_{j,t}$, time-dummies $\boldsymbol{\alpha_t}$ and country-dummies $\boldsymbol{s_j}$. The data span from 1990-2018 using OECD countries.[15]

Table 3 shows the results. For each type, the first column shows the point estimate and the second column shows the 95% confidence interval. As expected, the results are fairly close to a random walk, $\beta^{+} \approx \beta^{-} \approx 1$, though appreciations do exhibit some momentum, ending with a response of about 1.5 times the original shock after 18 months. Nonetheless, the difference between the two responses is small, the sign varies, and is always statistically indistinguishable from zero. At least statistically, exchange rates appear equally persistent across exchange rate appreciations and depreciations.

[15] We focus here on OECD countries as it includes most U.S. trading partners.

Table 3: Exchange rate response to own shocks

h	Appreciation		Depreciation		Difference	
1	1.05	[0.98,1.13]	1.07	[0.96,1.17]	-0.01	[-0.16,0.14]
2	1.14	[1.03,1.25]	1.09	[0.95,1.23]	0.05	[-0.16,0.25]
3	1.14	[1.02,1.27]	1.16	[0.94,1.37]	-0.01	[-0.31,0.28]
4	1.06	[0.92,1.2]	1.13	[0.94,1.32]	-0.07	[-0.35,0.21]
5	1.01	[0.85,1.17]	1.16	[0.94,1.38]	-0.14	[-0.46,0.17]
6	0.99	[0.81,1.16]	1.19	[0.96,1.43]	-0.21	[-0.55,0.13]
7	1.02	[0.83,1.22]	1.22	[0.95,1.49]	-0.20	[-0.59,0.19]
8	1.10	[0.89,1.31]	1.24	[0.96,1.51]	-0.14	[-0.54,0.27]
9	1.30	[1.08,1.52]	1.21	[0.93,1.48]	0.09	[-0.32,0.51]
10	1.33	[1.09,1.56]	1.23	[0.94,1.53]	0.10	[-0.35,0.54]
11	1.41	[1.16,1.66]	1.19	[0.87,1.51]	0.22	[-0.25,0.69]
12	1.45	[1.18,1.72]	1.20	[0.86,1.54]	0.25	[-0.25,0.75]
13	1.44	[1.16,1.72]	1.16	[0.82,1.51]	0.28	[-0.24,0.79]
14	1.34	[1.05,1.64]	1.14	[0.77,1.51]	0.20	[-0.35,0.75]
15	1.35	[1.05,1.66]	1.16	[0.76,1.55]	0.20	[-0.38,0.78]
16	1.42	[1.1,1.73]	1.16	[0.74,1.57]	0.26	[-0.35,0.87]
17	1.50	[1.17,1.83]	1.12	[0.69,1.55]	0.37	[-0.26,1.01]
18	1.54	[1.19,1.88]	1.09	[0.65,1.54]	0.44	[-0.22,1.11]