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

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Abstract

Although 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 U.S. import prices. In other words, country-specific exchange rate changes cause prices at the U.S. dock to rise faster than they fall. This result is obscured in aggregate regressions, which combine differentiated goods that exhibit this asymmetry with other goods which do not. A model with menu costs, strategic complementarities, and convex adjustment costs to expanding production can generally reproduce these pricing facts.

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 into overall inflation. As discussed in Yellen (2015), exchange rate changes are transmitted into overall inflation through import prices. As such, exploring how exchange rate changes pass through into product-level import prices helps us understand both inflation at an aggregate level and the nature of firm supply and demand at a micro level. Although the standard assumption is that exchange rate appreciations and depreciations pass through symmetrically to import prices, we document that pass-through is, in fact, asymmetric.

We show that foreign currency appreciations pass through more quickly and completely than foreign currency depreciations using 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. To better understand the observed asymmetry, we then estimate a similar model using product-level pricing. By taking advantage of microdata on product-level pricing, we find that the asymmetry exists even after controlling for a price change and that foreign appreciations do not induce a greater probability of a price change. In addition, we show that the asymmetry is not the result of selective exit, as exchange rate changes do not alter the probability of product exit.

Although we find empirical evidence for asymmetry, we do not find evidence that import prices respond nonlinearly to larger exchange rate changes. We look for potential nonlinearities in pass-through by adding higher order terms to our estimating equation. Some sources of asymmetries, like price stickiness, might also imply nonlinearities. Our findings suggest that any such mechanisms are less likely, which helps to narrow the range of explanations.

We evaluate the potential for standard models of exchange rate pass-through to match the asymmetries we identify. Incorporating sticky prices 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 incurred when increasing the quantity produced. This additional feature results in lower pass-through for producer currency depreciations relative to appreciations in the short run. While this model is generally capable of matching targeted price facts, it cannot simultaneously match the quantitative extent of asymmetry and the large absolute price changes we observe in the data. Intuitively this makes sense: convex adjustment costs encourage small price reductions and consequently small increases in production over time, while in the data we observe perhaps surprisingly large price changes.

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 but has converged on a number of stylized facts. For the U.S., studies find that pass-through is incomplete and low. In the

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

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. is lower now than it was in 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 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) consider both asymmetries and non-linearities in exchange rate pass-through into U.S. import prices. They use an industry-level analysis and find no clear direction of asymmetry, as in the previous literature. They do find that non-linearities exist; larger exchange rate fluctuations are generally associated with higher exchange-rate pass-through, even when taking asymmetries into account. In a study of French import prices, Razafindrabe (2017) finds evidence of asymmetry that is largely attributable to nominal rigidities.[3]

The paper proceeds as follows: Section 2 analyzes aggregate pass-through with publicly available data. Section 3 provides a description of the BLS microdata, with results for U.S. import microdata in Section 4, followed by a model capable of explaining our results in section 5. Section 6 concludes.

2 Asymmetries in the aggregate

To begin, we augment a standard aggregate pass-through regression typically used in the literature. We model pass-through of changes in (log) nominal effective exchange rates e_t to a (log) import price index p_t as:

$$\Delta p_t = \alpha + \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{t-k}^+ + \beta_k^- \Delta e_{t-k}^-\} + \sum_{k=0}^{6} \gamma_k \Delta p_{t-k}^c + \varepsilon_t, \tag{1}$$

[2] Other fields have considered asymmetric pass-through, however. For example, Batista Politi and Mattos (2011) finds evidence that value added tax increases are 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.

[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.

where p^c_{t-k} are an index of global non-fuel commodity prices.[4]

We define the multilateral nominal effective exchange rate e_t as the U.S. dollar per bundle of foreign currency at time t (that is, an increase in e is a foreign currency appreciation). Then foreign appreciations and depreciations are defined as:

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

and similarly,

$$\Delta e_t^- \begin{cases} \Delta e & \text{if } \Delta e < 0 \\ 0 & \text{otherwise.} \end{cases}$$

Because Equation 1 does not include lagged values of import prices, the pass-through at horizon h of a price to a one-time change in the exchange rate is simply $\sum_{k=0}^{h} \beta_k^+$ for foreign currency appreciations and $\sum_{k=0}^{h} \beta_k^-$ for foreign currency depreciations.[5] Of particular interest is the point estimate and statistical significance of the difference in pass-through at each horizon, $\sum_{k=0}^{h} \left[\beta_k^+ - \beta_k^-\right]$, shown in the right panel of Figure 1.[6] As a first pass, we consider pass-through to a price index of imported goods that excludes fuels (petroleum and natural gas), computers, and semiconductors.[7]

[4]We obtained the nominal effective exchange rate and commodity price index from the IMF and import prices by end-use code from the BLS. The sample period in the estimation runs from January 1995 to December 2018.

[5]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 pass-thhrough estimates presented here can be considered valid for large exchange rate shocks or shocks occurring in isolation.

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

[7]Remaining categories are weighted by BLS import weights.

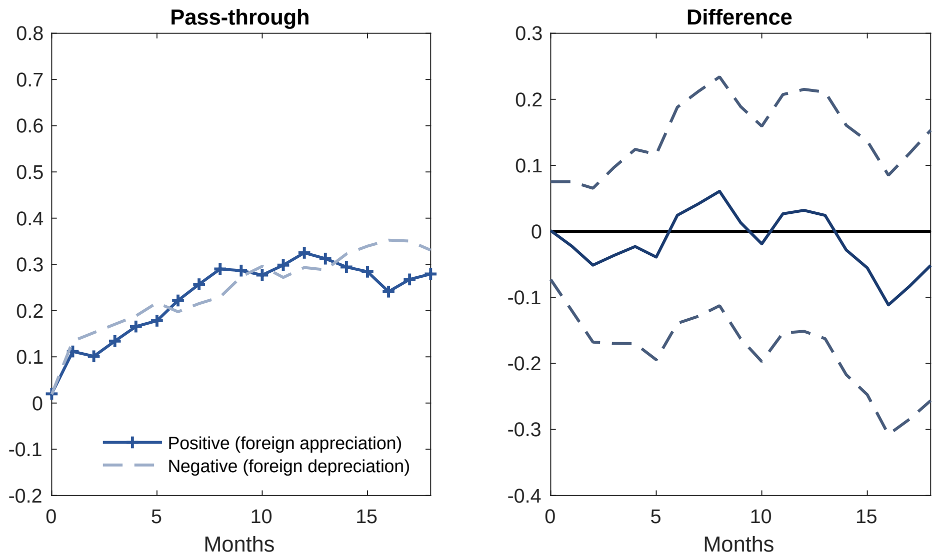


Figure 1: Pass-through for foreign currency depreciations (-) and appreciations (+) into non-fuel, non-tech products.

In the left panel, we confirm a common result from the existing literature: foreign appreciations (the solid dark line) have effectively the same exchange rate pass-through as foreign depreciations (the lighter dashed line): roughly zero in the short run and about 0.3 after 18 months. The difference, shown in the right panel, is essentially zero both economically and statistically.

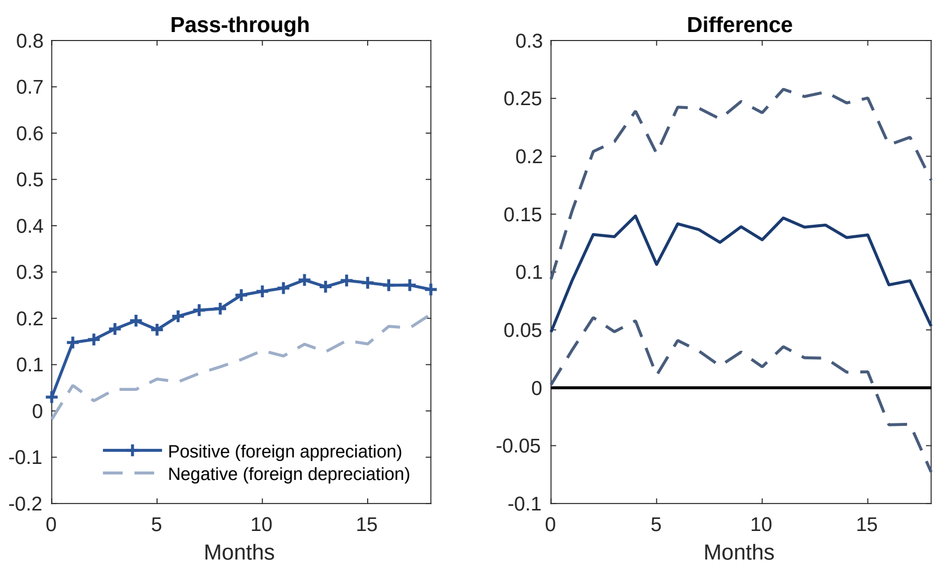


Figure 2: Pass-through for foreign currency depreciations (-) and appreciations (+) into non-tech finished goods.

This result belies underlying heterogeneity among sectors. Even with limited sectoral aggregate data, we can hint at this heterogeneity by splitting the sample into two categories. Finished goods include products by end-use code for consumer goods, capital goods, and automotive products (but exclude computers and semiconductors). Material-intensive goods include industrial supplies and foods, feeds, and beverages, but exclude oil and natural gas. In the left panel of Figure 2, we see that for finished goods, foreign appreciations pass through faster than depreciations. Pass-through is roughly 0.1 higher for foreign appreciations until about 16 months after the exchange rate shock (see the right panel). In terms of the price that importers pay, this result is consistent with price asymmetries sometimes found in other contexts: "prices rise faster than they fall".

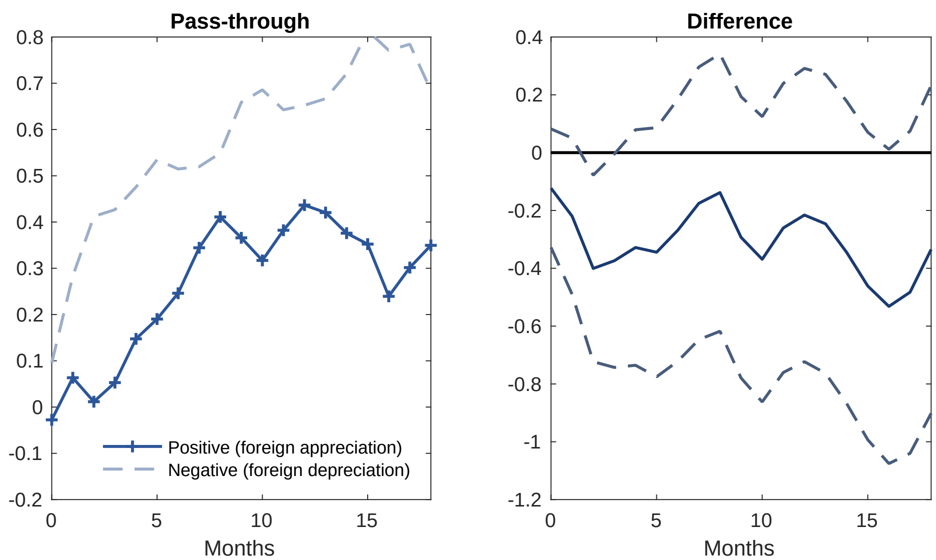


Figure 3: Pass-through for foreign currency depreciations (-) and appreciations (+) into non-energy industrial supplies and food, feed, and beverages.

By contrast, exchange-rate pass-through for material-intensive goods in Figure 3 is, if anything, asymmetric in the opposite direction. While it is difficult to distinguish foreign appreciations and depreciations statistically with this aggregate sample, this figure makes clear why in the aggregate, pass-through appears fairly symmetric, as total pass-through is a mix of all these sectors.

These regressions are indicative of some asymmetry. However, a number of questions cannot be answered using the aggregate data. In particular, it is impossible to investigate if the asymmetry results from firms being more or less likely to change their prices following a foreign appreciation. Likewise, we can not tell whether the asymmetry results from product selection, with a foreign depreciation coinciding with product exit rather than having a lower price passed through to U.S. consumers. As such, to address these questions, we proceed with analyzing the underlying product-level BLS microdata.

3 Microdata description

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 and exporters in order to produce monthly import and export price indexes. Reporters are sampled based on a probability proportionate to size sampling strategy at the reporter/item level.[8]

Reporters are asked to give 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 separate arms-length and intrafirm prices; we will focus on arms-length prices but also present results for intrafirm trade. We exclude estimated, imputed, services, and petroleum prices, as well as prices from/to countries with exchange rate regimes fixed to the dollar.[9]

Aside from prices, we observe information about the U.S. reporter, country of origin, invoicing currency, trade status, a product classification code, 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 used, we also include a monthly non-fuel commodity price index from the IMF.

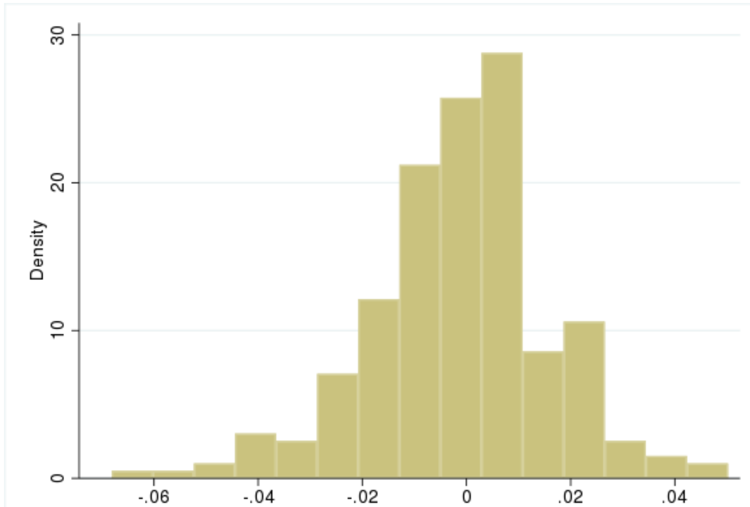
Of particular interest here is the distribution of exchange rate changes. With bilateral exchange rates, we are better able to capture the shifts in competitive conditions faced by firms as exchange rates change. Moreover, the inclusion of bilateral exchange rates allows us to observe much larger exchange rate appreciations and depreciations than 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 4.[10]

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

[9]Countries with dollar pegs are identified using the exchange rate regime classification dataset described in (Klein and Shambaugh 2008) and (Klein and Shambaugh 2010). Jay Shambaugh generously provided us with an updated dataset. For the missing countries, data is supplemented with information found in internet searches.

[10]The distribution of exchange rate changes illustrated here is based on our sample of arms-length imports.

Figure 4: Histogram of log exchange rate changes



4 Asymmetries and non-linearities in U.S. import microdata

Our estimating equation of the nominal price $p_{i,j,t}$ for product i originating from country j at time t at a monthly frequency is:

$$\Delta p_{i,j,t} = \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t}, \tag{2}$$

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.[11] Exchange rates e^+ and e^- are defined as in the aggregate regressions but at a country level. Given the construction of e^+, we are estimating the response to observed appreciations rather than to relative appreciations. 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 United States and its trading partners, rather than multilateral changes in the dollar or domestic conditions within the United States. Estimation in differences removes product-specific level effects, and sectoral dummies control for average inflation at a sectoral level.

[11]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.

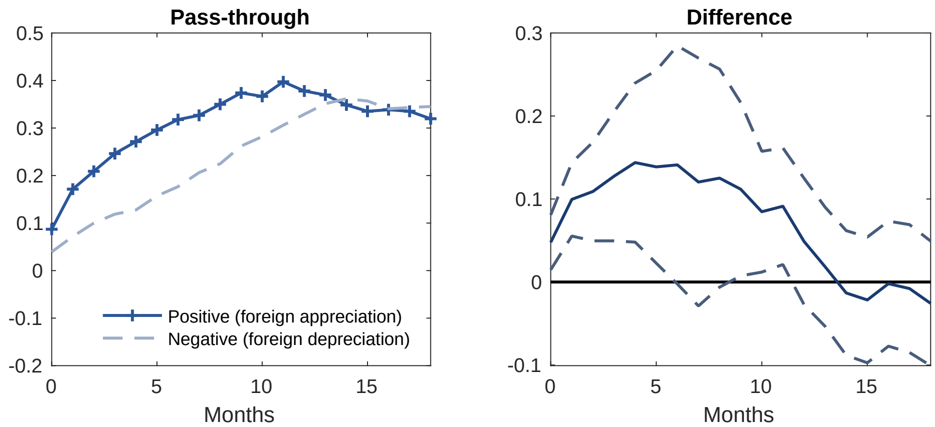


Figure 5: Pass-through for foreign currency depreciations (-) and appreciations (+) for all arms-length imports

Pass-through is calculated similarly to those for the aggregate regressions, and the result for all arms-length goods imports is shown in Figure 5. The left panel in the figure illustrates pass-through for appreciations and depreciations separately, and the right panel illustrates the difference in pass-through along with the 95% confidence interval. In the short-run (about the first 13 months), foreign currency appreciations pass-through significantly more than depreciations, but statistically this is not significant at the 95% level by month 7. At its peak, the difference in pass-through is roughly 0.13, or about one-third of the 0.3 pass-through elasticity observed by the end of 18 months. But the asymmetry is both economically and statistically zero after about 13 months; thus, like the result for aggregate finished goods, the asymmetry is again that foreign appreciations pass through faster, but not more completely, than foreign depreciations. That is, prices faced by the importer rise faster than they fall.

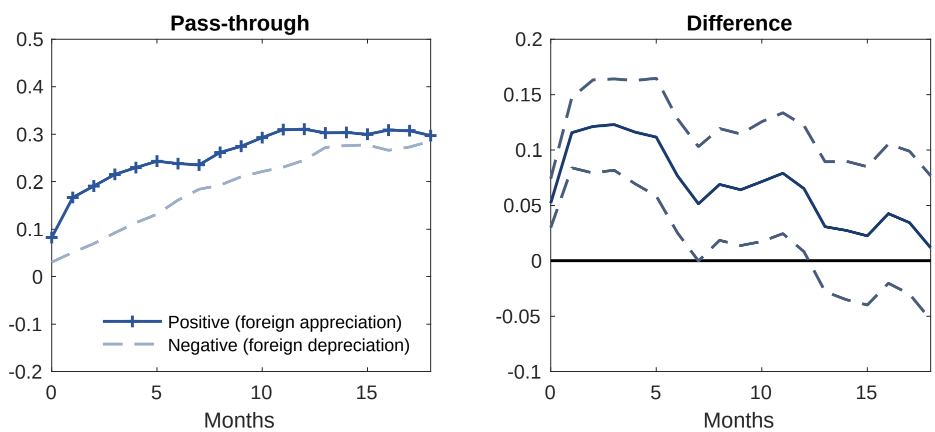


Figure 6: Pass-through for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length imports

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 pass-through of exchange rate changes at each horizon for differentiated goods is plotted in the left panel of Figure 6. Here, the magnitude of the asymmetry at its peak is similar, about 0.12, but the statistical significance is clearer throughout the first 12 months.

We have thus far established that for arms-length imported goods, especially differentiated ones, prices rise faster than they fall, but what about intrafirm prices? Figure 7 presents pass-through for intrafirm differentiated goods (all intrafirm goods are shown in the appendix). The pattern of asymmetry is similar, though a bit smaller in magnitude, about 0.09 at its peak. Also, as with arms-length imports, this asymmetry is eliminated both economically and statistically by 18 months.

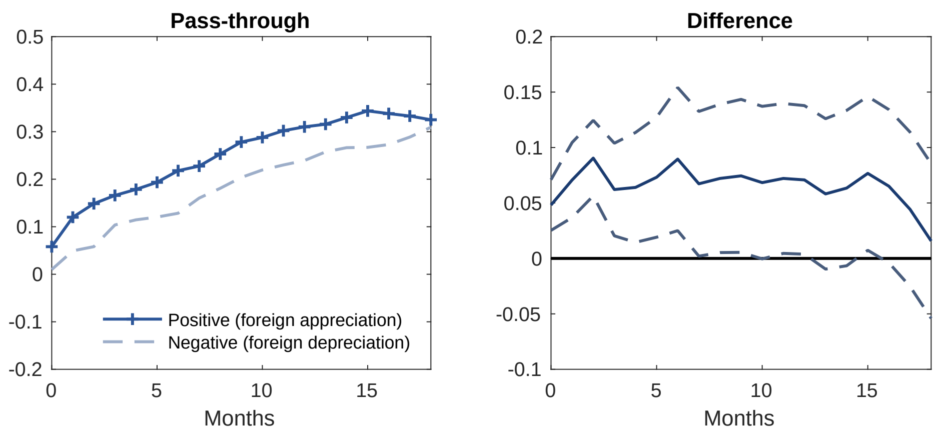


Figure 7: Pass-through for foreign currency depreciations (-) and appreciations (+) for differentiated intrafirm imports

4.1 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.[12]

[12] Unfortunately, the product classification provided by the BLS does not always map cleanly into end-use codes. These results are based on a subset of the sample for which we have a good match.

Foods, Feeds, and Beverages

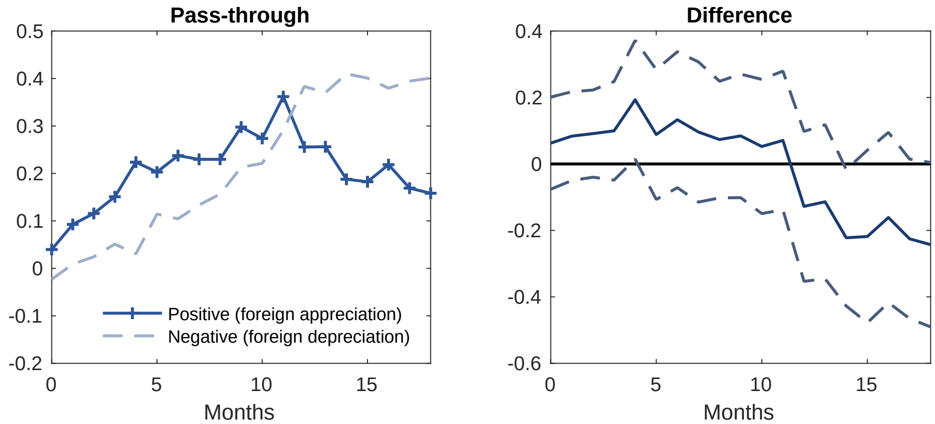


Figure 8: Pass-through for foreign currency depreciations (-) and appreciations (+)

Industrial Supplies and Materials

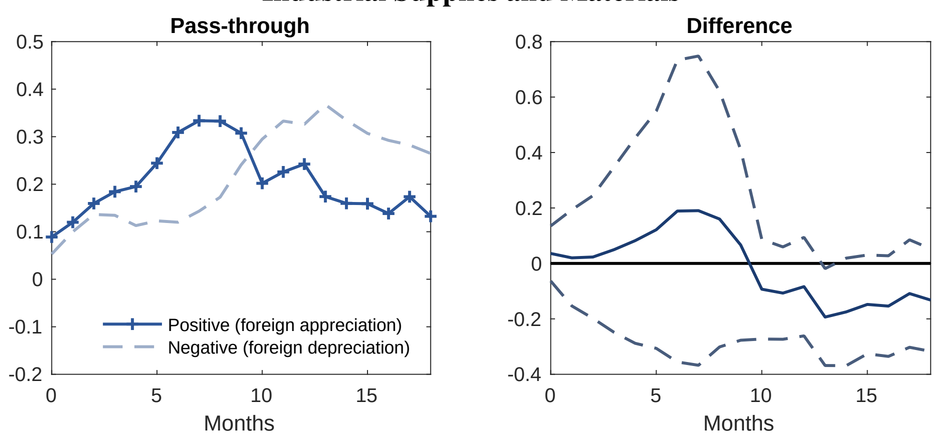


Figure 9: Pass-through for foreign currency depreciations (-) and appreciations (+)

Figures 8 and 9 present the results for foods, feeds, and beverages, and industrial supplies and materials. These categories roughly comprise the "material-intensive" goods used in Section 2. While the point estimates indicate some asymmetry, with foreign appreciations passing through faster in the first 8-10 months and then being overtaken by foreign depreciations, these estimates are noisy, and they are largely statistically insignificant.

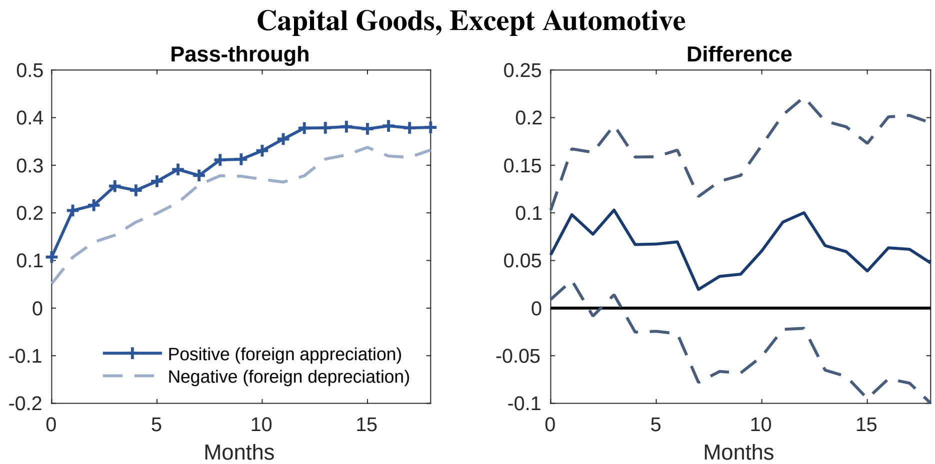


Figure 10: Pass-through for foreign currency depreciations (-) and appreciations (+)

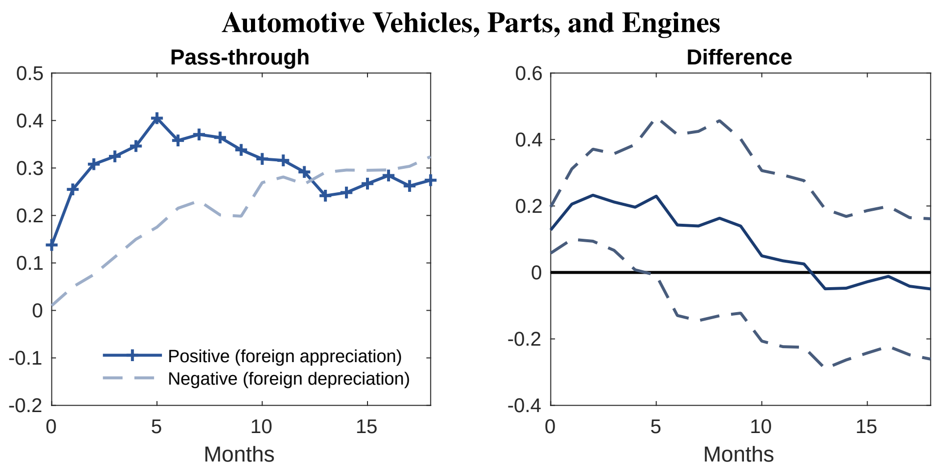


Figure 11: Pass-through for foreign currency depreciations (-) and appreciations (+)

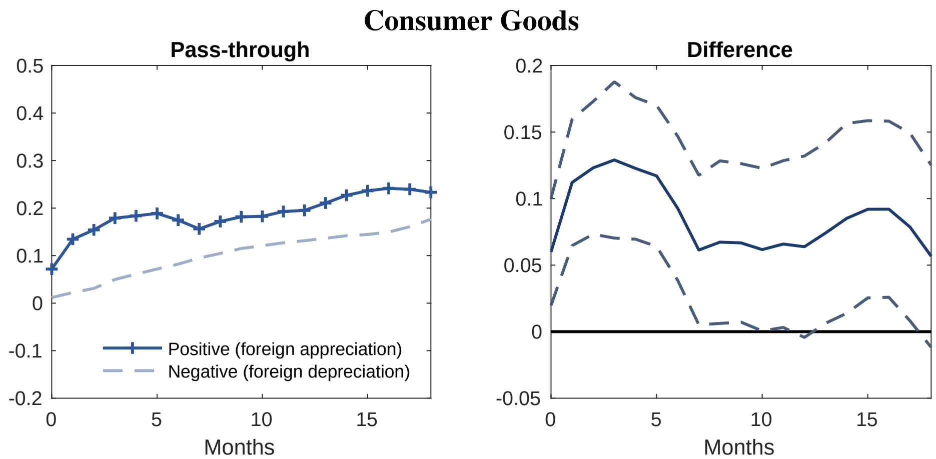


Figure 12: Pass-through for foreign currency depreciations (-) and appreciations (+)

Capital goods, in Figure 10, shows some evidence of asymmetry, but it is clearly stronger in automotive goods in Figure 11 and consumer goods in Figure 12. The estimated asymmetry for consumer goods is statistically significant for all of the reported months. Relative to consumer goods, the magnitude of the estimated pass-through asymmetry for automotive goods is larger initially, but it fades over time. Given these heterogeneous responses, it is not surprising that finding asymmetry in total aggregate import prices is difficult.

4.2 Non-linearity in pass-through

Next, we consider the potential for non-linear pass-through, as studies such as Ritz (2015) emphasizes that many theoretical explanations of asymmetric pass-through also imply non-linear pass-through. To look for non-linearities, we add square and cubic terms to our asymmetric pass-through regression:

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

$$+ \sum_{k=0}^{h} \{\beta_k^- (\Delta e^-)_{j,t-k} + \gamma_k^- (\Delta e^-)^2_{j,t-k} + \delta_k^- (\Delta e^-)^3_{j,t-k} \quad (4)$$

$$+ \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_t} + \varepsilon_{i,j,t} \quad (5)$$

Cubic terms are potentially important in that they could capture the possibility that the non-linearity may not be symmetric.

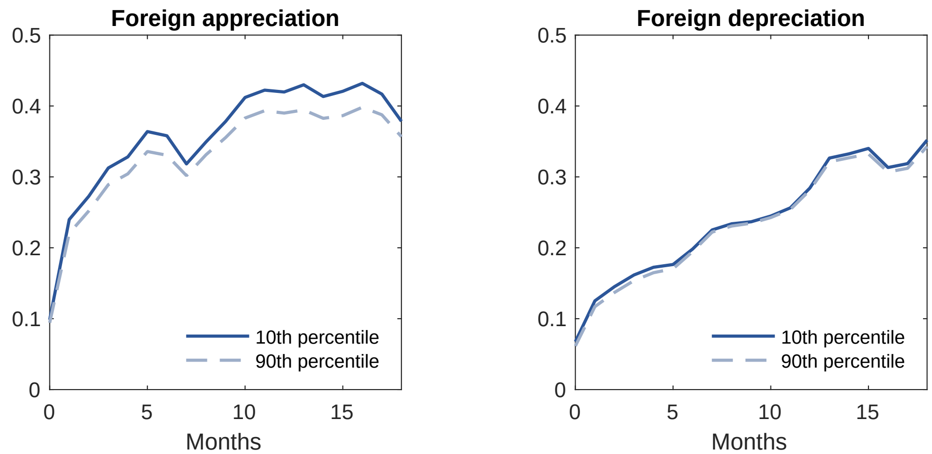


Figure 13: Pass-through of 1st and 9th decile of foreign exchange rate appreciations (left panel) and depreciations (right panel) for differentiated arms-length imports

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 13 plots the pass-through of each shock, with the pass-through for foreign appreciations in the left panel and foreign depreciations in the right panel. Clearly, their pass-through rates are nearly economically identical, suggesting that pass-through is not significantly non-linear.

4.3 Price stickiness

Having established that import prices rise faster than they fall for more differentiated and final goods, we turn to considering two potentially important factors that might be driving the results. First, since import prices are fairly sticky (Gopinath and Rigobon 2008), asymmetry in the short-run might simply be the result of prices remaining stuck longer for foreign depreciations than for foreign appreciations. Second, we measure pass-through for prices of goods that remain in the sample. If product exits are selectively induced, we might observe more pass-through. We explore this issue with selection in Section 4.4.

Although 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:

$$prob(\Delta p_{i,j,t} \neq 0) = \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t} \tag{6}$$

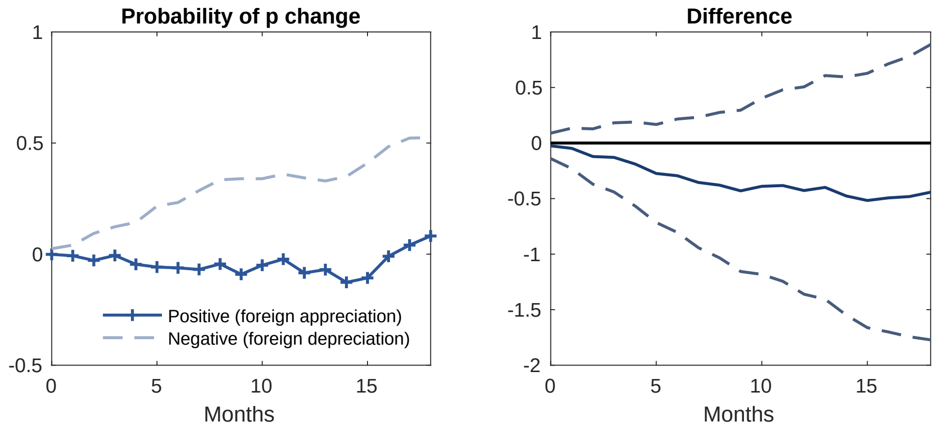


Figure 14: Change in the probability of price change for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length imports

Given that the observed asymmetry in pass-through is concentrated in differentiated goods, we focus our analysis on those goods here. Figure 14 shows the results for differentiated arms-length imports. Foreign appreciations do not have any effect on the probability that a firm changes its price. Economically speaking, foreign depreciations do raise the probability of a price change, up to about 50 percentage points after 18 months. However, the difference between the two, as shown in the right panel, is statistically insignificant. Even if foreign depreciations did significantly raise the probability of a price change more than appreciations, pass-through from foreign depreciations should then be faster than appreciations, which is the opposite of the asymmetry observed in our data. So this result points away from price stickiness being an underlying driver of the asymmetry in pass-through.

We employ a second method to further determine 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).[13]

We estimate the following:

$$\Delta p_{i,j,c} = \beta^{+} \Delta e^{+}_{j,c} + \beta^{-} \Delta e^{-}_{j,c} + \gamma \Delta P_{j,c} + \Delta Z_c + \mathbf{s_j} + \varepsilon_{i,j,c} \tag{7}$$

where subscript c denotes the cumulative change between time t and the time of 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 presents the results for arms-length imports. In the first line, imports of all goods have

[13]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	0.210***	0.178***	-0.032	138,877	0.08
Differentiated (stricter def)	0.154***	0.267***	0.113**	41,632	0.12
Differentiated (looser def)	0.175***	0.214***	0.039	62,545	0.12
By end-use:					
0. Foods, feeds, bev.	0.130***	0.065*	-0.065	24,026	0.03
1. Industrial supplies	0.320***	0.134**	-0.186	47,994	0.08
2. Capital goods ex auto	0.249***	0.145**	-0.104	13,200	0.19
3. Automotive products	0.133	0.369***	0.237**	1,157	0.22
4. Consumer goods	0.113***	0.225***	0.112	13,172	0.16

Note: *** denotes significance at the 99% level, ** at the 95% level, and * at the 90% level, with standard errors clustered at the sector (strata) level.

a similar pass-through rate conditional on a price change of about 0.2, and the difference is economically and statistically insignificant. When we focus on differentiated goods strictly following the Rauch (1999) classification (see the second line of Table 1), the asymmetry remains: foreign appreciations pass-through by about 0.27, while depreciations pass-through by 0.15, for a statistically significant difference of over 0.1.[14] So even after eliminating price stickiness, an asymmetry remains for differentiated goods.

Among end-use categories, foods feeds and beverages, industrial supplies and materials, and non-auto capital goods show, if anything, an asymmetry in the opposite direction, where foreign depreciations pass through more than appreciations. But this difference is not significant in this sample. Once again, the result seems to be driven by automotive products and consumer goods, though for consumer goods, the asymmetry is not statistically significant. All told, these results and Figure 14 suggest that price stickiness is not a primary factor driving the faster pass-through of foreign appreciations.

4.4 Selection bias and exit

We turn next to selection. More complete pass-through from foreign appreciations might be driven by selective exit: A foriegn export may choose to stop selling a particular product rather than reduce its price in response to a foreign currency depreciation. If the product exits our dataset then because of the depreciation, estimates of pass-through would be biased toward zero. As such, we would be more likely to find more complete pass-through for appreciations relative to depreciations. In particular, as is discussed in Nakamura and Steinsson (2012) and Gagnon et al. (2014), a notable risk to estimating pass-through regressions is that a product exiting in response to a need to make a

[14] The third line shows the results when we use a looser definition of differentiated goods. Here, goods missing a Rauch (1999) classification are assigned one based on the corresponding category for a more aggregated HS code. This looser definition yields an asymmetry of 0.04 that is statistically insignificant.

price change would not be counted as a price change by the BLS. To examine the scope for selective exit, we estimate a similar linear probability model as that for price change, but replace the left-hand side with the probability of exit:

$$prob(exit_{i,j,t}) = \sum_{k=0}^{18} \{\beta_k^+ \Delta e_{j,t-k}^+ + \beta_k^- \Delta e_{j,t-k}^-\} + \gamma \Delta P_{j,t} + \boldsymbol{\alpha_t} + \boldsymbol{s_j} + \varepsilon_{i,j,t}. \tag{8}$$

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, so we can limit our analysis to those product exits that are likely to be endogenous.[15]

Figure 15 reports the change in the probability of exit in response to exchange rate movements. (The average probability of exit is not shown.) Following an exchange rate appreciation, the probability of exit is roughly unchanged, very similar to that of a depreciation, and their difference is neither statistically nor economically significant.[16]

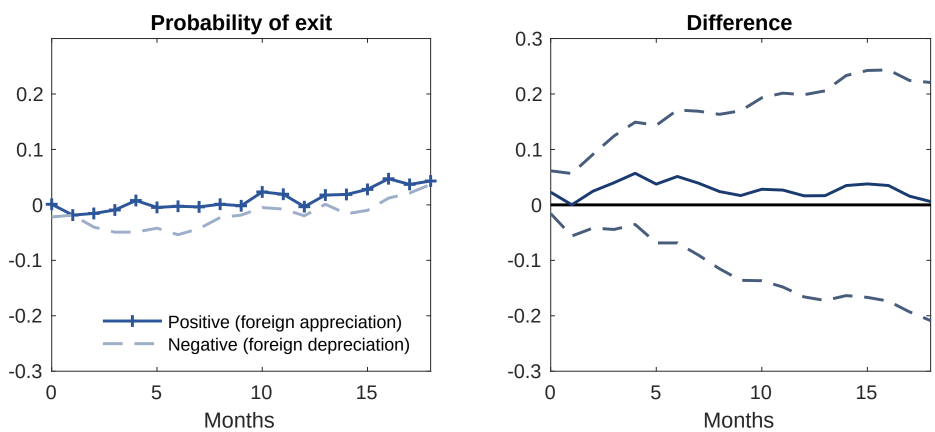


Figure 15: Change in the probability of product exit for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length imports

Having established empirical evidence for asymmetric pass-through, our next step is to understand what forces lead firms to choose to respond differently to appreciations versus depreciations. The next section presents an economic model to match these empirical facts.

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

[16] In the appendix, Figure 25 shows the same result for intrafirm imports. After a year, foreign depreciations have an elevated probability of exit, but the difference in the probability of exit between depreciations and appreciations is not statistically significant.

5 Model

In this section, we outline a model of trade prices that is capable of matching our empirical facts. 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 in the short-run, 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.[17] Optimal prices in these models 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.

Our non-CES setting is based on 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.[18] The demand function takes the form:

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

where p is the price of an individual product, $\bar{P}$ is the aggregate sectoral price, θ is the elasticity of demand, and ε is the "super-elasticity" of demand (the elasticity of the demand elasticity θ). With $\varepsilon = 0$, this demand system collapses to a standard CES case with elasticity of substitution θ.

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:

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

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

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

[17] See for example Gust et al. (2010).

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

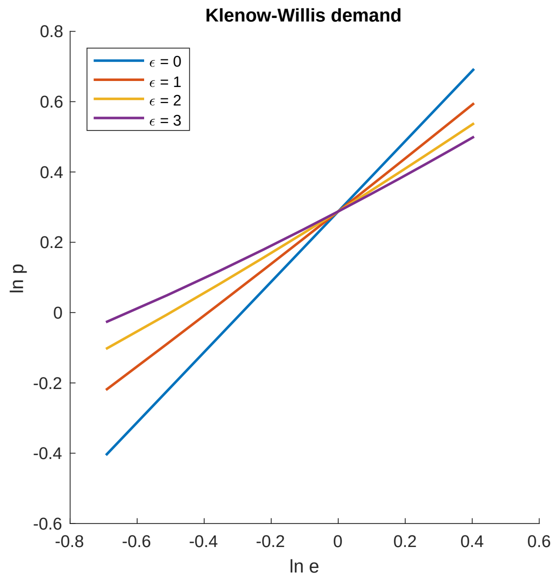


Figure 16: Optimal log prices under Klenow-Willis (2006) demand

Gopinath and Itskhoki (2010) demonstrate 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 16 shows optimal prices ($\ln p_i$) for a given exchange rate ($\ln e$), where a higher e corresponds to a destination currency depreciation. 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 cannot 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 increasing physical production (e.g. expanding a factory, finding new workers, etc) or could represent costs involved with finding new buyers.[19]

[19]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 the relationship is hump-shaped, with the lowest pass-through representing firms between those with no market share and complete monopoly power. Their evidence is based on the same U.S. import

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

With a menu cost model, the value of a firm is:

$$V(p,a,e) = max\{V^A(p,a,e), V^N(p,a,e)\}, \tag{11}$$

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. V^A is the value of the firm if it adjusts its price:

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

where, p' is the firm's new price, Π is the flow profit of the firm. V^N is the value of the firm if it does not adjust its price:

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

If a firm chooses to adjust prices, the equation for flow profit Π shows that the firm chooses prices such as to maximize the value of revenue minus the cost of production and the adjustment cost for changing production:

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

The value of revenue minus the cost of production depends on demand $q(p)$, derived from 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.

The adjustment cost for changing production is:

$$\mathbb{I}[q(p') > q(p)]\phi\bar{c}(q(p') - q(p))^2$$

Because of the indicator function $\mathbb{I}[q(p') > q(p)]$, the adjustment cost is asymmetric, with costs accrued for increasing production but not for decreasing production. In addition, the magnitude of the costs is determined by the value of ϕ.

In our parameterization, we examine the potential for these convex adjustment costs to generate

price data used in this paper.

Table 2: External Parameterization

Parameter	Value	Description
θ	4	Elasticity of substitution
β	$0.94^{\frac{1}{12}}$	Discount factor
ρ_a	0.96	AR(1) coefficient for productivity
ρ_e	0.99	AR(1) coefficient for exchange rates
σ_e	0.025	Standard deviation for exchange rates

Table 3: Parameterization via Indirect Inference

Parameter	Value	Description	Targeted Moment	Target	Model
ε	3.63	Super-elasticity	Long-run pass-through	0.4	0.43
κ	0.025	Menu Cost	Frequency of Δp	0.09	0.076
ϕ	2.80	Convex adjustment cost	PT asymmetry (max)	0.10	0.087
σ_a	0.047	Standard deviation of productivity	Median abs. Δp	0.08	0.026

the pattern of asymmetric pass-through that we find in the data. Table 2 presents the externally calibrated parameters of the model. Many parameters are fairly standard: the elasticity of substitution $\theta = 4$, β implies an annual discount factor of 0.94. Exchange rates are highly persistent ($\rho_e = 0.99$) with modest volatility ($\sigma_e = 0.025$). The autocorrelation of productivity, $\rho_a = 0.96$, is estimated with U.S. data by (Schoenle 2017).

This leaves four parameters, for which we use indirect inference by simulating the model under a given parameterization and comparing the simulated data's moments against the targets, minimizing the least squares distance between the two. Table 3 shows the results of this procedure. Each parameter is principally tied to a targeted moment. The super-elasticity of substitution ε primarily determines pass-through at the end of 18 months; at $\varepsilon = 3.63$, this super-elasticity is similar to the $\varepsilon = 3$ calibrated by (Gopinath et al. 2010), and the model generates pass-through essentially identical to the data. The menu cost $\kappa = 0.025$ generates the frequency of price change of 7.6% in our calibration, slightly less frequently than the 9% targeted. The asymmetry is pinned down by the convex adjustment cost $\phi = 2.8$, which generates a 0.087 wedge between foreign appreciations and depreciations at its max, very similar to the roughly 0.1 we observe in Figure 6.

On the other hand, the model generates small price changes. Idiosyncratic productivity shocks $\sigma_a = 0.047$ are only sufficient to cause firms to change their price less than half as much, on average, as they do in the data. The central tension in the model is that menu costs and idiosyncratic shocks induce firms to want to change their price infrequently but by large amounts, while for desired price reductions, convex adjustments costs induce firms change their prices more frequently but in smaller increments. Still, qualitatively, and in most cases quantitatively, the model is capable of reproducing the salient price facts we document.

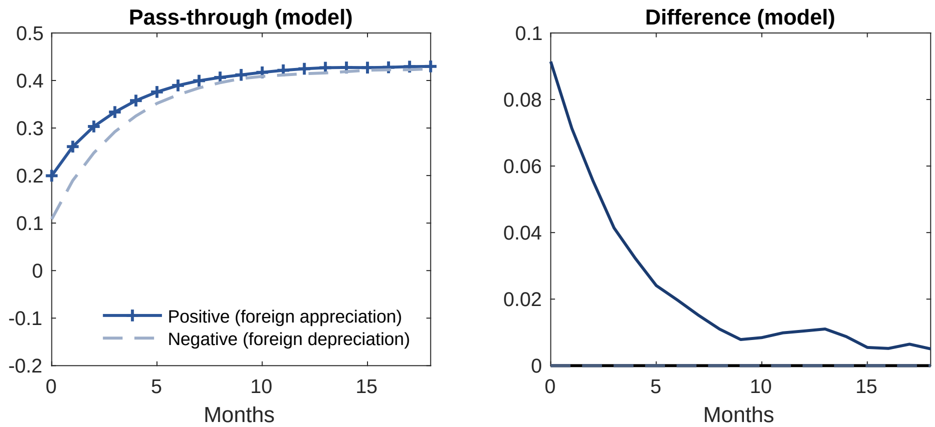


Figure 17: Pass-through in the benchmark model for foreign currency depreciations (-) and appreciations (+)

Figure 17 provides the same pass-through response from the model as we show with the data. Compared to Figure 6, the qualitative and quantitative pattern is similar. Pass-through is very low for the first few months, and the difference is nearly 0.1, though for the model, the difference peaks at time zero, rather than the hump shape we observe in the data. This difference declines over time until being essentially zero by 15 months, similar to the data.

As shown in Figure 13, U.S. imports exhibit little sign of nonlinearity, with a similar response to 10th and 90th percentile exchange rate shocks. In Figure 18, we show the same exercise in our model. Here too, large exchange rate changes pass through very similarly to small ones. Pricing decisions are still dominated by firms' relatively large idiosyncratic productivity shocks.

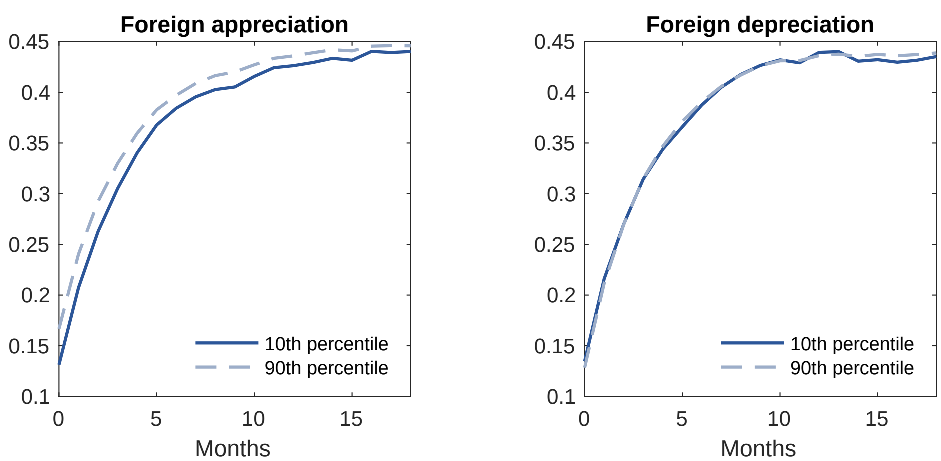


Figure 18: Pass-through of 1st and 9th decile of foreign exchange rate appreciations (left panel) and depreciations (right panel) in the model

6 Conclusion

In this paper, we demonstrate that product-level U.S. import prices from the BLS 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. A similar pattern exists for both arms-length transactions and intra-firm ones. While these asymmetries imply the existence of non-linearities, 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.

A model with menu costs, strategic complementarities in price setting, and convex adjustment costs can roughly match the salient price facts we document in the BLS microdata. Although we have successfully matched our main empirical findings, our model does have room for improvement. In particular, in our model, the same adjustment costs that help us match the asymmetry also cause price changes to be smaller in magnitude than the changes observed in the data.

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A Exchange rate persistence

One potential source of asymmetry stems from the firm's belief 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, we directly test the persistence of appreciations and depreciations separately in this appendix.

To do this, we estimate the response of bilateral log exchange rate $e_{i,t}$ at horizon h using a local projections 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.[20]

Table 4 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 statistically indistinguishable from zero. At least statistically, exchange rates appear equally persistent across exchange rate appreciations and depreciations.

B Other intrafirm import results

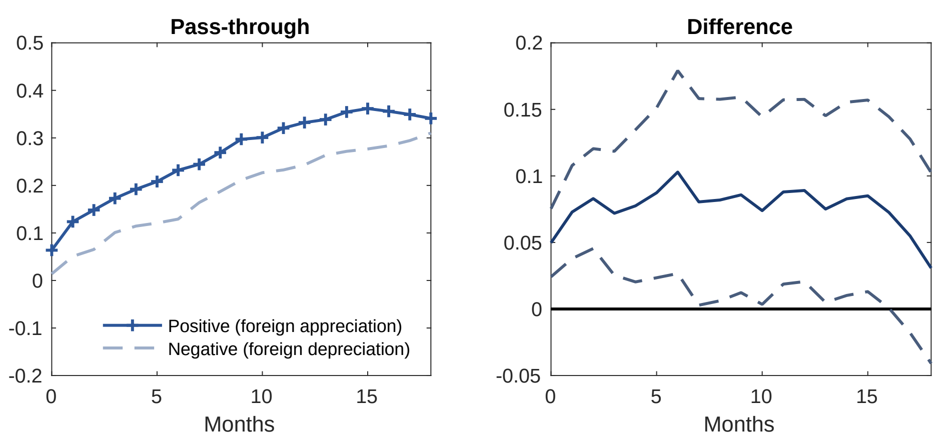

Figure 19: Pass-through for foreign currency depreciations (-) and appreciations for all intrafirm imports(+)

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

Table 4: 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]

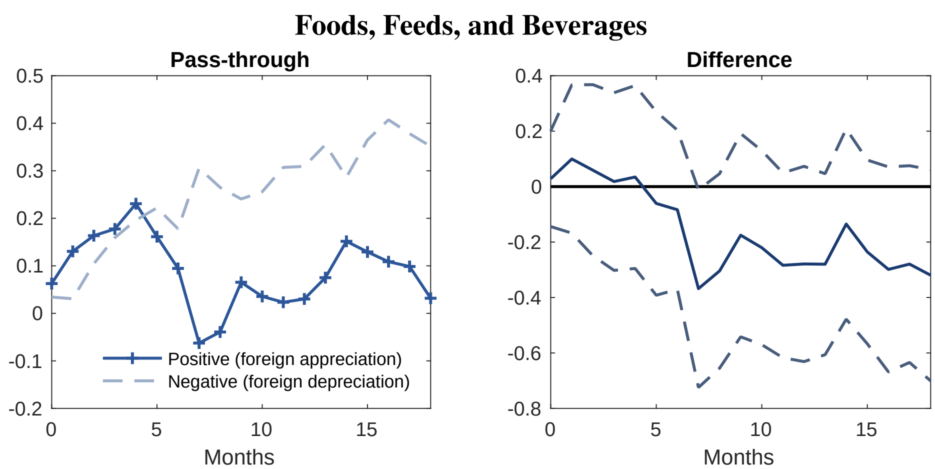

Figure 20: Pass-through for foreign currency depreciations (-) and appreciations (+)

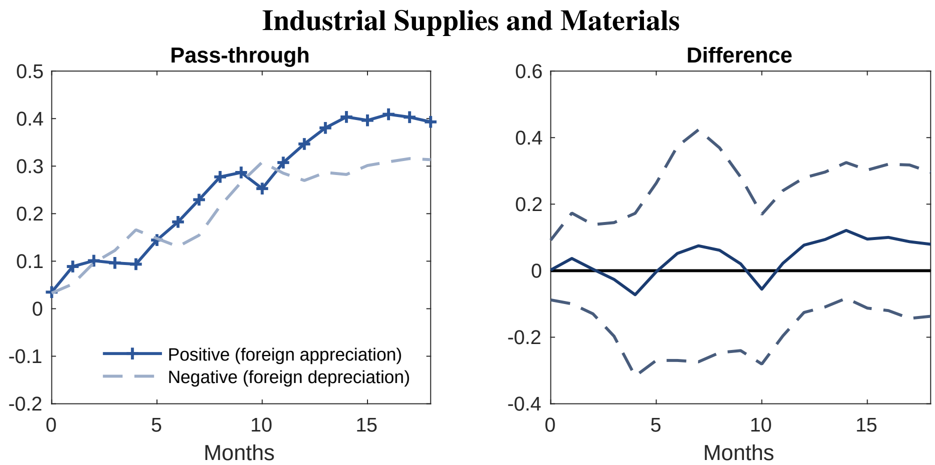

Figure 21: Pass-through for foreign currency depreciations (-) and appreciations (+)

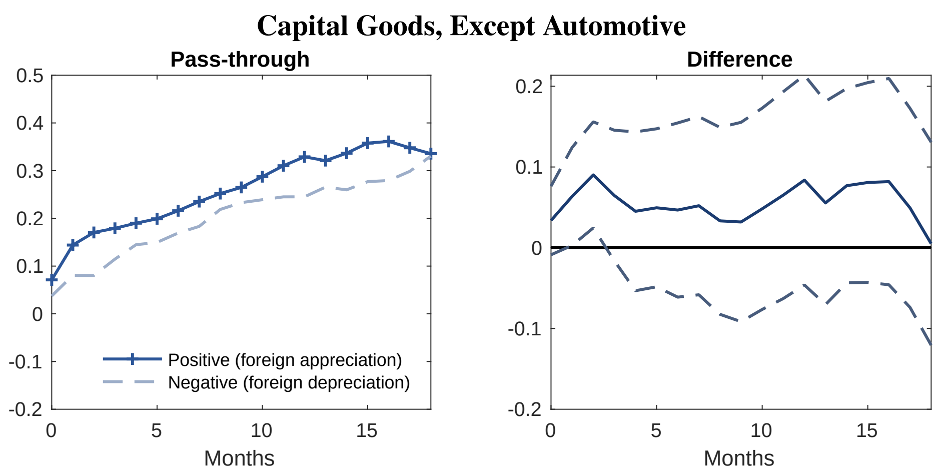

Figure 22: Pass-through for foreign currency depreciations (-) and appreciations (+)

Automotive Vehicles, Parts, and Engines

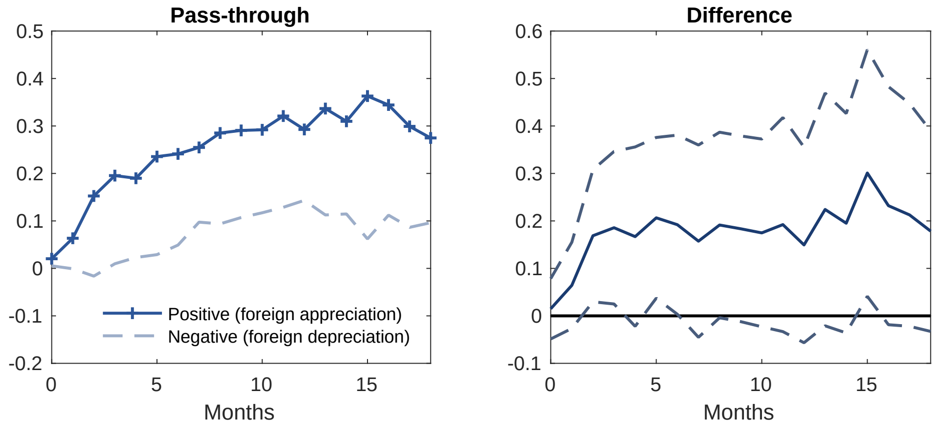

Figure 23: Pass-through for foreign currency depreciations (-) and appreciations (+)

Consumer Goods

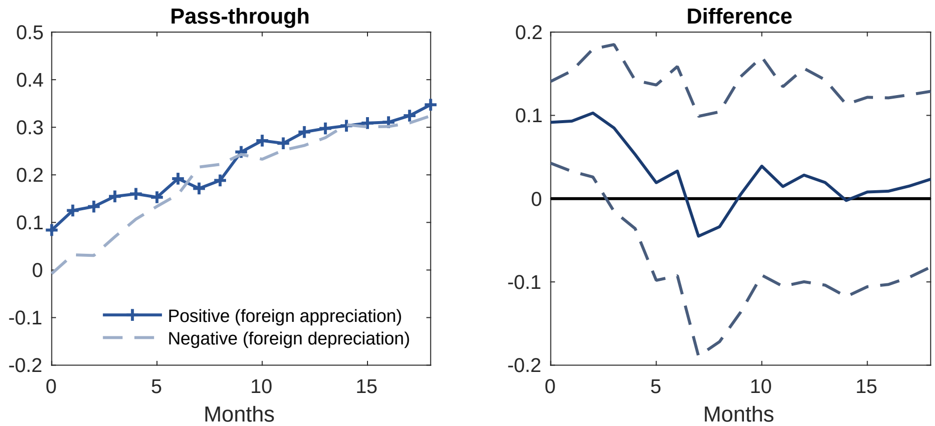

Figure 24: Pass-through for foreign currency depreciations (-) and appreciations (+)

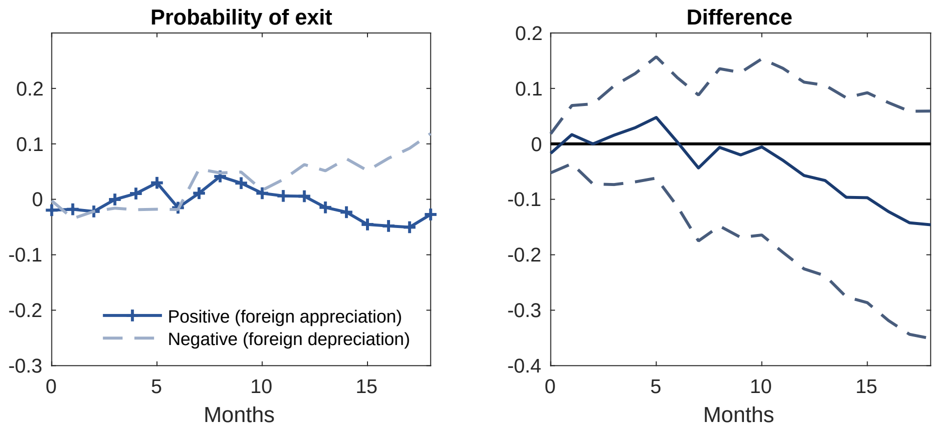

Figure 25: Probability of product exit for foreign currency depreciations (-) and appreciations (+) for differentiated intrafirm imports

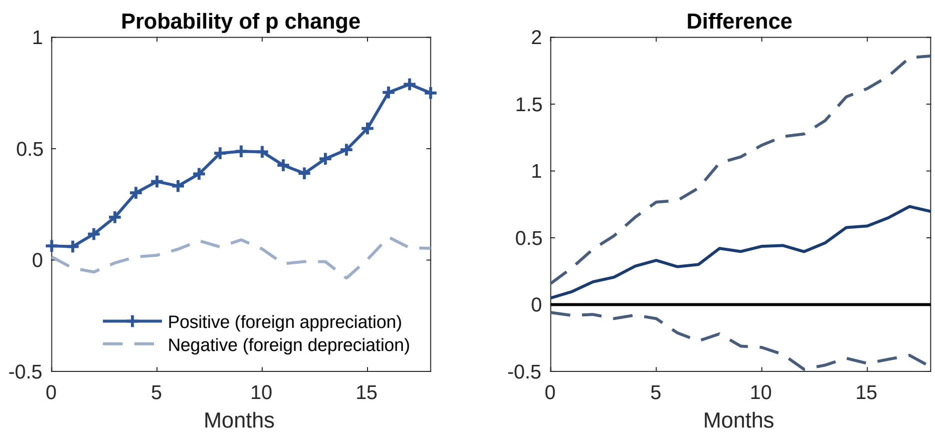

Figure 26: Probability of price change for foreign currency depreciations (-) and appreciations (+) for differentiated intrafirm imports

Table 5: Pass-through conditional on a price change

	Depreciation	Appreciation	Difference	N	R^2
All goods	0.134***	0.250***	0.116***	109,230	0.08
Differentiated (stricter def)	0.097***	0.279***	0.182***	49,753	0.09
Differentiated (looser def)	0.113***	0.259***	0.146***	80,194	0.08
By end-use:					
0. Foods, feeds, bev.	0.350***	0.240***	-0.109	8,200	0.05
1. Industrial supplies	0.215***	0.154**	-0.061	22,109	0.09
2. Capital goods ex auto	0.137***	0.242***	0.105*	28,908	0.09
3. Automotive products	-0.044	0.213***	0.257***	3,866	0.08
4. Consumer goods	0.030	0.364***	0.334***	12,399	0.12

Note: *** denotes significance at the 99% level, ** at the 95% level, and * at the 90% level, with standard errors clustered at the sector (strata) level.

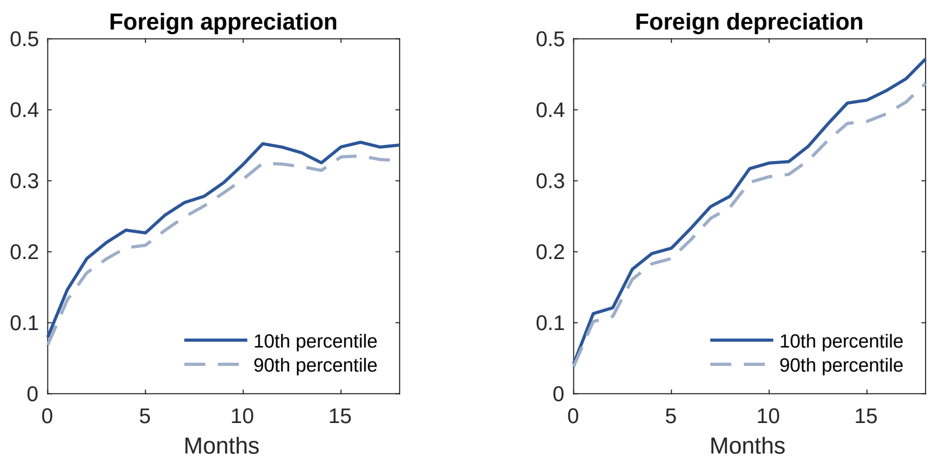

Figure 27: Pass-through of 1st and 9th decile of foreign exchange rate appreciations (left panel) and depreciations (right panel) for differentiated intrafirm imports

C Arms-length exports

In this section, we present complementary evidence on asymmetries and non-linearities in pass-through to arms-length U.S. exports. Since both exports and imports are priced and stuck in dollars (Gopinath and Rigobon 2008), exports provide a contrasting set of evidence on the nature of international price setting. In the short run, pass-through to the foreign local currency is effectively complete, as the price is stuck in dollars.

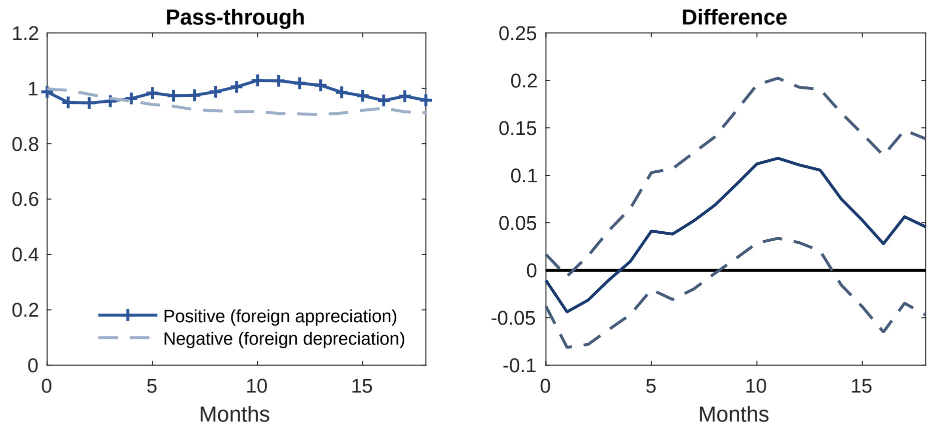

Figure 28: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

Figure 28 shows pass-through for all U.S. goods exports, translated into local (foreign) prices. Pass-through is effectively complete in both the short- and long-run in this sample, with some evidence of greater pass-through for foreign appreciations after 12 months. But note that this asymmetry works in the opposite way from what we observe with U.S. imports. Furthermore, it appears to be quite transitory, being statistically significant for only a few months.

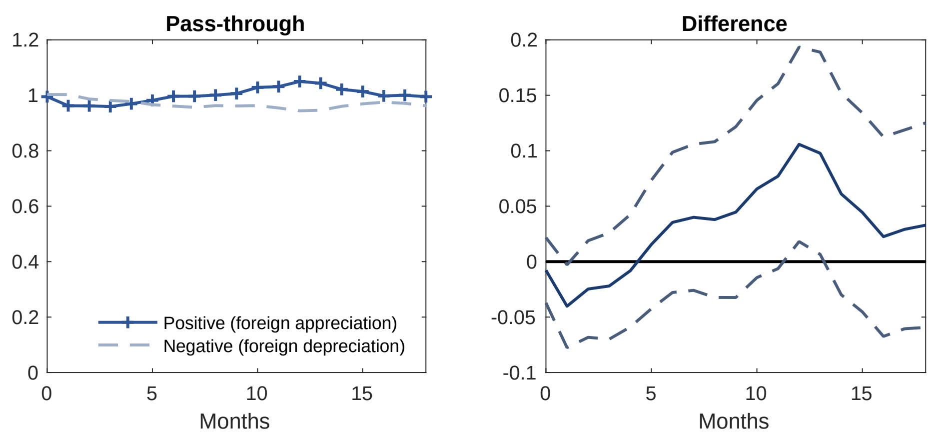

Figure 29: Pass-through for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length exports

Any asymmetry becomes even smaller when considering differentiated goods (see Figure 29). While foreign appreciations do have higher pass-through briefly around the 12-month mark, it is fleeting.

Foods, Feeds, and Beverages

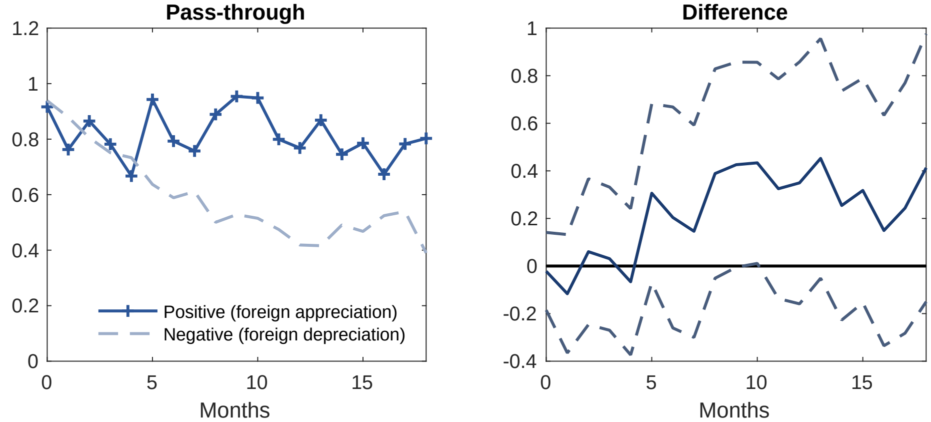

Figure 30: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

Industrial Supplies and Materials

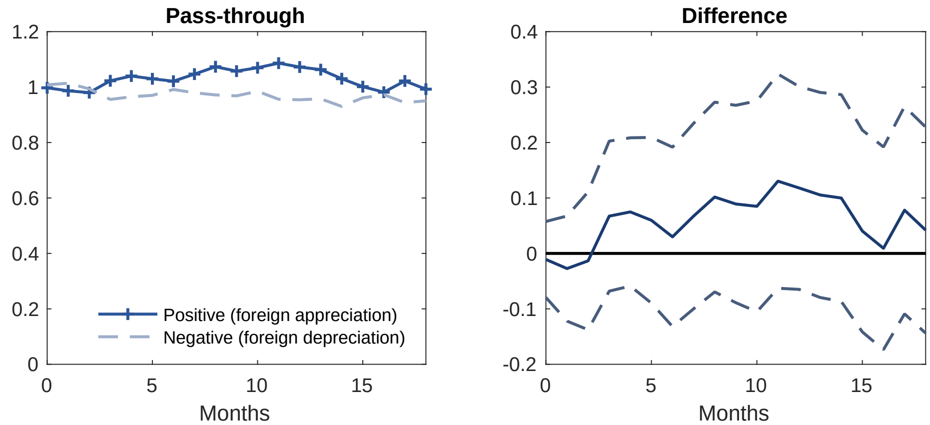

Figure 31: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

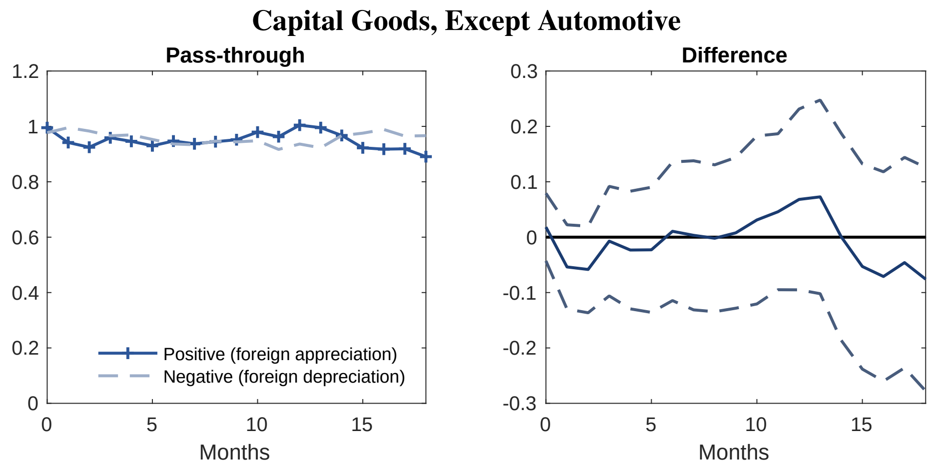

Figure 32: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

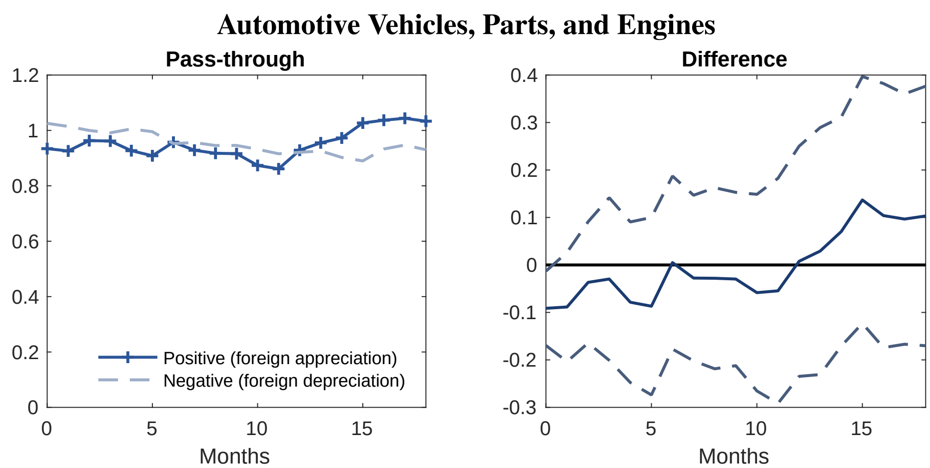

Figure 33: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

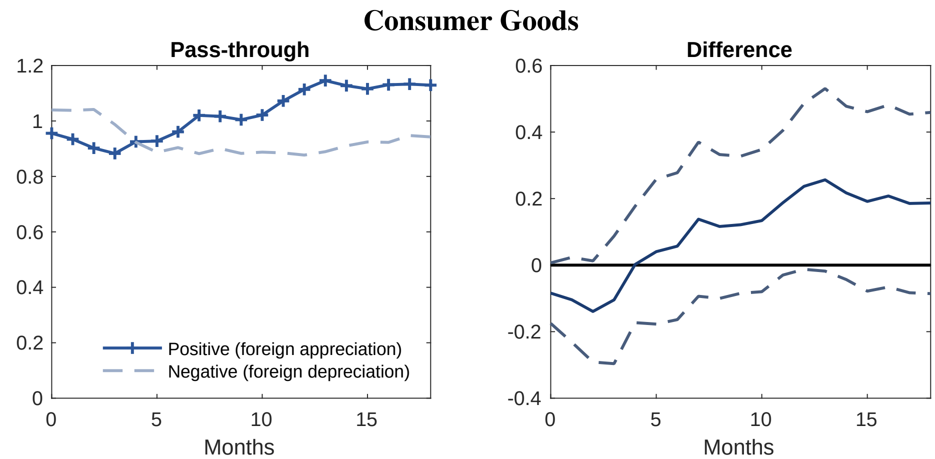

Figure 34: Pass-through for foreign currency depreciations (-) and appreciations (+) for arms-length exports

Pass-through by end-use category is shown in Figures 30 through 34. Category by category, there is no statistically significant evidence of asymmetries, though the point estimates suggest that if an asymmetry exists, it is that foreign appreciations pass through at a higher rate than foreign depreciations.

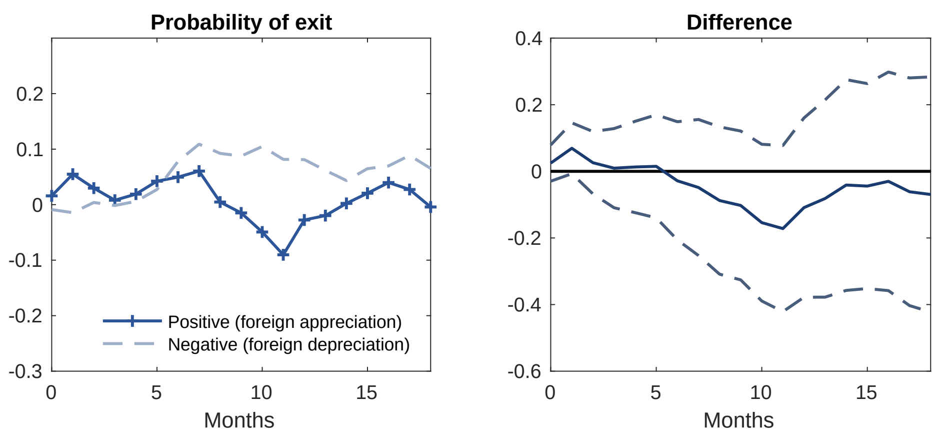

Figure 35: Probability of product exit for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length exports

Similar to arms-length imports, Figure 35 demonstrates that foreign appreciations and depreciations have similar, negligible effects on the probability that a product endogenously exits the BLS sample.

Table 6: Pass-through conditional on a price change

	Depreciation	Appreciation	Difference	N	R^2
All goods	0.887***	0.882***	-0.005	86,009	0.09
Differentiated (stricter def)	0.970***	0.878***	-0.092*	26,135	0.14
Differentiated (looser def)	0.953***	0.906***	-0.047	40,410	0.13
By end-use:					
0. Foods, feeds, bev.	0.705***	0.851***	0.146	7,817	0.07
1. Industrial supplies	0.835***	0.876***	0.041	22,877	0.10
2. Capital goods ex auto	0.937***	0.919***	-0.018	6,145	0.20
3. Automotive products	1.201***	0.768***	-0.433***	1,774	0.13
4. Consumer goods	1.030***	0.766***	-0.264	2,331	0.27

Note: *** denotes significance at the 99% level, ** at the 95% level, and * at the 90% level, with standard errors clustered at the sector (strata) level.

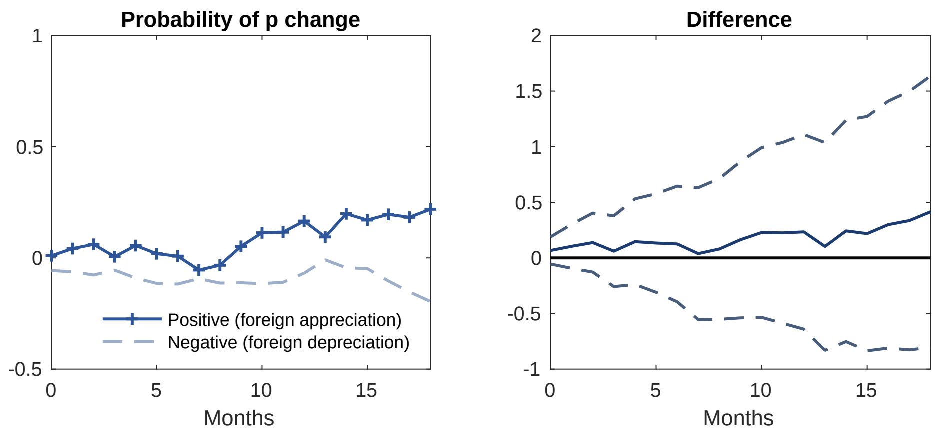

Figure 36: Probability of price change for foreign currency depreciations (-) and appreciations (+) for differentiated arms-length exports

Likewise, Figure 36 demonstrates that foreign appreciations and depreciations have minimal influence on the probability that a firm changes its price. This is in contrast to arms-length imports in Figure 14, where foreign depreciations increased the probability of a price change.

Conditional on a price change, pass-through is roughly symmetric overall, as demonstrated in Table 6. For all goods, pass-through is 0.9 for both appreciations and depreciations. For differentiated goods, foreign appreciations have lower pass-through than foreign depreciations, though the difference is only marginally statistically significant. Note that in this case, the asymmetry of foreign appreciations having lower pass-through is consistent with the asymmetry found in U.S. imports.

Across sectors, to the extent there is an asymmetry for differentiated goods, it is being driven again by automotive products and consumer goods, though the latter is statistically insignificant.

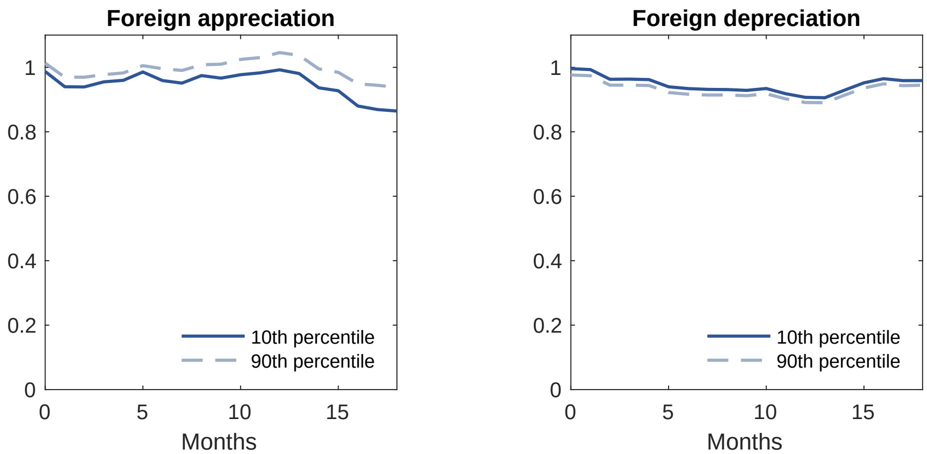

Figure 37: Pass-through of 1st and 9th decile of foreign exchange rate appreciations (left panel) and depreciations (right panel) for differentiated arms-length exports

Figure 37, comparable to Figure 13, shows pass-through for the 1st and 9th deciles of foreign appreciations and depreciations, respectively. For foreign depreciations, pass-through appears quite linear and very close to one. For foreign appreciations, there may be a modest nonlinearity, with slightly higher pass-through for large exchange rate changes than for small ones.