Essays on International Economics

by

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Dedication

To my sister Yasmin, my ultimate friend and mentor, whom I missed every day during the last five years.

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Abstract

The first chapter, “Trade Policy Uncertainty and Import Prices”, studies how trade policy uncertainty (TPU) affects the pass-through of import tariff and exchange rate changes into import prices. Little is known about the effects of tariff changes accompanied by TPU on import prices, especially when price rigidities are present. Using a dynamic model of exporting with costly price adjustments and variable markups, we show that TPU significantly increases tariff pass-through into the tariff-inclusive import price. TPU raises tariff pass-through via two channels relative to a one-time permanent tariff increase. First, TPU decreases the likelihood of costly price adjustment on impact (“wait-and-see” effect), which immediately induces high tariff pass-through. Second, TPU leads exporters to set higher markups due to a precautionary pricing motive, resulting in higher tariff pass-through even after prices are adjusted. Conversely, exchange rate pass-through is unaffected by TPU and remains low and incomplete. Quantitatively, high TPU accounts for half of the gap between the puzzling complete pass-through estimated for U.S. tariffs on China in 2018-2019 into U.S. import prices and the prediction of a standard model without TPU. High TPU also increases tariff deadweight loss by 51% and increases the share of tariff incidence borne by U.S. importers by 36%.

The second chapter, “Multiple Invoicing Currencies in a Small Open Economy”, explores the impact of multiple invoicing currencies on a small open economy. We present a New Keynesian model where firms vary by the currency in which they set sticky export prices: producer, local, or vehicle. We explore the difference in the economy’s reaction under different pricing paradigms and with multiple invoicing currencies. Multiple invoicing currencies limit the pass-through rate of bilateral and dollar exchange rate fluctuations into export and import prices. The milder impact on prices leads the terms of trade to be less responsive to exchange rate fluctuations relative to producer or local currency pricing but more responsive than under dominant currency pricing in dollars. Using Swedish data, we find that exchange rate shocks have an incomplete pass-through into import and export prices. However, the pass-through rate of the bilateral exchange rate is higher than under local currency or dominant currency pricing, in line with an economy with a significant share of pricing in the producer's currency. We calibrate the model to Sweden and show that accounting for multiple invoicing currencies is crucial for explaining observed rates of exchange rate pass-through and understanding the response of such an economy to exogenous shocks.

Contents

Chapter 1

Trade Policy Uncertainty and Import Prices

1.1 Introduction

Who bears the incidence of import tariffs is a crucial question in the design of trade policy. U.S. importers pay a tariff-inclusive import price at the dock, which includes a border price set by the foreign exporter and a tariff set by the U.S. government. In standard models of a large open economy like the U.S., a tariff increase induces border price adjustment by the foreign exporter and, as a result, a less than one-for-one increase in the import price. In 2018-2019, the U.S. imposed tariffs on imports from major trading partners–an increase in protectionism unseen since the 1930s. In particular, the U.S. imposed large tariff increases on almost all imports from China. U.S. tariff-inclusive import prices rose by nearly the full tariff increase (i.e., there was close to 100% pass-through rate of the tariff into tariff-inclusive import prices), as border prices (exclusive of tariff) barely changed. In other words, U.S. importers bore the overwhelming share of the tariff incidence.[1] Not only is it at odds with theory, but the lack of response in Chinese exporters' border prices also contradicts past empirical findings about other tariff changes and exchange rate fluctuations. In this paper, we

[1]This finding is documented in Amiti, Redding & Weinstein (2019), Amiti, Redding & Weinstein (2020), Fajgelbaum et al. (2020), and Cavallo et al. (2021).

propose a mechanism that can reconcile the theory and past evidence with the data: trade policy uncertainty.

A salient feature of the 2018-2019 tariffs was that they were accompanied by extremely high levels of trade policy uncertainty (TPU).[2] Yet, little is known theoretically or empirically about the effects of TPU on prices in international transactions, especially in the short- to medium-run when prices adjust infrequently. Could the observed extreme level of TPU explain the puzzling high pass-through rate of the 2018-2019 tariffs? More generally, what is the effect of TPU on (i) import prices and (ii) the pass-through of tariffs and other shocks into these prices? We address these questions using a dynamic model of exporting to the U.S. that builds on findings from the international prices literature and incorporates TPU and tariffs. We calibrate the model to U.S. import prices and show that TPU substantially increases tariff pass-through into import prices, tariff deadweight loss, and the tariff incidence on U.S. importers.

We start by constructing a partial equilibrium dynamic model of exporting to the U.S. with price rigidities, tariffs and TPU. In the model, we connect the literature about sticky international prices with the literature about trade policy uncertainty. The literature about the effects of TPU focuses mostly on medium- or long-run outcomes, in particular on investment and participation in exporting, and assumes that prices adjust freely.[3] However, in the short-run, border prices of imports to the U.S. are highly rigid, with a median duration of a border price around one year.[4] Price rigidity is important for understanding the effect of tariffs and TPU on import prices in the short-run, when prices adjust infrequently. However, price rigidity alone cannot account for the high tariff pass-through in 2018-2019 which lasted for more than one year, giving prices ample time to adjust. Therefore, the observed high tariff pass-through is also a result of a high desired pass-through rate for Chinese exporters, which they maintain even once they adjust the border price.

In the model, domestic (American) and foreign (Chinese) competitive monopolists sell their

[2]In fact, by multiple measures, uncertainty regarding U.S. trade policy reached its all-time high during this period. See Caldara et al. (2020), Hassan et al. (2021), and Benguria et al. (2022).

[3]See Handley & Limão (2022). Conversely, Alessandria et al. (2019) examine short-run decisions by exporters under TPU, but focus on inventories. Caldara et al. (2020) embed TPU in a New-Keynesian model with nominal rigidities, but their setup is considerably different than the one in this paper since their main focus is on the effect of TPU on investment.

[4]See, e.g.,Gopinath & Rigobon (2008), Nakamura & Zerom (2009), Schoenle (2017).

differentiated final goods in the U.S. The model includes tariffs and TPU, and several key components that account for well-documented facts about U.S. import prices. First, price adjustments incur a fixed adjustment cost, which makes price setting a dynamic problem affected by expectations about future shocks, and thus by TPU. Second, Chinese exporters set their (potentially rigid) border prices in dollars, which insulates the American importers from exchange rate fluctuations.[5] Third, variable markups arise from a Kimball (1995) demand structure with variable elasticity. This simple demand structure captures price complementarities, where a firm does not want to deviate too much from the price of competitors. Variable markups are an important channel for explaining incomplete exchange rate pass-through into border prices, since they adjust to absorb shocks that affect the border price. However, variable markups also lead to some decrease of the border price in response to a tariff increase, and as a result, incomplete tariff pass-through into the import price. This theoretical prediction in a model with variable markups makes the 2018-2019 near-perfect tariff pass-through puzzling, and this paper presents a plausible explanation.

We show how the model with TPU can increase tariff pass-through into import prices. A tariff on imports is set exogenously by the U.S. policy maker. In the model, the tariff level can be low (the case before 2018) or high (the case since 2018). In the absence of TPU, tariff changes are a one-time permanent change.[6] When TPU is present, firms perceive tariff changes as transitory and volatile. We model TPU as a simultaneous decrease in the persistence of the tariff regime, and an increase in the unconditional variance of the tariff forecast error.

The pass-through rate of a tariff change into the import price is determined by how much the exporter adjusts their border price in response. An increase in TPU in the model affects the pass-through rate of a tariff increase into import prices via both the extensive and the intensive margin of border price adjustment. First, on the extensive margin, a mean-preserving increase in TPU reduces the likelihood of border price adjustment. Since price adjustments are costly, an increase in TPU increases the option value of waiting (a "wait-and-see" effect). If there is no border

[5]Dollar pricing is an assumption in the model, and it relies on the stylized fact that over 90% of U.S. import prices are set in dollars (Gopinath & Itskhoki 2011, Gopinath 2015).

[6]A tariff change can be transitory but certain if the policymaker clearly communicates what is the duration of the policy. To the extent that the duration of the tariff is prolonged, this policy will have the same effect on prices as a one-time permanent change.

price adjustment, the import price rises one-for-one with the tariff, i.e., complete tariff pass-through.

Second, conditional on adjustment, the optimal reset border price increases with TPU due to a precautionary pricing motive that leads to a higher markup–the intensive margin of price adjustment. Even once the border price is reset, the precautionary markup effect leads to a smaller decrease in the border price, and thus larger increase in the import price, relative to a one-time permanent tariff increase. The intensive margin effect increases the desired tariff pass-through into the import price over longer horizons, and not just on impact.

Intuitively, the effect of TPU on the intensive margin of price adjustment arises from the combination of variable markups and costly price adjustment. The tariff is paid by American importers, and therefore affects the relative import price directly, and as a result the demand for foreign goods. When markups are variable, a mean preserving increase in uncertainty about the future tariff level affects the exporter's expected profit. The expected profit function is not symmetric: setting the border price "too low" leads to greater losses than setting the border price "too high" when the future level of tariff is uncertain. That is, marginal profit is convex in the tariff. The result is a precautionary increase in markup and in the border price, which increases with the level of uncertainty.[7] The convexity of the marginal profit relies on variable markups in combination with costly price adjustment. We show that these effects hold for various levels of markup elasticity, and increase with the size of the price adjustment cost.

We calibrate the model to U.S. import prices and estimate the effect of TPU on pass-through quantitatively. We estimate tariff and exchange rate pass-through into U.S. import prices in the simulated data and compare the results to the empirical findings from the trade war tariffs. In the model, a one-time permanent 10% increase in tariff raises import prices by 5.9% after one year, while in the data a similar size of tariff increase raises import prices by 9.9%. When high TPU is present, tariff pass-through increases and a 10% tariff increase raises import prices by 8.1% in the model. This represents an increase of more than 20 percentage points in the tariff pass-through rate. Conversely, exchange rate pass-through remains low and is unaffected by the level of TPU: a 10%

[7] Precautionary markups play an important role in other studies of uncertainty that involve price rigidities (Kimball 1989, Fernández-Villaverde et al. 2015, Oh 2020, Caldara et al. 2020, Born & Pfeifer 2021). My setup differs in that it looks specifically at uncertainty about a demand shifter that does not affect the firm's costs. In this setup, variable markups play an important role in creating the precautionary markup motive.

real depreciation of the U.S. dollar raises import prices by 3.8%-3.9% after one year, both in the data and in the model. TPU does not affect exchange rate pass-through since the exchange rate is a volatile process, disconnected from tariff changes or TPU.[8] The effect of TPU on pass-through is robust to different specifications of the tariff process, across various levels of tariff rate increases, and to a case where tariffs are also imposed on imported intermediate inputs. Therefore, TPU can account for up to a half of the gap between the tariff pass-through rate observed in 2018-2019, and the rate predicted by a standard model in the absence of TPU.

Finally, we analyze policy implications of a tariff increase accompanied by TPU. Over one year, the deadweight loss created by tariffs increases by 51% when high TPU is present, relative to a similar tariff increase without TPU. Government revenue is almost unaffected by an increase in TPU. However, the tariff incidence shifts towards American importers, from a share of 58.6% with a one-time permanent tariff increase to 79.8% when TPU is high. These results point towards unintended, undesirable effects of TPU that might be counterproductive to the goals policymakers wish to obtain by imposing a tariff.

This is the first paper to incorporate tariffs accompanied by TPU in a dynamic framework with costly price adjustments and variable markups. We contribute to both the literature about international prices and their reaction to shocks in the short- and medium-run, and the literature about tariffs and TPU. Understanding how import prices react to trade policy with uncertainty is crucial for the design of trade policy, and for our understanding of the effects of tariffs on the macroeconomy. Furthermore, in this work we show that TPU affects price rigidity through the extensive margin of price adjustment and, therefore, potentially affects monetary non-neutrality. Thus, the effect of TPU on sticky prices could be relevant for monetary policy.

The rest of the paper is organized as follows. The next subsection reviews the related literature. Section 1.2 provides an institutional background for the 2018-2019 trade war and the high levels of TPU, and presents the high tariff pass-through puzzle. Section 1.3 presents a dynamic model of exporting to the U.S. Section 1.4 presents policy functions and inspects the mechanism. Section 1.5 describes the quantitative analysis conducted using simulated data from the model, including tariff

[8]There are ample evidence for the disconnect of exchange rates from macroeconomic fundamentals, let alone from tariff changes. See for example Engel & West (2005) and Itskhoki & Mukhin (2021).

and exchange rate pass-through estimation, and shows that TPU can explain a large part of the high tariff pass-through observed in 2018-2019. Section 1.6 presents policy implications from the quantitative analysis. Finally, Section 2.6 concludes.

1.1.1 Related literature

The focus of this paper is the effect of TPU on tariff and exchange rate pass-through into import prices. It connects to the literature about exogenous shock pass-through into import prices, the effects of tariffs on exporters, and the effects of TPU.

Relatively few studies focus on estimating the pass-through of tariffs into tariff-inclusive import prices. These studies have shown varied results. Overall, tariff pass-through into tariff-inclusive import prices in different settings appears to be fairly high but far from complete, an indication for the existence of variable markups (Feenstra 1989, Edmond et al. 2015, De Loecker et al. 2016, Ludema & Yu 2016, Fontagné et al. 2018, Irwin 2019, Chen & Juvenal 2022).[9] Importantly, these papers do not take the uncertainty around the tariff change into account.[10] The relationship between tariffs and prices also connects to the international elasticity puzzle, presented in Ruhl (2008). The international elasticity puzzle states that export participation, internationally traded quantities, and export revenue are much more responsive to changes in tariffs than to exchange rate fluctuations (an observation documented in several empirical studies, for example in Fitzgerald & Haller (2018) for Irish firms).

Several studies have examined empirically the effects of the 2018-2019 trade war on the U.S. and China economies. One shared result among these studies was a nearly complete pass-through of the U.S. tariffs into U.S. tariff-inclusive import prices, roughly 95%-100% for more than one

[9]Estimates of tariff pass-through into import prices have been quite variable. Feenstra (1989) finds U.S. tariffs on Japanese autos in the 1980s were passed-through between 58%-100%, with a wide variation between different types of differentiated goods. Fontagné et al. (2018) estimate tariff pass-through of around 65% for French exporters to various destinations and in various product markets. Chen & Juvenal (2022) estimate tariff pass-through for Argentinian wine exporters to be around 80%-90% and depend on the quality of the product.When taking product quality into account, Ludema & Yu (2016) find that tariff pass-through into tariff-inclusive import price crucially depends on the level of differentiation and product quality. Irwin (2019) finds that U.S. tariff increases on sugar at the end of the 19th century were passed-through at around 40%. The results are quite varied, but a common interpretation in the literature is that they point towards the existence of variable markups.

[10]As a matter of fact, some papers have emphasized the fact that they treat tariff changes as permanent (Feenstra 1989).

year (Amiti, Redding & Weinstein 2019, 2020, Cavallo et al. 2021, Fajgelbaum et al. 2020). While tariff-inclusive import prices increased, quantities of imported goods subject to these tariffs declined sharply.[11] Cavallo et al. (2021) also find that the effect of the tariffs on retail prices of imported goods within the U.S. was much smaller. Conversely, Flaaen et al. (2020) examine the reaction of washing machines' retail prices to the 2016 anti-dumping duties and then to the 2018 tariffs and observe a much higher pass-through of more than 100% for the 2018 tariffs (where this effect includes increases in the price of dryers as a complementary good and in the prices of domestic competitors). These results emphasize how much is yet to be uncovered about the effects of tariffs on import prices. The effect of TPU on tariff pass-through and on import prices has not been explored yet, and this paper is a first step towards filling this gap.

Sticky import prices have not been the main focus of the tariffs literature, which usually focuses on the medium-run when prices adjust freely. A literature that has focused on rigid prices in the short-run is the one that examines why the pass-through of exchange rate shocks into import prices is incomplete. Dornbusch (1987) and Krugman (1986) suggested that variable markups are an important factor in explaining incomplete exchange rate pass-through. The higher is the elasticity of the markup, the more likely a firm is to limit exchange rate pass-through into the import price (and absorb the shock in its revenue). A large literature developed this variable markup channel theoretically and provided ample empirical evidence for its existence (Bacchetta & van Wincoop 2005, Engel 2006, Gopinath & Itskhoki 2010, Gopinath et al. 2010, Amiti et al. 2014, Cao et al. 2015, Goldberg & Tille 2016, Devereux et al. 2017, Mukhin 2022). Variable markups can arise from multiple sources, such as demand structure that induces variable elasticity, oligopolistic competition where strategic price complementarities between firms are present, or distribution costs (Atkeson & Burstein 2008, Berman et al. 2012, Chatterjee et al. 2013, Burstein & Gopinath 2014, Corsetti et al. 2018, Crowley, Corsetti & Han 2018, Amiti, Itskhoki & Konings 2019). Another factor limiting exchange rate pass-through is price linkages created by the use of imported intermediate inputs. A higher share of imported intermediate inputs is associated with a lower desired pass-through into import prices and higher tendency for setting prices in a local or a vehicle currency (Gopinath et al.

[11] It should be noted that the level of product differentiation probably played an important part (Amiti, Redding & Weinstein 2020, Cavallo et al. 2021).

2010, Amiti et al. 2014, Chung 2016, Mukhin 2022). The choice of currency is an important aspect in the determination of exchange rate pass-through, since the currency of invoicing mitigates the effects of exchange rate fluctuations on prices when the price is sticky in that currency (Devereux & Engel 2002, Devereux et al. 2004, Engel 2006, Gopinath et al. 2010, 2020, Mukhin 2022). Referring to the effects of exchange rate fluctuations on prices of U.S. imports from China in 2018-2019, it is important to note that due to the size of its economy and the dominant currency role of the dollar, the vast majority of both imports and exports in the U.S. are priced in dollars. This limits the pass-through of exchange rate fluctuations into U.S. import prices. There is also indication that Chinese exports are widely invoiced in dollars (e.g., Corsetti et al. (2018) for exports to the U.K., Ito et al. (2018) for exports to Japan). The well-established existence of variable markups should lead to incomplete tariff pass-through into tariff-inclusive import prices, making the high tariff pass-through observed in 2018-2019 puzzling. This paper introduces tariffs and TPU into a framework with variable markups, imported intermediate inputs, and dollar pricing, and shows that tariff changes accompanied by TPU can lead to high tariff pass-through even when markups are variable.

Many studies have examined the role of price adjustment costs in firms' pricing decisions, which leads to price rigidity in the short-run (see Klenow & Malin (2010) for an extensive survey). Over the past couple of decades new high-frequency micro level data shed new light on the existence of price adjustment costs and their magnitude in domestic markets (Golosov & Lucas 2007, Nakamura & Steinsson 2008, Midrigan 2011, Karadi & Reiff 2019, Bonomo et al. 2020). Price adjustment costs in international trade have been proposed as a leading reason for price stickiness (e.g., Delgado (1991)). Studies have found that price adjustment costs are larger in international markets than in domestic markets, in a way that contributes to the lower frequency of price adjustments in international transactions relative to domestic ones (Wolf & Ghosh 2001, Gopinath & Rigobon 2008, Nakamura & Zerom 2009, Gopinath & Itskhoki 2010, Schoenle 2017). We rely on this literature in including fixed price adjustment costs in the model in order to explain infrequent price adjustments. These costs play an essential role in explaining the sluggish and incomplete price adjustment in the short-run in response to exogenous shocks in international prices.

Finally, a growing literature examines trade policy uncertainty (TPU) in the context of U.S. trade policy towards China at the beginning of the 21st century (Handley & Limão 2017, Crowley, Meng & Song 2018, Alessandria et al. 2019, Handley et al. 2020, Alessandria et al. 2022, Benguria et al. 2022). These studies show that TPU affects exporters' decisions, such as entry / exit from export markets, investment, and inventories, and especially the timing of these decisions. However, the TPU literature focuses on medium- and long-run decisions by firms, and assumes that import prices are fully flexible. The effects of TPU on import prices in the short-run, when prices adjust infrequently, received almost no attention thus far. This paper fills this gap. Caldara et al. (2020) and Hassan et al. (2020) develop empirical measures for TPU based on textual analysis of news and firms' reports. They find a significant increase in uncertainty around the 2018-2019 trade war. Caldara et al. (2020) build a general equilibrium two-country model with nominal rigidities and show that increased TPU has a chilling effect on economic activity, especially on investment. This paper builds on these findings and their formulation of TPU and shows how including TPU in a standard model of infrequent price adjustments with variable markups can decrease the size of ex-tariff border price adjustments in reaction to changes in tariffs. This paper also relates to the wider literature about the effects of uncertainty on firms (Kimball 1989, Bloom 2014, Born & Pfeifer 2014, Fernández-Villaverde et al. 2015, Bloom et al. 2018, Hassan et al. 2019). The response of prices to TPU in this paper is in line with findings from this literature. Namely, variable markups together with price rigidity creates the convexity of marginal profit, and the mechanism that increases markups in response to an increase in uncertainty. This paper extends some of the findings about broad uncertainty to the case of TPU and tariffs.

1.2 The 2018-2019 U.S.-China trade war: Institutional background and tariff pass-through puzzle

This section describes the events that led to the U.S.-China trade war. The first subsection provides details about the nature and extent of trade policy uncertainty in 2018-2019, which are crucial for the proposed mechanism in the next section. Then, we provide details about estimates of tariff pass-through into U.S. import prices from the trade war and explain the puzzling nature of the high tariff pass-through in light of the literature.

1.2.1 The 2018-2019 tariffs and record high TPU

Since the negotiation and signing of the North American Free Trade Agreement (NAFTA) in 1994, trade liberalization and removal of trade barriers have been a consensus position in U.S. politics. Between the mid-1990s and 2016, there was relatively little change in U.S. trade policy. This is evident in the news-based trade policy uncertainty index constructed by Caldara et al. (2020), which was around or slightly below its long-run mean throughout this period (Figure 1.1). The news-based index measures the joint salience of trade-related and uncertainty-related terms in major U.S. newspapers.[12] The index captures two aspects of uncertainty about trade policy. First, uncertainty could arise from an increase in the probability of a regime switch from from high to low trade barriers, or vice versa. Second, uncertainty could be an increase in tail risk or concerns about heightened volatility of tariffs. Both of these aspects are captured in the TPU index.

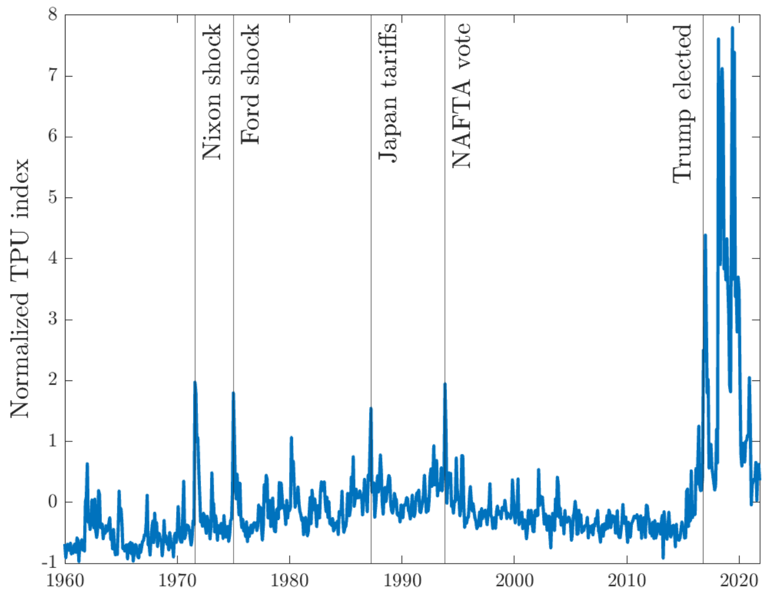
The ascent of candidate, and then president, Donald J. Trump brought this era of trade policy stability to an abrupt end. Trump campaigned in 2015-2016 urging the withdrawal of the U.S. from NAFTA and the Trans-Pacific Partnership (TPP), which had been signed by President Obama in 2015.[13] Trump's election in November 2016 was perceived as a major shock to U.S. trade policy, with the TPU index sky-rocketing 2.5 standard deviations above its long-run mean - a level unseen in this index, surpassing the NAFTA negotiations in the early 1990s (event (a) in Figure 1.2).

Upon his election and throughout the transition period, Trump promised to enact a trade policy of "America First", reconsidering all U.S. trade agreements and relations. Upon taking office in January 2017 (event (b)), Trump immediately withdrew from the TPP. TPU levels remained elevated in the first quarter of 2017, as the administration announced a reexamination of NAFTA and of

[12] We normalize the TPU index for its entire availability period, from 1960 through the end of 2019, so that changes in the index represent higher or lower levels of TPU relative to the long-run mean. We use the news-based index, but a similar narrative arises from other TPU indices, such as the earning calls index in Caldara et al. (2020), or firms- and industry-level indices constructed by Hassan et al. (2019), Hassan et al. (2021), and Benguria et al. (2022).

[13] 2015-2016 was characterized by a wider, global shift away from the free trade paradigm. The most notable event that caused a spike in trade policy uncertainty was the Brexit referendum in 2016 which catapulted the UK and the EU into years of trade negotiations.

Figure 1.1: News-based TPU index for the U.S. (normalized), monthly, 1960-2020



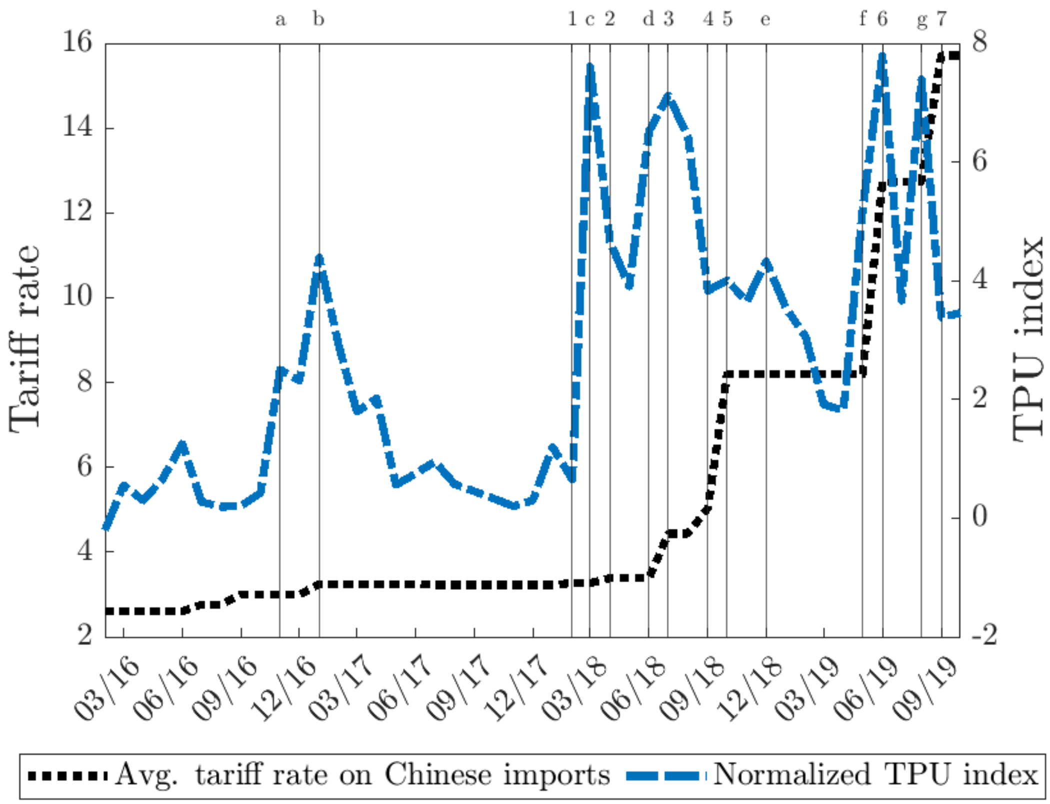
Note: Monthly news-based TPU index for the U.S., 1960-2020, normalized. Source: Caldara et al. (2020), author's own calculations.

trade relations with the European Union and China. TPU levels declined throughout the rest of 2017, but in 2018 the administration started taking steps to execute its trade agenda. Specifically, a series of investigations by the U.S. International Trade Commission (USITR) that were initiated in 2017 came to conclusion at the beginning of 2018.

In the early months of 2018, the administration announced a series of tariffs on a limited and relatively small set of products. In January 2018, the administration announced it would impose tariffs on washing machines and solar panels (event (1)). In March 2018, the administration announced tariffs on steel and aluminum imports, which went into effect in April 2018 (event (2)). In both cases the tariffs were not directed at one country in particular, but rather encompassed products imported from multiple trading partners.[14] As can be seen clearly in Figure 1.2, these tariffs were limited in scope and did not have a meaningful effect on the overall average U.S. tariff rate on Chinese imports, since the affected products make up a very small share of Chinese exports

[14]The washing machines and solar panel tariffs were issued under Section 201 of the Trade Act of 1974, and the steel and aluminum tariffs were issued under Section 232.

Figure 1.2: Average U.S. tariff on imports from China and normalized news-based TPU index, 2016-2019



Tariff changes

1. Solar panels & washing machines
2. Steel & Aluminum
3. 1st wave of Section 301 tariffs ($34B)
4. 2nd wave of Section 301 tariffs ($16B)
5. 3rd wave of Section 301 tariffs ($200B)
6. 15% rate increase on 3rd wave products
7. 4th wave of Section 301 tariffs ($112B)

TPU events

a. Trump wins presidential elections
b. Trump takes office
c. USTR section 301 report
d. List 3 ($200B) news
e. News of trade negotiations
f. Trade negotiations fail
g. List 4 ($300B) news

Note: Average U.S. tariff rate (in log points × 100) on Chinese imports, weighted by annual 2017 trade weights, and news-based trade policy uncertainty index (normalized to long-run mean over 1973-2019). Source: USTR, source data of Caldara et al. (2020), own calculations.

to the U.S.

Parallel to these more limited actions, in March 2018 the U.S. Trade Representative (USTR) announced the conclusion of a Section 301 investigation against China (event (c)). The report found China conducted unfair trade practices, and in response the administration announced tariffs of 25% on $34 billion of Chinese imports, which went into effect in July 2018 (event (3)). Additional tariffs on $16 billion of Chinese products went into effect in September 2018 (event (4)). A third list of 10% tariff was announced in June 2018 (event (d)) and went into effect in October 2018 (event (5)). This list was much larger in scope, containing around $200 billion of Chinese imports. This list also contained many more final consumption products than the first list, which was almost entirely composed of intermediate inputs. Trade policy uncertainty during this period soared to its highest level on record, nearly 8 standard deviations above its long-run mean. TPU remained highly elevated throughout 2018.

After the two initial tariff waves on Chinese imports, an attempt to start trade negotiations between the U.S. and China was announced in December 2018 (event (e)). During the trade talks, TPU levels steadily declined. However, in May 2019 the talks collapsed (event (f)), sending the TPU index back to extreme levels of 8 standard deviations above its long-run mean. After the failure of the negations, the U.S. increased the tariff rate on list 3 products by an additional 15% (event (6)). Finally, a fourth list of 25% tariffs on $300 billion of products was announced in August 2019 (event (g)) and went into effect in September 2019 (event (7)). TPU levels remained elevated through the end of 2019, until the Phase 1 deal between the U.S. and China was reached. This deal halted further tariff increases, but almost all of the Section 301 tariffs remained in effect well into 2022. It should be noted that all the tariff actions taken by the U.S. were retaliated by China, which imposed tariffs on U.S. imports shortly after each wave of U.S. tariffs. The average tariff rate on Chinese imports had increased from less than 3% at the beginning of 2018 to almost 16% at the end of 2019.

The events of the "U.S.-China trade war" of 2018-2019 were unprecedented and signaled a sharp break from the longtime trend of trade liberalization and openness. The unilateral tariffs imposed by both countries were the largest in scope and magnitude between the world's two largest economies since the 1930s. Furthermore, the use of Section 301 of the Trade Act of 1974 to impose these tariffs was unprecedented. Since the establishment of the World Trade Organization (WTO) in 1995, the U.S. used Section 301 investigations on a limited scope and mostly to build cases and dispute settlements at the WTO.[15] In contrast to previous U.S. administrations, the Trump administration used Section 301 for unilateral measures which were openly touted as a tool to bring forth a new trade regime with China that would correct what the administration described as unfair practices.

Therefore, exporters in both countries were subject to unprecedented trade policies. Furthermore, it was unclear whether the new tariffs were *a permanent regime change*, to a prolonged state of higher tariffs, or whether they were merely a punitive *transitory* policy aimed at initiating negotiations which would lead to a reversion back to a permanent state of low tariffs. Furthermore, the administration refrained from stating any expected duration for this policy.[16] This high uncertainty is clearly captured by the TPU index in Figure 1.2. Anecdotal evidence from Trump's twitter account and media statements also contributed to the high uncertainty surrounding U.S. trade policy during this era.[17]

1.2.2 High tariff pass-through puzzle

The economic impact of the 2018-2019 U.S.-China trade war has been studied extensively in recent years.[18] In this subsection, we focus on the effect of the 2018-2019 tariffs on U.S. import prices. An ad-valorem tariff is a tax levied directly on the product's price which is paid by the importer at the dock. Standard models of a large open economy such as the U.S., and models of imperfect competition in imports, predict that in response to a tariff increase, exporters will reduce

[15] Between 2000 and 2017, there were only 6 investigations opened under Section 301, compared to 5 since 2018. For a comprehensive analysis of Section 301 and its history, see Schwarzenberg (2020).

[16] The inability to assess how long tariffs will be imposed has been clearly demonstrated by the steel and aluminum tariffs on Canada. Initially, the tariff was imposed in March 2018 but with exemptions for Canada. In April 2018, the exemption was extended, but then ended in June 2018 and the tariffs were imposed on Canadian imports as well. During the USMCA trade negotiations, the tariffs were lifted in May 2019. Aluminum tariffs were then re-imposed on Canada in August 2020, only to be lifted again in September 2020. These tariffs represent a case of high realized volatility, but high uncertainty was present for all other tariffs as well.

[17] For example, on August 1st, 2019, it was reported by Fox Business: "And 10 percent could just be the beginning, Trump warned. He told reporters on Thursday that he could "always do much more" or he could "do less" with respect to tariffs, depending on what happens with the trade negotiations. "

[18] Different areas of research included investment (Amiti, Kong & Weinstein 2020), the effect on Chinese exporters (Jiao et al. 2020, Benguria et al. 2022), agricultural and food products (Carter & Steinbach 2020), supply chains and reallocations (Huang et al. 2019, Flaaen et al. 2020, Grossman & Helpman 2020, Fajgelbaum et al. 2021), the exchange rate (Jeanne & Son 2020), and consumption (Waugh 2019).

border prices to retain market share.[19] In those models, some of the tariff incidence is borne by the exporters (Amiti, Redding & Weinstein 2019).

In contrast, Amiti, Redding & Weinstein (2019), Amiti, Redding & Weinstein (2020), Fajgelbaum et al. (2020), and Cavallo et al. (2021) have found that the 2018-2019 U.S. tariffs on China had virtually no effect on border prices. That is, tariff-inclusive import prices rose nearly one-for-one with the tariff (close to 100% tariff pass-through into the import price).[20] At the same time, the tariff increases had a substantial impact on the quantity of U.S. imports from China, where the imported quantity of targeted varieties fell by more than 30%. These findings are puzzling in light of the theory: Why did Chinese exporters keep their border prices unchanged and allow import prices to increase by nearly the full amount of the tariff, while suffering a huge decline in demand?

A natural explanation is that in the short-run, prices are rigid due to high adjustment costs (Ball & Romer 1990, Ball & Mankiw 1994, Bils & Klenow 2004, Zbaracki et al. 2004, Nakamura & Steinsson 2008, Midrigan 2011, Kehoe & Midrigan 2015, Klenow & Willis 2016).[21] While directly observed product-level evidence of international price rigidities are scarce due to data limitations, it appears that prices of imports to the U.S. are much more rigid than prices of U.S. domestic goods (Gopinath & Rigobon 2008, Gopinath & Itskhoki 2010, Schoenle 2017). However, border prices remained unresponsive to the tariff increases over a period of at least one year. This time span is greater than the documented median duration of a border price of imports to the U.S. Thus, if the source of this unresponsiveness was price rigidity, a substantial adjustment should have occurred within the first year, which it did not.

A different explanation is that there are no good substitutes to Chinese imports due to the dominance of China in production. If Chinese products are highly differentiated and do not have close substitutes, then there is little pressure on Chinese exporters to adjust their border prices even as tariffs increase. However, if Chinese products are highly differentiated then exchange rate

[19] For example, Broda et al. (2008) find that export supply elasticities imply upward-sloping supply curves.

[20] Using micro data from two large retailers, Cavallo et al. (2021) document that the tariffs were passed-through at a much lower rate into the retail prices paid by U.S. consumers. It is possible that the retailers dispersed the tariff increase across many affected and unaffected products' prices. Another possibility is that the retailers absorbed this tariff increase in their own profit margin. The discrepancy between the import prices and the retail prices is outside the scope of this work which focuses on import prices at the dock and does not model a retail sector.

[21] Price adjustment costs can arise from various sources, such as managerial attention, information accumulation, communication, and physical costs ("menu cost").

pass-through into the border price should be significantly higher than its observed levels. Since border prices of imports to the U.S. are overwhelmingly set in U.S. dollars (Gopinath et al. 2010, Gopinath 2015), the price paid by the importer is stable and does not fluctuate with the exchange rate. However, the revenue received by the exporter fluctuates one-for-one with the exchange rate, since the border price needs to be converted back into the exporter's currency. If imports from China cannot be substituted easily, Chinese exporters could pass-through exchange rate fluctuations at a substantially higher rate than that which is observed. Cavallo et al. (2021) document that a depreciation of the U.S. dollar during the trade war was passed-through at a rate of 25%-40% into border prices, in line with previous estimates for imports to the U.S. These findings indicate that variable markups absorb some exchange rate fluctuations, and should therefore absorb some of the tariff increase as well.

In this paper, we propose an alternative explanation to the unresponsiveness of border prices to the tariff increases during the trade war: the high levels of uncertainty that surrounded trade policy during this period. A growing literature studies the effects of TPU on economic activity (see Handley & Limão (2022) for an extensive survey of the literature), but the effect of TPU on the price of imports has received little attention in the past. This is especially true for the short-run, when border prices adjust infrequently. One reason for the absence of sticky prices from the TPU literature is that trade policy is often complicated and slow to change, for example due to multilateral aspects of any policy decision. Many realized tariff changes in the past were associated with a *resolution* of uncertainty, rather than with an increase in uncertainty.[22] The 2018-2019 tariffs were a sharp break from this paradigm, where each policy announcement and change in tariffs were associated with extreme levels of uncertainty. At no point was it clear if the tariffs would be permanent or transitory. Furthermore, there was a large increase in realized tariff volatility, as the Trump administration changed tariff rates on many products multiple times in a period of less than two years.

The combination of relatively frequent tariff changes with very high levels of uncertainty about the policy itself makes the 2018-2019 trade war a unique opportunity to motivate the theoretical

[22]An example which has been studied extensively is the annual vote that the U.S. congress used to take in the 1990s to renew normal trading relations with China. The vote itself resolved uncertainty about the policy. Tariff changes in the 1990s-2000s were also overwhelmingly associated with gradual tariff reductions and removal of barriers to trade.

examination of the effect of TPU on import prices.[23] Furthermore, if TPU increases tariff pass-through into import prices, this could be an important factor in explaining the observed high tariff pass-through.[24] There is no guarantee that the 2018-2019 trade war was the last episode of extremely uncertain trade policy in the near future. There is much to be uncovered, theoretically and empirically, about the relationship between TPU and prices in international trade.

In the rest of this paper, we establish how increased levels of TPU can lead to high tariff pass-through into import prices while maintaining low exchange rate pass-through into the same prices. On the extensive margin of price adjustment, when TPU is high, the likelihood of a border price adjustment decreases. On the intensive margin of price adjustment, once the firm decides to reset its border price, high levels of TPU lead the firm to keep a precautionary markup which increases the border price. Both margins lead to higher tariff pass-through into the tariff-inclusive import price when TPU is present, on impact and even after the border price is reset. In the next section we present the dynamic model of price setting and exporting to the U.S.

1.3 Dynamic model

In this section, se present a sectoral partial equilibrium dynamic model of exporting to the U.S.[25] We include tariffs and TPU in the model following Handley & Limão (2017). We discuss how exporters' prices react to changes in tariffs and to cost shocks, and how these reactions change when TPU is present. We calibrate the model to pre-2017 U.S. moments of import price adjustment from

[23] Another episode of tariffs that were perceived to be transitory was the Bush steel tariffs in 2002-2003. These tariffs were much more limited in scope and the rhetoric that accompanied them was substantially different than the 2018-2019 tariffs, which can be seen in their muted effect on the TPU index. Nevertheless, these tariffs were communicated as a temporary measure with uncertain duration. Cox (2022) finds that import quantities responded strongly to these tariff changes, but border prices did not respond in a statistically or economically significant manner. That is, tariff pass-through into import price was very high. These patterns are quite similar to the 2018-2019 tariffs.

[24] It should be noted that exchange rates are highly volatile but also highly persistent. Engel & West (2005) establish that exchange rates follow a process almost indistinguishable from a random walk. That is, changes in the exchange rate are actually perceived to be permanent. Uncertainty around exchange rates that resembles TPU would be more along the lines of uncertainty about the future policy of managed exchange rates or interventions in FX markets, rather then around free-floating currencies like the dollar. It should be emphasized that during the relevant period there wasn't any exceptional uncertainty about the PBOC's exchange rate policies as the RMB was following a managed float relative to a basket of currencies and this policy has remained stable for years.

[25] The model is standard and based on Gopinath & Itskhoki (2010). It includes components used widely in the literature about sticky international prices, with variable markups and imported intermediate inputs.

the Bureau of Labor Statistics import prices microdata.[26] We then show that the model can account well for exchange rate pass-through into U.S. import prices, but it generates a counterfactually low tariff pass-through rate into tariff-inclusive import prices in response to a one-time permanent tariff change. We discuss how trade policy uncertainty increases tariff pass-through while not affecting exchange rate pass-through and how this corresponds to patterns observed in the data.

The model focuses on demand in a specific sector in the Home country (e.g., the U.S.).[27] A continuum of domestic ("American") and foreign ("Chinese") competitive monopolists produce varieties which they sell in the Home country. Producers use Home and Foreign intermediate inputs in production. The prices of varieties produced by both Home and Foreign firms are set in the Home unit of account (dominant currency pricing in "dollars"), which is overwhelmingly the case for the U.S. and China (Gopinath & Rigobon 2008, Gopinath et al. 2010, Gopinath 2015, Gopinath et al. 2020). Thus, Home producers are not directly exposed to exchange rate risk since all of their input prices are set in their own unit of account, but Foreign producers are exposed to the real exchange rate twice: They must convert the revenue from the Home unit of account into their own Foreign unit of account; and the imported intermediate inputs they are using are also priced in the Home unit of account, which exposes their cost of production to real exchange rate fluctuations. The Home country may impose an ad-valorem tariff on the foreign exporters' varieties. We explore the effect of different tariff regimes on prices. Firms might perceive a tariff change to be a deterministic one-time and permanent change, but alternatively they might perceive tariffs to be transitory and following a Markov process where there is uncertainty about the future rate of the tariff (TPU).

1.3.1 The Firm's Problem

Demand There is a continuum of Home and Foreign competitive monopolists in a specific sector who sell their varieties in the Home market. The set of all firms in the sector is Ω, with size $|\Omega|$. Each firm sells one differentiated variety, thus $\omega \in \Omega$ indicates both a firm and a variety. The

[26] These moments are computed and documented in several studies that used these data, including Gopinath & Rigobon (2008) and Schoenle (2017).

[27] In general, an economy is composed of multiple sectors that differ in their elasticity of substitution between varieties and between sectors, the share and the number of Foreign producers, the production technology, the currency of invoicing, and more. A multi-sector economy introduces substantial complexity, which se abstract from by focusing on a single "average" sector. Expanding the model to include multiple sectors is left to future work.

demand function that the firm ω faces is derived from a Kimball (1995) homothetic aggregator. The main advantage of using this aggregator is that it is a "reduced form" way of introducing pricing complementarities into the firm's problem, since markups are variable and thus the firm's optimal price depends on other firms' prices and not just its own marginal cost.[28] This demand structure also leads to a "smoothed kink" demand function, where there is a cutoff price above which demand for the firm's variety is zero (a "choke price"). This feature allows some varieties to "disappear" from the market without modeling exit and entry explicitly as costly decisions. This is a desirable feature in a short-run model, where costly exit and entry do not occur in large numbers but some varieties are not observed in the data for long periods of time (Nakamura & Steinsson 2008).

Individual varieties are aggregated into a consumption bundle which is defined implicitly by

$$\frac{1}{|\Omega|}\int\limits_{\omega\in\Omega}\Upsilon\left(\frac{|\Omega|\,Q_{\omega,t}}{Q_t}\right)d\omega=1 \tag{1.3.1}$$

where $\Upsilon(\cdot)$ is a twice continuously differentiable function that satisfies $\Upsilon(1)=1, \Upsilon'(\cdot)>0, \Upsilon''(\cdot)<0$; Q_ω is Home demand for variety ω, and Q is (exogenous) Home aggregate consumption level. Assume that the measure of domestic varieties is 1, and the measure of imported varieties is of size $m<1$, such that $|\Omega|=1+m$. This formulation is a simple way of capturing home bias.

This consumption aggregator gives rise to a demand function of the form

$$Q_{\omega,t}=\frac{1}{|\Omega|}\psi\left(D_t\frac{(1+\tau_t)\,P_{\omega,t}}{P_t}\right)Q_t \tag{1.3.2}$$

where $\psi\equiv\Upsilon'^{-1}(\cdot)$, $D_t\equiv\int_{\omega\in\Omega}\Upsilon'\left(\frac{|\Omega|Q_{\omega,t}}{Q_t}\right)\left(\frac{Q_{\omega,t}}{Q_t}\right)d\omega$ is an aggregate demand factor which is exogenous from the firm's perspective,[29] τ_t is ad-valorem tariff on imported varieties for final consumption, $P_{\omega,t}$ is the border (net of tariff) price of the variety in the local (Home) unit of account, and P_t is the Home sectoral price index of all varieties.[30] The import price inclusive of tariff is

[28] In the limit, the aggregator nests a constant elasticity of substitution (CES) structure.

[29] Gopinath & Itskhoki (2010) prove that deviations of D_t from the average $\overline{D}$ are nil, and this factor does not affect demand substantially.

[30] All prices are relative to the Home aggregate CPI which is normalized to 1 at all periods, relying on the partial equilibrium environment.

therefore $(1+\tau_t)\,P_{\omega,t}$. The sectoral price index is defined by

$$P_tQ_t = \int_0^1 P_{\omega,t}Q_{\omega,t}d\omega + \int_1^{1+m} (1+\tau_t)\,P_{\omega,t}Q_{\omega,t}d\omega \tag{1.3.3}$$

Thus, changes in tariff τ_t affect the sectoral price index directly through the tariff-inclusive import price paid by importers and indirectly by the reaction of all other ex-tariff border and domestic prices to a change in tariff rate (which arises from pricing complementarities).

Real exchange rate The unit of account in each country is its price of aggregate consumption, which is exogenous. The real exchange rate, $\mathcal{E}_t$, is defined as the ratio of Foreign price of aggregate consumption in Home unit of account, to Home price of aggregate consumption in Home unit of account. Thus, an increase in $\mathcal{E}_t$ is an increase in the number of units of Home aggregate consumption it takes to buy one unit of Foreign aggregate consumption - a Home real depreciation.[31] The real exchange rate follows a highly persistent AR(1) process in logs, $e_t \equiv \log \mathcal{E}_t$, given by

$$e_t = \rho_e e_{t-1} + \sigma_e \varepsilon_t^e, \qquad \varepsilon_t^e \sim \text{i.i.d.}\mathcal{N}(0,1) \tag{1.3.4}$$

Marginal cost Firms use a constant returns to scale technology with domestic and imported intermediate inputs, given by

$$\text{Foreign exporters: } Y_{\omega,t}^* = e^{a_{\omega,t}^*}\left(X_t^*\right)^{1-\phi^*} X_t^{\phi^*} \tag{1.3.5}$$

$$\text{Home producers: } Y_{\omega,t} = e^{a_{\omega,t}} X_t^{1-\phi}\left(X_t^*\right)^{\phi} \tag{1.3.6}$$

where Y_ω is the firm's output, X_ω is an intermediate input, $\phi \in [0,1]$ is the share of imported inputs in production, and $a_{\omega,t}$ is an idiosyncratic firm ω productivity level. Variables with an asterisk (*) denote Foreign variables. In partial equilibrium and in the short-run, we make the simplifying assumption that firms do not change the makeup of their intermediate inputs, which are common

[31] Formally, Let P_C^H denote Home price of aggregate consumption, and P_C^{*H} denote Foreign price of aggregate consumption expressed in Home unit of account. We normalize $P_C^H = 1$, then the real exchange rate is $\mathcal{E} \equiv P_C^{*H}/P_C^H = P_C^{*H}$.

across all firms.[32] The idiosyncratic productivity level for firm ω follows an AR(1) process in logs, given by

$$a_{\omega,t} = \rho_a a_{\omega,t-1} + \sigma_a \varepsilon^a_{\omega,t}, \qquad \varepsilon^a_{\omega,t} \sim \text{i.i.d.}\mathcal{N}\left(0,1\right) \tag{1.3.7}$$

where we assume that ρ_a and σ_a are identical in the Home and the Foreign countries.

This production function results in a marginal cost which is constant in quantity. Let W_t and W^*_t denote the price of Home and Foreign inputs in their domestic units of account, respectively, and let W^{*H}_t denote the price of the Foreign input in the Home unit of account.[33] The marginal cost is thus given by

$$MC^*_{\omega,t} = \tilde{\phi}^* e^{-a^*_{\omega,t}} \left(W^*_t\right)^{1-\phi^*} \left(W_t/\mathcal{E}_t\right)^{\phi^*} \tag{1.3.8}$$

$$MC_{\omega,t} = \tilde{\phi} e^{-a_{\omega,t}} \left(W_t\right)^{1-\phi} \left(W^{*H}_t\right)^{\phi} \tag{1.3.9}$$

for Foreign and Home firms, respectively, where $\tilde{\phi}$ and $\tilde{\phi}^*$ are constants that result from cost minimization.

We make the following simplifying assumptions to reduce the size of the state space. Relying on the short-run focus of the model and the partial equilibrium setting, input prices are taken as exogenously determined and do not vary over time. This assumption relies on the fact that producer price indices in the U.S. and its major trading partners are an order of magnitude more stable than the exchange rate, especially over short horizons.[34] The exchange rate, conversely, follows a volatile and highly persistent AR(1) process, close to a random walk.

[32] Handley et al. (2020) find evidence in Chinese firms for firm-variety level sunk costs in imported intermediate inputs' adoption that lead to input hysteresis over several years.

[33] Recall that all international prices are set in the Home unit of account.

[34] See e.g. Itskhoki & Mukhin (2021) for wage-based real exchange rates.

The profit function Foreign and Home firms' profit functions in their domestic units of account are given, respectively, by

$$\Pi^* \left(P_{\omega,t}; a^*_{\omega,t}, P_t, \mathcal{E}_t, \tau_t\right) = \left(\frac{P_{\omega,t}\left(a_{\omega,t}, P_t, \mathcal{E}_t, \tau_t\right)}{\mathcal{E}_t} - MC^*_{\omega,t}\left(a^*_{\omega,t}, \mathcal{E}_t\right)\right) Q_{\omega,t}\left(P_{\omega,t}, P_t, \tau_t\right) \tag{1.3.10}$$

$$\Pi\left(P_{\omega,t}; a_{\omega,t}, P_t, \mathcal{E}_t, \tau_t\right) = \left(P_{\omega,t}\left(a_{\omega,t}, P_t, \mathcal{E}_t, \tau_t\right) - MC_{\omega,t}\left(a_{\omega,t}\right)\right) Q_{\omega,t}\left(P_{\omega,t}, P_t, \tau_t\right) \tag{1.3.11}$$

Foreign firms' profits are affected directly by the real exchange rate and by the tariff. Domestic firms' profits are affected indirectly by the real exchange rate and the tariff, through the sectoral price index and their relative price. Firms are price setters, and choose the price to satisfy any level of demand for their variety, $Y_{\omega,t} = Q_{\omega,t}$.

The firm's dynamic problem The state vector for firm ω is given by $\mathbf{S}_{\omega,t} = (a_{\omega,t}, P_{\omega,t-1}, \mathcal{E}_t, \tau_t, P_t)$. The firm has full knowledge of the stochastic processes that drive $\mathcal{E}_t$, $a_{\omega,t}$, and τ_t (described in the next paragraph). At the beginning of every period, the firm observes the realization of $\mathbf{S}_{\omega,t}$. Then, the firm has to decide whether to reset the border price, $P_{\omega,t}$, and pay a fixed cost κ, or keep last period's border price, $P_{\omega,t-1}$, and avoid paying the fixed cost. As common in models with price adjustment costs , we define κ as a percent of steady state revenue (Midrigan 2011, Nakamura & Steinsson 2008). The system of Bellman equations that define the firm's problem is

$$V^N\left(\mathbf{S}_{\omega,t}\right) = \Pi\left(P_{\omega,t-1}; \mathbf{S}_{\omega,t}\right) + \beta \mathbb{E}\left[V\left(\mathbf{S}_{\omega,t+1}\right) | \mathbf{S}_{\omega,t}\right] \tag{1.3.12}$$

$$V^A\left(P_{\omega,t}; \mathbf{S}_{\omega,t}\right) = \max_{P_{\omega,t}} \left\{\Pi\left(P_{\omega,t}; \mathbf{S}_{\omega,t}\right) + \beta \mathbb{E}\left[V\left(\mathbf{S}_{\omega,t+1}\right) | \mathbf{S}_{\omega,t}\right]\right\} \tag{1.3.13}$$

$$V\left(\mathbf{S}_{\omega,t}\right) = \max\left\{V^A\left(P_{\omega,t}; \mathbf{S}_{\omega,t}\right) - \kappa, V^N\left(\mathbf{S}_{\omega,t}\right)\right\} \tag{1.3.14}$$

where $V^N\left(\mathbf{S}_{\omega,t}\right)$ is the firm's value with no border price adjustment, $V^A\left(P_{\omega,t}; \mathbf{S}_{\omega,t}\right)$ is the value with border price adjustment, and $\beta \in (0, 1)$ is the discount factor.[35]

The firm's policy function yields two margins of price adjustment. On the *extensive margin*, the

[35] The constant discount factor follows from the partial equilibrium setting of this problem.

firm has to decide whether to adjust the border price or not:

$$P_{\omega,t} = \begin{cases} \overline{P}_{\omega,t} & \text{if } V^A\left(P_{\omega,t};\mathbf{S}_{\omega,t}\right) - \kappa > V^N\left(\mathbf{S}_{\omega,t}\right) \\ P_{\omega,t-1} & \text{otherwise} \end{cases} \tag{1.3.15}$$

On the *intensive margin*, the firm has to decide what is the optimal reset border price:

$$\overline{P}_{\omega,t}\left(\mathbf{S}_{\omega,t}\right) = \arg\max_{P_{\omega,t}} \left\{\Pi\left(P_{\omega,t};\mathbf{S}_{\omega,t}\right) + \beta\mathbb{E}\left[V\left(\mathbf{S}_{\omega,t+1}\right)|\mathbf{S}_{\omega,t}\right]\right\} \tag{1.3.16}$$

Importantly, the Foreign firm's problem is to set the ex-tariff border price in "dollars". That is, the exporter sets a price which is potentially sticky for several periods and might not adjust to tariff or exchange rate changes. Therefore, the exporter must form expectations about future levels of the tariff and the exchange rate when setting the price today. These expectations affect both the extensive and the intensive margin of price adjustment.

1.3.2 Tariff and trade policy uncertainty

We now discuss the modeling of tariffs and TPU. It is often assumed that a tariff is a static variable determined by the policy maker. A change in tariff is then a regime change. It does not induce uncertainty since once the level is set, it is constant over time. As described in Section 1.2, this was not perceived to be the case with the 2018-2019 tariffs imposed by the U.S. Rather, this episode was accompanied by very high levels of uncertainty about the path of the policy in the future. The time period between an announcement about a new tariff and its implementation was relatively very short (Bown 2021). There was a high degree of uncertainty surrounding the persistence of the tariff and its future level.

We model TPU as the switching probability in a Markov process. The actual realized tariff rate is set by the policy maker and might not end up being very volatile. This was indeed the case with the 2018-2019 tariffs after the initial waves of tariff increases. While the level of uncertainty about its future path was high, the tariff rate was in fact stable from late 2019 and until at least mid 2022. The TPU literature emphasizes that the uncertainty is about the probability of tariff changes, but that the actual realized volatility of tariffs might be very low since they tend to change infrequently (Caldara et al. 2020). This was the case even in 2018-2019 when U.S. tariffs changed several times over two years, but these changes were still infrequent relative to high-frequency volatile processes, such as the exchange rate, and even relative to other taxes (Fernández-Villaverde et al. 2015).

Let τ_t denote the rate of net ad-valorem tariff in period t. τ_t can be low or high, $\tau \in \left\{\tau^L, \tau^H\right\}$, where $\tau^L < \tau^H$. Let $\gamma \equiv \Pr\left(\tau_t = \tau^j | \tau_{t-1} = \tau^i\right), i \neq j$ denote the probability the tariff rate switches from the previous period. A state i is absorbing and induces no uncertainty if $\gamma = 0$. The tariff transition matrix is given by

$$\Lambda\left(\gamma\right) = \begin{bmatrix} 1-\gamma & \gamma \\ \gamma & 1-\gamma \end{bmatrix} \tag{1.3.17}$$

The higher is γ, the higher is trade policy uncertainty. If $\gamma = 0$ then firms just perceive the tariff rate to be completely stable. A change in the tariff when $\gamma = 0$ is akin to changing a parameter in the model, a one-time deterministic permanent change. However, if $\gamma > 0$ then there is some probability that the tariff will switch to the other state. In that case, the change is perceived to be transitory and there is uncertainty about the future level of tariff.[36] We explore an alternative formulation for TPU and the tariff process, discussed in Section 1.5.5. The different specifications do not alter the mechanism or the main results.

This process captures uncertainty in two ways. First, the persistence of the policy, defined as its asymptotic autocorrelation, $Corr\left(\tau_t, \tau_{t-1}\right)$, is given by $|2\gamma - 1|$. Persistence decreases with γ and reaches its minimum when $\gamma = 1/2$. Second, the unconditional variance of the forecast error, $Var\left(\tau_t - \mathbb{E}\left[\tau_t | \tau_{t-1}\right]\right)$, increases with γ and reaches its maximum when $\gamma = 1/2$. Additionally, the volatility of tariff increases with γ. We limit my attention to $\gamma \in [0, 1/2]$, where larger values of $\gamma > 1/2$ seem unrealistic. In the data, the period in the 1990s-2000s could be thought of as $\gamma \to 0$, while Trump's election and subsequent policies represent a sharp increase in γ, as depicted in Figure 1.1.

[36] This formulation builds on the TPU process presented Handley & Limão (2017) and resembles the fiscal regime uncertainty in Aizenman & Marion (1993).

1.3.3 Sectoral equilibrium

A sectoral equilibrium is a path of sectoral price levels $\{P_t\}$ consistent with optimal pricing policies of firms $\{P_{\omega,t}\}$, where the firm satisfies any level of demand for its chosen price $Q_{\omega,t} = Y_{\omega,t}$, given exogenous shocks $\left\{a_{\omega,t}, a^*_{\omega,t}, \mathcal{E}_t, \tau_t\right\}$.

To ensure the consistency of the sectoral price level, P_t and $\{P_{\omega,t}\}$ must satisfy (1.3.3).

1.3.4 Functional form and pass-through

We adopt the Klenow & Willis (2016) specification for the Kimball aggregator. This yields the demand function

$$\psi\left(p_\omega\right) = \left[1 - \varepsilon \ln\left(\frac{\sigma}{\sigma-1} p_\omega\right)\right]^{\sigma/\varepsilon} \tag{1.3.18}$$

where $p_\omega \equiv D\frac{(1+\tau)P_\omega}{P}$, and $\sigma > 1$, $\varepsilon \geq 0$ are parameters that govern the price elasticity of demand, and the price elasticity of the elasticity ("superelasticity"), respectively.[37]

The price elasticity of demand and the superelasticity are given by

$$\sigma\left(p_\omega\right) \equiv -\frac{\partial \log \psi\left(p_\omega\right)}{\partial \log p_\omega} = \frac{\sigma}{1 - \varepsilon \ln\left(\frac{\sigma}{\sigma-1} p_\omega\right)}, \quad \varepsilon\left(x_\omega\right) \equiv \frac{\partial \log \sigma\left(p_\omega\right)}{\partial \log p_\omega} = \frac{\varepsilon}{1 - \varepsilon \ln\left(\frac{\sigma}{\sigma-1} p_\omega\right)} \tag{1.3.19}$$

The firm's markup is given by

$$\mathcal{M}\left(p_\omega\right) \equiv \frac{\sigma\left(p_\omega\right)}{\sigma\left(p_\omega\right) - 1} = \frac{\sigma}{\sigma - 1 + \varepsilon \ln\left(\frac{\sigma}{\sigma-1} p_\omega\right)} \tag{1.3.20}$$

and the price elasticity of the markup is given by

$$\Gamma\left(p_\omega\right) \equiv -\frac{\partial \log \mathcal{M}\left(p_\omega\right)}{\partial \log p_\omega} = \frac{\varepsilon}{\sigma - 1 + \varepsilon \ln\left(\frac{\sigma}{\sigma-1} p_\omega\right)} \tag{1.3.21}$$

Thus, both the price elasticity of demand, and therefore the markup, depend on the firm's relative import price. This leads to variable markups, which can be thought of as a "reduced form" way of capturing strategic price complementarities between firms (for example, those arising from

[37] When $\varepsilon = 0$, the demand function collapses to a CES demand function.

oligopolistic competition as in Atkeson & Burstein (2008)).

If there is no tariff on imported varieties, the mean values of shocks are $\overline{e} = \tau^L = \overline{a}_\omega = 0$. The firm's corresponding border price is $P_\omega = \frac{\sigma}{\sigma-1}$, which is identical for all firms in the economy. Therefore the sectoral price level is also $P = \frac{\sigma}{\sigma-1}$. The demand for the firm's product is $Q_\omega = \frac{C}{|\Omega|}$, and therefore $D = \frac{\sigma-1}{\sigma}$. We can thus think about σ and ε as the elasticity and the superelasticity when $\overline{e} = \tau^L = \overline{a}_\omega = 0$.

Next, we briefly describe why variable markups lead to counterfactually low tariff pass-through into the import price when there is no TPU. If the firm could set its optimal border price each period without any adjustment cost, this optimal flexible desired border price would satisfy the familiar condition of markup above marginal cost, $\tilde{P}_{\omega,t} = \mathcal{M}\left(p_{\omega,t}\right) MC_{\omega,t}\left(a_t, \mathcal{E}_t\right)$. A one-time permanent shock in either tariff or the real exchange rate would be passed-through into this desired border price.

It can be shown that the pass-through rate of a one-time permanent change in tariff or exchange rate into the tariff-inclusive flexible desired import price of a Foreign firm is approximately given by

$$\Phi_\omega^\tau \equiv \frac{\partial \log \tilde{p}_{\omega,t}}{\partial \log\left(1+\tau_t\right)} \approx \frac{1}{1+\Gamma\left(\tilde{p}_{\omega,t}\right)} \in [0,1] \tag{1.3.22}$$

$$\Phi_\omega^e \equiv \frac{\partial \log \tilde{p}_{\omega,t}}{\partial \log \mathcal{E}_t} \approx \frac{1-\phi^*}{1+\Gamma\left(\tilde{p}_{\omega,t}\right)} \in [0,1] \tag{1.3.23}$$

holding all else constant.

The strength of price complementarities in the form of the elasticity of the markup, $\Gamma\left(\tilde{p}_{\omega,t}\right)$, pulls these pass-through rates in opposite direction. Exchange rate pass-through and tariff pass-through into the desired *import* price decrease with the elasticity of the markup. However, this means that while exchange rate pass-through into the desired *border* price also decreases with the elasticity of the markup, tariff pass-through into the desired border price actually increases with the elasticity of the markup. As long as $\varepsilon > 0$ then $\Gamma\left(\tilde{p}_{\omega,t}\right) > 0$, there will always be incomplete tariff and exchange rate pass-through (i.e., lower than 1 in absolute value). Intuitively, when markups are variable the firm wants to limit the size of deviations of its import price from the prices of competitors. The competitors include both other Foreign exporters, but also domestic Home producers who are not affected by tariff or exchange rate changes. If markups are constant, $\varepsilon = 0$ and $\Gamma\left(\tilde{p}_{\omega,t}\right) = 0$, and there are no pricing complementarities, then the border price would not react to tariff changes. This creates complete tariff pass-through into the import price, $\Phi_{\omega}^{\tau} = 1$, but at the price of counterfactually high exchange rate pass-through. This is why the empirical findings about complete tariff pass-through into import prices vis-a-vis low exchange rate pass-through are puzzling.

While there is no closed-form analytical expression for pass-through with uncertainty when variable markups are present, in the next section we show numerically how an increase in uncertainty leads to an increase in tariff pass-through, while still maintaining variable markups.

1.3.5 Calibration and Model Solution

The model does not have closed-form solution and has to be solved numerically. We use standard methods of value function iteration. Since there are idiosyncratic productivity shocks, two aggregate shocks, and the sectoral price level is endogenously determined, we use the Krusell & Smith (1998) method to estimate the firms' forecasting rule for the sectoral price level. The solution method is described in detail in Appendix 1.A.

To calibrate the model's parameters, we rely on values adopted in previous studies, and moments from studies that examine firm-level data of imports to the U.S. (mostly data from the International Price Program (IPP) database of the BLS). Parameter values are summarized in Table 1.1.

The duration of a period in the model is one month. The discount factor is set at the conventional level of $\beta = 0.96^{1/12}$ which implies a 4% annualized interest rate. The size of the continuum of imports is set at $m = 0.2$, which implies that the steady state share of U.S. imports in manufacturing is $m/\left(1+m\right) = 16.7\%$, in line with average values calculated from OECD input-output tables. The value of $\phi^{*} = 0.25$ is taken from estimates of imported foreign value-added content of gross exports in Chinese production. While there are several methods of estimating this share (see Kee & Tang (2016)), we rely on the average of OECD estimates. As mentioned above, intermediate inputs used by U.S. firms in production are overwhelmingly invoiced in U.S. dollars, which eliminates Home producers' exposure to exchange rate shocks, thus the value of ϕ has no effect on their marginal

Table 1.1: Parameter values

Parameters from the data and literature		
Parameter	Baseline Value	Source
Discount factor β	$0.96^{1/12}$	4% annual interest rate
Measure of Foreign varieties m	0.2	$m/(1+m) \approx 17\%$ Share of imported goods in U.S. manufacturing from I/O tables
Share of imported inputs, ϕ and ϕ^*	0.25	Foreign value-added content of gross exports, OECD
Price elasticity of substitution parameter σ	5	Broda & Weinstein (2006)
Superelasticity parameter ε	4	Unit markup elasticity in Amiti, Itskhoki & Konings (2019)
Real exchange rate AR coefficient ρ_e	0.99	Real dollar exchange rate data
Real exchange rate standard deviation σ_e	0.025	

Calibrated parameters from moment matching				
Parameter	Baseline Value	Targeted moments	Data	Model
Productivity AR coefficient ρ_a	0.98	Autocorrelation of new prices	0.77	0.77
Productivity standard deviation σ_a	0.04	Median absolute size of price adjustment	7.5%	7.45%
Menu cost κ	0.041	Median annual frequency of price adjustment	0.091	0.093

cost in the baseline model. The U.S. real exchange rate follows a highly persistent process with $\rho_e = 0.99$ and $\sigma_e = 0.025$. These parameters values are also in line with the mean estimates for U.S. real exchange rate vis-a-vis a set of other countries, reported in Schoenle (2017).

For the consumption aggregator parameters, we set $\sigma = 5$, in line with standard estimates of trade elasticities (for example, Eaton & Kortum (2002), Broda & Weinstein (2006), and Simonovska & Waugh (2014)). We set $\varepsilon = 4$ in the baseline calibration. These parameter values imply a stochastic steady state price elasticity of the markup of $\Gamma = 1$, and a measure of price complementarities equal to 1/2.[38] Directly measuring the strength of price complementarities and the elasticity of the markup in international markets is highly challenging due to data limitations. However, these values are in line with the findings in Amiti, Itskhoki & Konings (2019). Furthermore, parameter values that lead to unit elastic markups are commonly used in recent international macro models, such as Gopinath et al. (2020) and Itskhoki & Mukhin (2021).

The parameters that govern price rigidity cannot be observed directly in the data and have to be calibrated. We use simulated method of moments to jointly calibrate the fixed price adjustment cost κ, the persistence of the idiosyncratic productivity shocks ρ_a, and their standard deviation σ_a, to match moments of U.S. imports price adjustment from the BLS international prices program microdata. The data is from before the 2018-2019 trade war and therefore not affected by any temporary disturbances caused by the tariffs.[39] A detailed description of the database is is presented in Gopinath & Rigobon (2008), Gopinath & Itskhoki (2010), and Schoenle (2017). We target the following moments: Median duration of import prices of 11 months, autocorrelation of new (reset) import prices of 0.77, and median size of reset import price changes of 7.5%.[40] The calibrated parameter values are $\kappa = 4.1\%$, $\rho_a = 0.98$, and $\sigma_a = 0.04$.[41] The size of the price adjustment cost is

[38]The steady state absolute value price elasticity of the markup is unitary, $\Gamma \equiv \frac{\varepsilon}{\sigma-1} = 1$. This leads to the price complementarities measure $\alpha \equiv \frac{\Gamma}{1+\Gamma} = 1/2$. The log deviations of the price from the mean values of the shocks can be expressed as $p_t = \alpha\mu_t + (1-\alpha)\, mc_t$, where μ_t is the variable markup. Therefore, approximately 1/2 of a cost shock are absorbed in the markup while approximately 1/2 of the shock affects the price directly. In this model, the exchange rate shocks do not affect the marginal cost perfectly, but rather imperfectly due to the share of intermediate inputs. The final result is that exchange rate pass-through is roughly $(1-\alpha)(1-\phi^*) = 0.375$.

[39]Furthermore, the working paper version of Cavallo et al. (2021) which also uses BLS data reported no observable change in the frequency of price setting during the trade war.

[40]These moments are documented in Gopinath & Rigobon (2008), and are also in line with additional statistic of U.S. import prices from the same BLS dataset in Schoenle (2017).

[41]Note that this idiosyncratic productivity process is highly persistent relative to estimates of domestic U.S. prices

well within the conventional range used in calibration of similar models, and implies a cost of 0.37% of annual profits.

We solve the model separately for different values of τ^H and γ that characterize different economies. $\tau^L = 0$ in all cases. For τ^H we create a grid with $\tau^H \in \{1\%, 2\%, ..., 20\%\}$. These values are in line with the range of U.S. tariffs imposed on different varieties. Namely, they are in line with the 2018-2019 tariff increases, as documented in Bown (2021). We take the baseline case to be $\tau^H = 10\%$ as this was the initial rate imposed on Chinese imports in 2018.

For trade policy uncertainty variation, we choose different values of $\gamma \in \{0, 0.1, \dots 0.5\}$. There is no clear method of calibrating or estimating γ or its comparable parameters in the literature. The issue of parameterization of TPU is discussed in recent papers, including Handley & Limão (2017),Alessandria et al. (2019), Alessandria et al. (2021), and Handley & Limão (2022).[42] Rather than choosing a baseline parameter, we conduct several comparative quantitative exercises with different values of γ to show the effect of TPU on prices. As the next section describes, $\gamma = 0.5$ brings tariff pass-through estimates in the simulated model closest to the data, but a substantial increase in tariff pass-through is present even for smaller values of γ.

1.4 Inspecting the mechanism: Equilibrium pricing policies

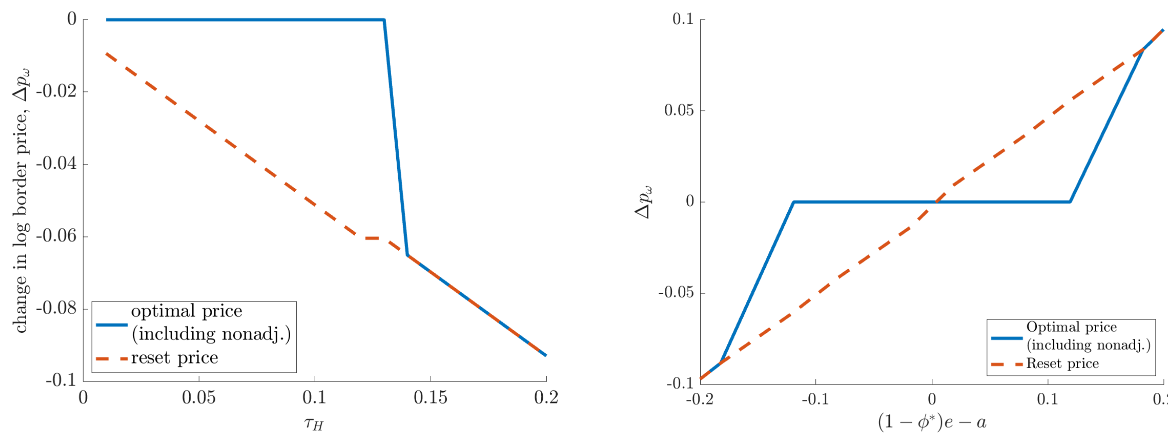
A shock's pass-through rate into the import price can be interpreted as the elasticity of the import price with respect to that shock. The pass-through rate of a tariff into the import price is $1 + \Delta \log P_\omega / \Delta \log(1+\tau)$. Thus, for a given change in tariff level, $\Delta \log(1+\tau)$, the pass-through rate is determined by the change in the ex-tariff border price $\Delta \log P_\omega$. TPU affects tariff pass-through into the import price through the change in the border price.

(for example in Klenow & Willis (2016)), but also does not require a huge standard deviation to match the moments, an issue that plagued the literature modeling fixed price adjustment costs. Other studies tend to have much lower persistence of idiosyncratic shocks, which requires lower standard deviations (Nakamura & Steinsson 2008, Karadi & Reiff 2019, Midrigan 2011). Overall, the parameters of the idiosyncratic process are within the same order of magnitude as those in other models with menu costs. This is a result of targeting the absolute median size of price adjustment, while other studies target moments such as the standard deviation of relative price. The idiosyncratic productivity process is also only 1.6 times more volatile than the real exchange rate process and is still able to generate considerable heterogeneity in price dispersion.

[42] Alessandria et al. (2022) use a structural model to estimate TPU related to U.S.-China trade relations since the 1960s. However, their specification and data are not applicable to this paper's topic.

Figure 1.3: Optimal (including nonadjustment) and reset border price, without TPU

(A) An increase in tariff from $\tau^L = 0$ to τ^H, for $\gamma = 0$ (B) Cost shock $(1-\phi^*)\,e - a$, for $\tau^L = \gamma = 0$



Note: Change in the optimal border price and the reset border price of a representative Foreign firm, from $\log P_0$ with $a = e = \tau^L = 0$ and no TPU $\gamma = 0$. In panel (a), tariff increases to various levels of τ^H, holding all other shocks, TPU, and the sectoral price level constant. Panel (b) depicts different levels of the cost shock $(1-\phi^*)\,e + a$ (the marginal cost is expressed in Home unit of account), holding tariff, TPU, and the aggregate price level constant.

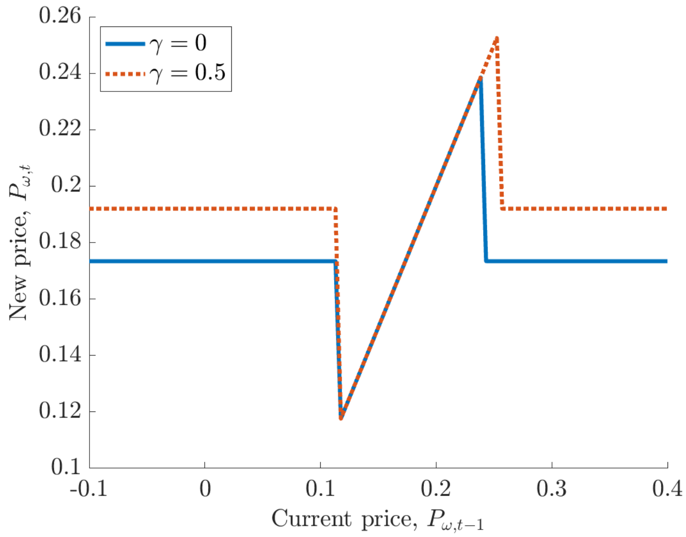
To break down the mechanism of the response of an exporter's border price to tariffs and TPU, we first examine a representative Foreign exporter's policy functions. When there is a fixed cost to reseting the price, a firm faces a two-tiered decision. First, whether to reset the border price—*the extensive margin*. Then, if it is optimal to reset the border price, what the new reset border price should be—*the intensive margin*. In this section, we show that TPU affects both margins. On the extensive margin, a tariff increase accompanied by TPU increases the firm's inaction region and makes price adjustment less likely. On the intensive margin, TPU induces a precautionary markup which reduces the size of the decrease in the border price, relative to a case without uncertainty about tariffs.

Figure 1.3(a) presents the policy function for a change in tariff. Initially, $\tau^L = a = e = \gamma = 0$, and the corresponding border price (which is also the sectoral price level) is $P_0 = \frac{\sigma}{\sigma-1}$. The policy function depicts an increase from $\tau^L = 0$ to τ^H without an increase in TPU ($\gamma = 0$), while holding all else constant. The figure presents the change between the new log border price and the initial border price, $\Delta p_\omega \equiv \log P_\omega - \log P_0$, both the optimal price including nonadjustment and the optimal reset border price (the policy function in equation (1.3.15)). The firm's reset border price (the dashed red line) decreases with the size of the tariff increase. There is a wide inaction region, and the firm resets the price only for very large values of τ^H (the solid blue line). This wide inaction region results from the fact that cost shocks are much more volatile than tariffs. Here, cost shocks remain at their mean level, and therefore the firm would prefer to wait and see if there will be larger cost shocks in the future and only then reset its price. Note that for all levels of τ^H the reset border price decreases by roughly 60% of the size of the tariff increase. This incomplete pass-through is the result of price complementarities. Since the aggregate price level remains P_0, the firm does not want to let its tariff-inclusive import price increase too much, and must decrease the border price to do so. As we show later, the size of the decrease in the border price increases with the elasticity of the markup (determined by ε), and decreases with uncertainty, γ.

Figure 1.3(b) presents the policy function for a change in the cost shock, $(1 - \phi^*)\, e - a$, from the initial level $a = e = 0$ with corresponding border price P_0, while holding tariff and TPU constant at $\tau^L = \gamma = 0$, and also the sectoral price level. The inaction region covers values of the cost shock that occur in this case with probability of about 0.78, which is in line the parameterization of the model. Over time, cost shocks accumulate to the point where the firm finds it optimal to reset the price. The new price will reflect the new level e and a. This causes a delayed response of the firm's price to cost shocks and rigidity of the price. The reset price does not change by the full size of the cost shock, but rather by around 38%-40% of the cost shock. This incomplete pass-through of the cost shock is due to price complementarities. Recall that a is an idiosyncratic shock, e does not affect domestic firms directly, and the sectoral price level is held constant. Thus, the exporter wants to limit deviations of the relative price from the sectoral price level as much as possible.

Next, we examine the border price policy function in the baseline scenario of a tariff increase from $\tau^L = 0\%$ to $\tau^H = 10\%$. In Figure 1.4, we compare an exporter's border price policy function when $\gamma = 0$ (no uncertainty about τ) relative to the case when $\gamma = 0.5$ (0.5 probability that τ will go back to τ^L next period). Other exogenous variables are held at their mean level, $a = e = 0$, and the sectoral price level is held at P_0. The diagonal part of the policy functions is the inaction region. If the initial border price of the exporter is close enough to the optimal reset price, the exporter prefers to avoid paying the fixed cost and will not adjust the price. There is an increase in the inaction

Figure 1.4: Optimal border price response, tariff $\tau^H = 10\%$, with no TPU ($\gamma = 0$) or high TPU ($\gamma = 0.5$)



Note: Optimal border price of a representative Foreign firm, $P_{\omega,t}$, as a function of its initial border price, $P_{\omega,t-1}$, with tariff $\tau^H = 10\%$ and $a = e = 0$, holding sectoral price level at P_0. The solid blue line depicts the policy functions without uncertainty, $\gamma = 0$. The dashed red line depicts the policy function with uncertainty, $\gamma = 0.5$.

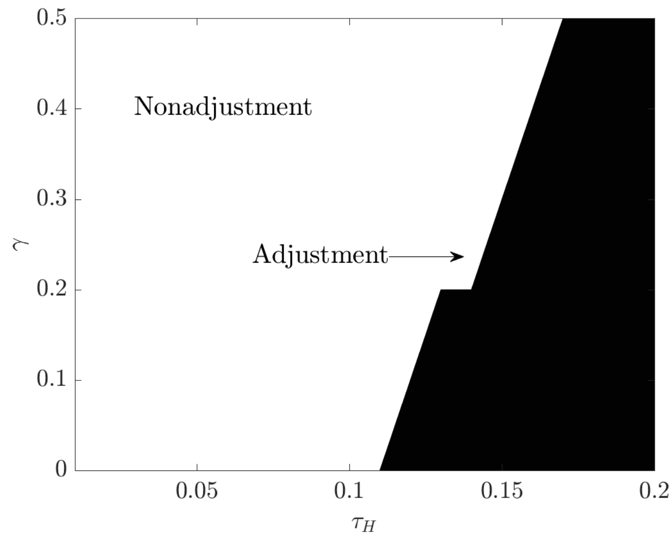
region (the extensive margin) when TPU is present, as the firm has an incentive to postpone the costly price adjustment if there is a non-negative probability that the tariff will go back to 0% the following period. The horizontal part of the policy function is the optimal reset border price. When the initial price is far enough from the reset price, the exporter pays the fixed adjustment cost and resets the border price to this level. The reset border price when TPU is present (the dashed red line) is higher than the reset border price when there is no uncertainty (the solid blue line). As a result, the tariff-inclusive import price is higher and more of the tariff would be passed-through into the import price.

To decouple the effects of the extensive and the intensive margins in response to TPU, we first look at an indicator of the optimal border price adjustment decision of a Foreign exporter, and then at the optimal reset border price (regardless of the optimality of adjustment itself). Figure 1.5(a) presents a Foreign firm's decision whether to adjust or not to adjust the border price in response to an increase from $\tau^L = 0$ to τ^H. There is a large nonadjustment region.[43] The likelihood that the

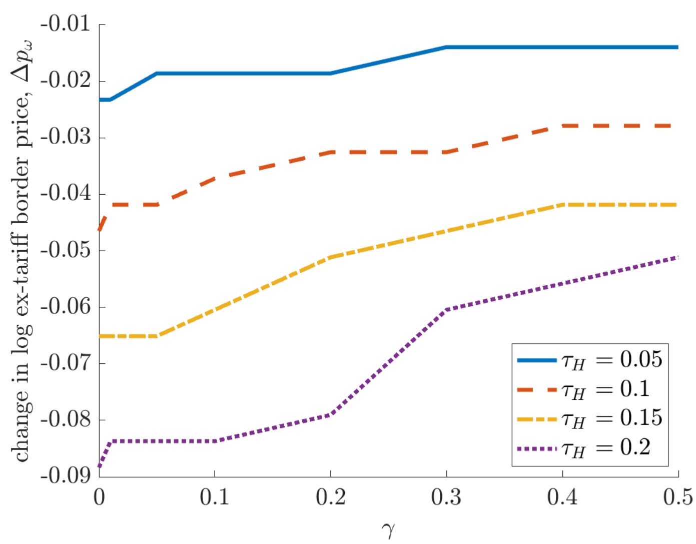
[43] This nonadjustment region depends on parameters of the model that determine the size of the price adjustment cost, κ; the firm's exposure to the real exchange rate, ϕ^*; and the volatility of the cost shocks, σ_a, σ_e.

Figure 1.5: Policy functions: Extensive and intensive margins

(A) Border price adjustment indicator in response to a tariff increase from $\tau^L = 0$ to different τ^H (horizontal axis), and a TPU increase from $\gamma = 0$ (vertical axis)



(B) Optimal reset border price change for an increase in tariff to selected values of τ^H for different levels of TPU γ



Note: Panel (a) presents nonadjustment vs. adjustment of the border price of a representative Foreign firm, from $\log P_0$ with $a = e = \tau^L = 0$ and no TPU $\gamma = 0$, to various levels of τ^H and TPU γ, holding all other shocks, and the aggregate price level constant. Panel (b) presents the optimal reset border price change in logs of a representative Foreign firm, from $\log P_0$ with $a = e = \tau^L = 0$ and no TPU $\gamma = 0$, to selected values of τ^H and different value of γ, holding all other shocks, and the aggregate price level constant.

firm will adjust the price increases with the size of the tariff increase, τ^H, and it decreases with the level of TPU, γ. It is important to emphasize that the unconditional mean of τ remains constant as γ and τ^H increase, therefore the changes here represent a mean preserving spread and should not be affected by an expected mean effect. Higher γ makes τ^H less persistent and increases the variance of the exporter's forecast error. Both of the effects make it more likely that the firm will find it optimal not to adjust the price now, but to wait for next period to see if the value of τ changes, something that might require an additional costly price adjustment. This "wait-and-see" effect in price is setting is in line with the literature that finds similar extensive margin effects of TPU on other costly decisions, such as entry / exit from exporting, inventories, and investment (Handley 2014, Handley & Limão 2017, Crowley, Meng & Song 2018, Alessandria et al. 2019, Caldara et al. 2020). If the exporter decides not to adjust the border price, then $\Delta \log P_\omega = 0$. This immediately leads to 100% tariff pass-through into the tariff-inclusive import price. Therefore, high TPU γ increases the likelihood of high tariff pass-through on impact, after a tariff increase.

Figure 1.5(b) presents the optimal change in the reset border price of a Foreign exporter for an increase in tariff from $\tau^L = 0$ to selected levels of $\tau^H \in \{5\%, 10\%, 15\%, 20\%\}$, and for various levels of TPU, γ, holding all else constant. That is, the figure depicts the optimal decrease in the reset border price, $\Delta \log P_\omega$, in response to a tariff increase, regardless of whether it is actually optimal to adjust the price. The size of the price change in absolute value, $|\Delta \log P_\omega|$, increases with the size of the tariff increase, τ^H. Importantly, $|\Delta \log P_\omega|$ decreases with γ for all values of τ^H.[44] A smaller change in the ex-tariff border price, $|\Delta \log P_\omega|$, means higher tariff pass-through into the tariff-inclusive import price. Therefore, TPU γ increases tariff pass-through into the import price even after the border price has been reset. The effect of TPU on tariff pass-through is not just on impact after a tariff increase, is lasts into the post-adjustment period as well.

The effect of TPU on the optimal reset border price at the intensive margin is due to a precautionary pricing motive, sometimes referred to in the literature as "precautionary markup" (Kimball 1989, Fernández-Villaverde et al. 2015, Oh 2020, Born & Pfeifer 2021). Precautionary markup arises since the exporter's (static) marginal profit is convex in the tariff, τ. The fixed price

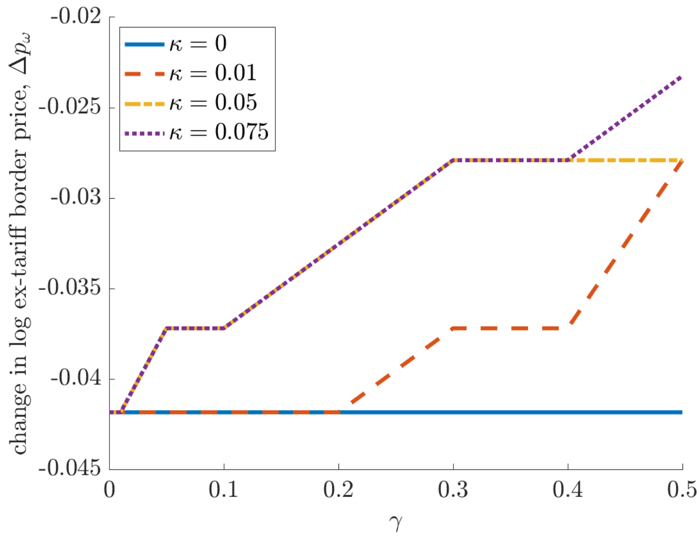
[44]The full set of policy functions for different values of τ^H is presented in an online appendix. .

adjustment cost, κ, creates an element of pre-commitment in the exporter's pricing decision. Since price adjustments are costly, the exporter must take into account today that they might be "stuck" with the current border price in the next period. Therefore, when the tariff increases today from τ^L to τ^H, there are two "risks" the exporter must weigh when reseting the border price. First, if the border price is reset "too low" and the tariff goes down next period to τ^L, the exporter will be forced so supply a sub-optimally high demand at a low price. Second, if the border price is reset "too high" and the tariff remains at τ^H next period, demand for the exporter's demand might be choked off. With marginal profit convex in the tariff, the "too low" price is more damaging than the "too high" price. An increase in γ exacerbates this problem because it changes the curvature of the expected profit function and makes the "too low" price even more damaging. In Appendix 1.B, we discuss this precautionary markup effect in more detail, using a simplified static model. The convexity of the marginal profit depends crucially on two parameters of the model: the fixed price adjustment cost, κ, and the superelasticity, ε. Next, we show how these parameters affect the intensive margin.

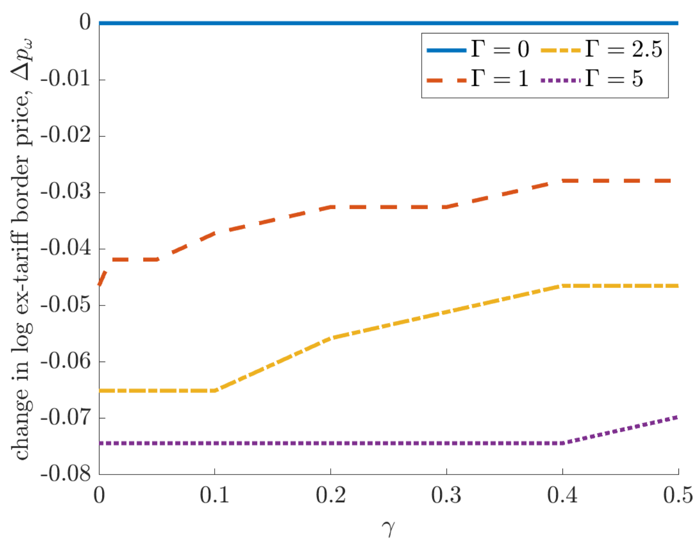
First, consider the effect of a change in the fixed price adjustment cost κ. Figure 1.6(a) presents the change in the optimal reset border price when tariff increases from 0% to 10% for different levels of uncertainty, γ, and different values of the adjustment cost, κ. When $\kappa = 0$, prices are fully flexible. In this case, the level of uncertainty has no effect on the optimal reset border price since the firm's price setting problem becomes static. As κ increases, the effect of an increase in γ becomes more pronounced. This manifests in a smaller decrease in the optimal reset border price, $|\Delta \log P_\omega|$, in response to the increase in tariff. As price adjustment become more costly, it is not only the extensive margin that is affected, but also the intensive margin. Recall from equation (1.3.16) that the firm takes into account the discounted expected value of its profit in all future periods. Costlier price adjustment increases the precautionary markup motive as the probability of getting stuck with a "too low" pre-committed border price increases.

Next, figure 1.6(b) presents the effect of varying the superelasticity parameter ε, and as a result the elasticity of the markup Γ, on the change in the optimal reset border price, $|\Delta \log P_\omega|$, in response to an increase in tariff from 0% to 10% for different levels of γ. When $\varepsilon = 0$ and $\Gamma = 0$, demand has constant elasticity of substation (CES). The exporter maintains a constant markup and the

Figure 1.6: Optimal reset border price change for an increase in tariff to $\tau^H = 10\%$ and an increase in TPU from $\gamma = 0$, different values of price adjustment cost κ, markup elasticity Γ



(A) κ



(B) Γ

Note: Optimal reset border price change of a representative Foreign firm, from $\log P_0$ with $a = e = \tau^L = 0$ and no TPU $\gamma = 0$, to $\tau^H = 10\%$ and different value of γ, holding all other shocks, and the aggregate price level constant. The baseline parameter values are $\kappa = 0.041$ and $\Gamma = 1$ (corresponding to $\varepsilon = 5$).

precautionary markup motive disappears, since the tariff only affect the exporter's markup and not its cost of production. When $\varepsilon = 0$, an increase in γ has no effect on the border price. Furthermore, since the tariff does not affect the markup in this case, the increase in tariff has no effect on the border price at all (which would also cause counterfactually high exchange rate pass-through, as discussed in Section 1.3). When $\varepsilon > 0$ and therefore $\Gamma > 0$, markups are variable and precautionary markups play a role in the firm's price setting decision. Specifically, when $\varepsilon > 0$ the marginal profit is convex in tariff, and an increase in γ changes the curvature of the expected profit function in a way that increases the optimal reset border price. It is interesting to note that an increase in uncertainty leads to smaller reset border price reduction in all cases where variable markups are present, even when the markup is very elastic ($\varepsilon = 20$). For a given γ, the size of the border price reduction increases with the elasticity of the markup. This is a result of an increase in price complementarities, as demand for the firm's variety become more responsive to changes in its relative price.

1.5 Quantitative Analysis

In this section, we present results for quantitative exercises conducted with the dynamic model. The main takeaway is that in the absence of TPU, a 10% tariff increase which is perceived to be a one-time permanent change is passed-through into the tariff-inclusive import price at around 59% after one year. When TPU is present, however, tariff pass-through increases up to 81% with the level of uncertainty. At the same time, exchange rate pass-through is roughly 39% and is almost unaffected by the presence of TPU. These results indicate that TPU has an important role in explaining the high tariff pass-through vis-a-vis low exchange rate pass-through observed for the 2018-2019 tariffs.

We simulate 1,000 economies[45] from the model, each with 1,200 domestic firms and 240 foreign firms for 240 months (a period in the model is one month). All economies start at tariff rate $\tau_L = 0$ with no TPU ($\gamma = 0$). This was approximately the state of the U.S. prior to 2017. In the baseline case, at period $\bar{t} = 145$ there is an unexpected increase in tariff to $\tau^H = 10\%$. If $\gamma = 0$ after the shock, then firms perceive this change to be a one-time permanent policy change. However, if there is an increase in TPU to $\gamma \in (0, 0.5]$ in addition to the tariff increase, firms expect the tariff level

[45]An economy is a random draw for the processes of a and e.

to revert back to τ^L at some point in the future. Thus, the tariff shock is seen as transitory and there is uncertainty because the policy has lower persistence and the variance of the forecast error increases. We compare different levels of γ that create different levels of uncertainty and constitute a mean preserving spread. In all cases, while firms might expect tariffs to change, the exogenous policy maker keeps the tariff at the same level after the shock. This approximates the state of the U.S. after March 2018, where TPU was very high and there was uncertainty about the persistence of the tariff increases in 2018-2019, but ex-post the tariff was in place at a steady level for over four years.

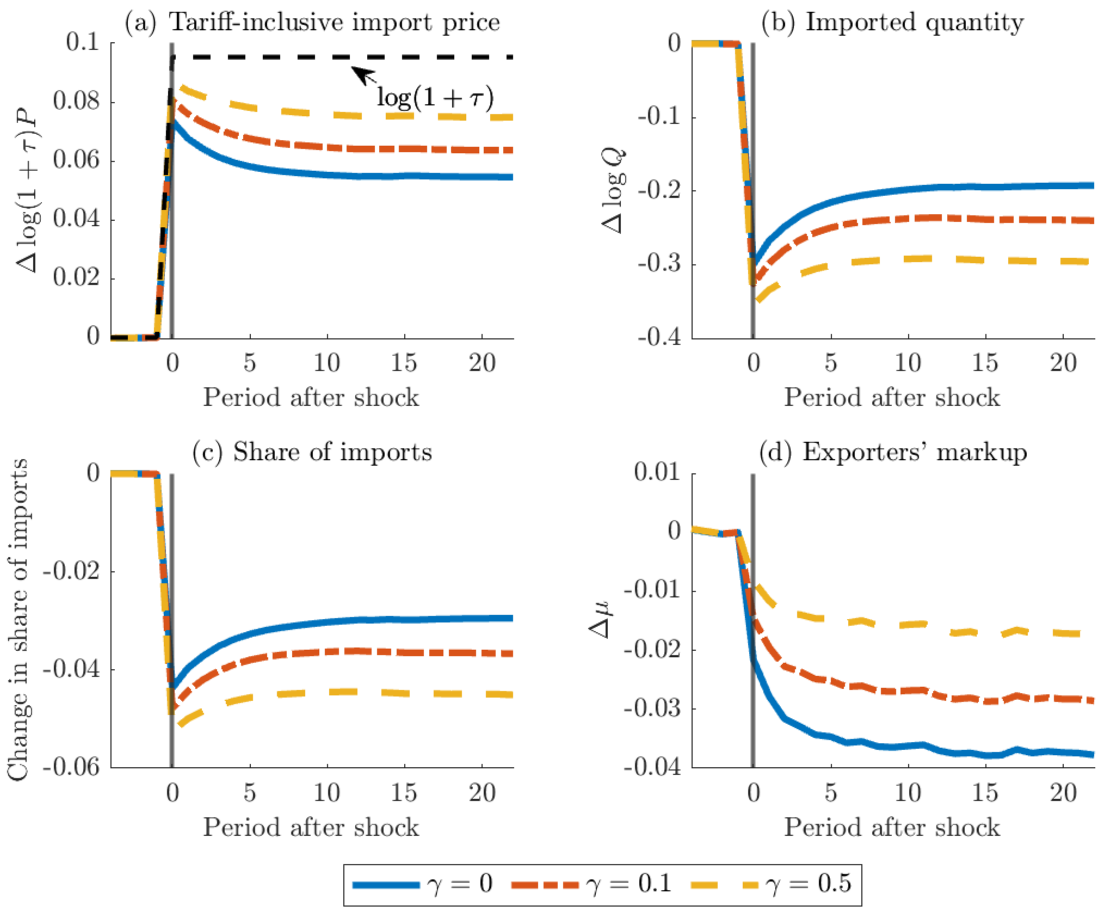
1.5.1 Impulse response functions

We follow the standard procedure in the literature in computing impulse response functions (IRFs). The IRFs are in log deviations from the stochastic steady state with τ^L and $\gamma = 0$. Full details of the computation of the IRFs are in Appendix 1.A.

Prices Ceteris paribus, following an increase of tariff to 10%, the tariff-inclusive import price paid by importers increases. As a result, demand for the imported Foreign varieties decreases. Since Foreign exporters are competing against domestic producers, whose varieties are not taxed and who make up 83% of available varieties, the relative import price of Foreign varieties paid by the importer jumps up. Exporters now face pressure to reduce their border price and absorb some of the tariff increase, so that their relative import price will not increase so dramatically. Since price adjustments are costly, this process does not necessarily happens immediately at the time of the tariff increase. Instead, different exporters adjust their prices at different points in time, so that the sectoral import price index adjusts gradually. The speed of price adjustment also depends on the realization of the more volatile cost shocks: the exchange rate and the productivity level.

This process is depicted in panel (a) of Figure 1.7. The dynamic response of firms has the same direction at all levels of uncertainty: an initial jump in the import price when the tariff increases, but by less than the full amount of the tariff since some exporters adjust their border price on impact. Then, a gradual adjustment follows over 11-12 months as all exporters eventually adjust their border price. The fact that there is always some absorption of the tariff by the exporters is due to pricing

Figure 1.7: IRFs for a 10% tariff increase, various levels of uncertainty γ



Note: IRFs computed from 1,000 simulated economies with 1,200 domestic and 240 foreign firms each. All economies start with $\tau^L = 0\%$ and $\gamma = 0$ until period $\bar{t} = 145$ when the tariff unexpectedly jumps to $\tau^H = 10\%$. The aggregate tariff-inclusive import price, aggregate exporter markup, aggregate imported quantity index are computed as the geometric mean of log variables of each exporter. The aggregate variables from all economies are averaged. The import share is calculated as the aggregated quantity imported out of total consumption and averaged across all economies. For import prices, imported quantity, and exporter' markup, the figure shows the percent deviation of the cross-economy average from its value in the last period before $\bar{t}$. The IRFs for the share of imports is in percentage points change from period $\bar{t} - 1$. IRFs are presented for selected values of γ. The black dashed line shows the log value of tariff, $\log(1 + \tau)$.

complementarities created by variable markups, and the fact that exporters do not want to let their import price deviate too much from the aggregate sectoral price level.

Panel (a) of Figure 1.7, shows clearly that the import price increases with the level of uncertainty, γ. As discussed in the previous section, this is the result of the effect of uncertainty on the two margins of price adjustment. On impact, at the shock period $\bar{t}$, the likelihood that a firm adjusts its price decreases with γ. This is the "wait-and-see" effect on the extensive margin. Until the firm adjusts its price, the import price will automatically increase by the full amount of the tariff. On average, the import price increases on impact by 7.4% when firms perceive the tariff increase to be a one-time permanent change ($\gamma = 0$), and this rate increases to 8.1% when $\gamma = 0.1$, and to 8.7% when $\gamma = 0.5$. When the firm finally adjusts the price, the new optimal reset border price increases with γ. This is the precautionary markup effect on the intensive margin. After 12 months, the average import price increases by 5.5% when $\gamma = 0$, relative to period $\bar{t} - 1$, and by 6.5% and 7.6% when $\gamma = 0.1$ and $\gamma = 0.5$, respectively. Both of these channels lead to higher border prices, and therefore higher import prices.

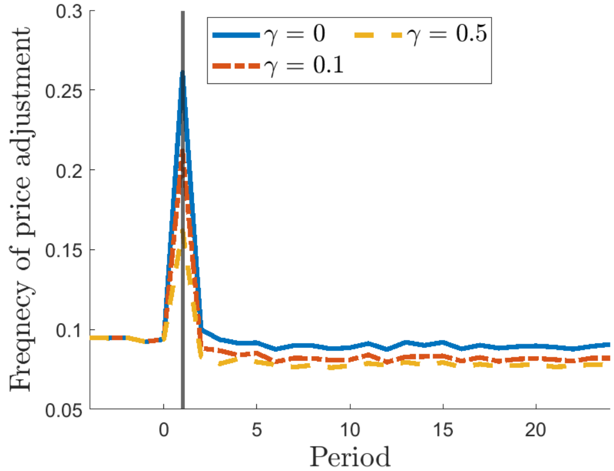
Markup Panel (d) of Figure 1.7. shows the effect of precautionary markups and its relationship with uncertainty explicitly. In this figure, we compute the IRFs for the log markup $\mu_\omega = \log\left(\sigma\left(p_\omega\right) / \left(\sigma\left(p_\omega\right) - 1\right)\right)$. The average markup adjusts over time and declines as firms adjust their border prices. After 12 months, the largest decline in markup of 3.6%, relative to the markup at period $\bar{t} - 1$, occurs when there is no uncertainty about the future path of tariff ($\gamma = 0$). When $\gamma = 0.1$, the markup decline by 2.7%, and when $\gamma = 0.5$ the markup declines by only 1.6%. That is, the markup is significantly higher when TPU is present. It should be emphasized that this markup is variable and chosen by the firm. This emphasizes the role of precautionary markups even further relative to similar arguments made in the literature in environments with Calvo pricing and CES demand, where variable markups were only a temporal side effect of time-dependent price rigidities (Fernández-Villaverde et al. 2015, Oh 2020, Born & Pfeifer 2021).

Quantities Given that import prices soar after the tariff increase, it is not surprising that demand for imported varieties plummets. Panel (b) of Figure 1.7 shows that demand for imports collapses on impact as the tariff and the import price increases. Over time as firms adjust their border prices, the import price declines somewhat and demand for imports inches back upwards. Demand in this model is not affected directly by TPU, only through the effect TPU has on import prices. When $\gamma = 0$, demand decreases after 12 months by 19.6% relative to its level at $\bar{t} - 1$, and when $\gamma = 0.1$ and $\gamma = 0.5$, demand decreases by 23.6% and 29.2%, respectively. The size of these decreases is in line with findings in Amiti, Redding & Weinstein (2019) and Fajgelbaum et al. (2020), who estimate around a 30% decrease in U.S. imports from China after a similar size tariff increase.

It is not only the absolute quantity of imports that decreases after the tariff increase, but the composition of the consumption basket changes as well. Panel (c) of Figure 1.7 shows that 12 months after the tariff increase, the share of imports in consumption decreases by 3 percentage points when $\gamma = 0$, relative to its share at $\bar{t} - 1$ (from 16.7% to 13.7%). When $\gamma = 0.1$, the share of imports decreases by 3.6 percentage points, and when $\gamma = 0.5$ it decreases by 4.4 percentage points. Expenditure switching from Foreign to Home varieties causes this effect, as well as an increase in the number of exporters who prefer not to sell any positive quantity rather than decrease their border price drastically.

Frequency of price adjustment To illustrate the effect of uncertainty on the extensive margin of price adjustment, we calculate the average frequency of price adjustment across all economies. Figure 1.8 shows the average cross-economy frequency of price adjustment around the tariff increase shock for selected levels of TPU. When the tariff increase is perceived to be a one-time permanent change ($\gamma = 0$), the share of firms adjusting their border price on impact jumps from 0.094 to 0.26 but then almost immediately returns to its original level. In contrast, under both $\gamma = 0.1$ and $\gamma = 0.5$, there is less adjustment of the border price on impact (0.19 and 0.13, respectively). Additionally, there is also a small but meaningful decrease in the frequency of price adjustment in all future periods (0.081 and 0.077, respectively). This decline in frequency is important as it represents an increase from an average price duration of 11 months to 12.3 and 13 months, respectively. TPU not only decreases the likelihood of price adjustment to the tariff increase on impact, it also increases price rigidity

Figure 1.8: Change in frequency of price adjustment, various levels of uncertainty γ



Note: Change in the average frequency of price adjustment computed from 1,000 simulated economies with 1,200 domestic and 240 foreign firms each. All economies start with $\tau^L = 0\%$ and $\gamma = 0$ until period $\bar{t} = 145$ when the tariff unexpectedly jumps to $\tau^H = 10\%$. The frequency of price adjustment is calculated as the share of exporters in each period adjusting their price. The frequency from all economies is averaged.

while it is present.[46]

1.5.2 Tariff and exchange rate pass-through estimation

Next, we estimate tariff and exchange rate pass-through into import prices in the simulated data. we follow the specification laid out in Cavallo et al. (2021). This is a standard pass-through regression that has been used extensively in the literature. For comparability with the 2018-2019 tariff pass-through estimations, we limit the sample used in the regression to 24 months before and after $\bar{t}$.

In each economy, we estimate the following panel regression:

$$\Delta \log (1 + \tau_t) P_{\omega,t} = \sum_{l=0}^{L} \beta_l^{\tau} \Delta \log (1 + \tau_{t-l}) + \sum_{l=0}^{L} \beta_l^{e} \Delta e_{t-l} + \epsilon_{\omega,t} \tag{1.5.1}$$

where Δ denotes the first lag, L is the number of lags (up to 23), and $\epsilon_{\omega,t}$ is a firm level error

[46]While outside the scope of this work, this model prediction opens up an interesting avenue for both empirical and theoretical research about monetary non-neutralities amplified by TPU. Specifically, periods of high TPU could have implications for monetary policy. This might be especially relevant for FX interventions during times of heightened TPU.

Table 1.2: Tariff and exchange rate pass-through into import prices estimation

	Data	Simulated model			
		(1)	(2)	(3)	(4)
Trade policy uncertainty		no TPU	intermediate TPU	high TPU	no TPU
γ		$\gamma = 0$	$\gamma = 0.1$	$\gamma = 0.5$	$\gamma = 0$
Markups		variable	variable	variable	constant
1 year cumulative tariff PT $\sum_{l=0}^{11} \hat{\beta}_l^{\tau}$	0.994★ (0.188)	0.595	0.692	0.812	0.998
1 year cumulative exchange rate PT $\sum_{l=0}^{11} \hat{\beta}_l^{e}$	0.381 (0.052)	0.392	0.402	0.397	0.654

Note*:* The empirical estimation results under the "Data" column are taken from Cavallo et al. (2021). Robust standard errors in parentheses. The regression in the BLS data controls for PPI in the exporter's country, as well as dummy variables for Chinese varieties affected and unaffected by the tariffs, and includes sector fixed effects. Adjusted $R^2 = 0.018$. The estimation results of the of regression equation (1.5.1) in the simulated data is averaged across 1,000 simulated economies. The regression is estimated for a tariff increase to $\tau^H = 10\%$, and for different levels of uncertainty, γ. In the baseline model with Kimball aggregator, the superelasticity parameter is $\varepsilon = 4$ and the elasticity parameter is $\sigma = 5$. In the CES specification, $\varepsilon = 0$ and $\sigma = 5$.
★Cavallo et al. (2021) estimate the regression using ex-tariff border prices, therefore their estimator is 0.006. To get the pass-through estimate into the import price, we subtract this estimate from 1. The original estimator is not statistically significant.

term.[47] We estimate the regression with $L = 11$ in each simulated economy.[48] We then average the estimators across all simulated economies.

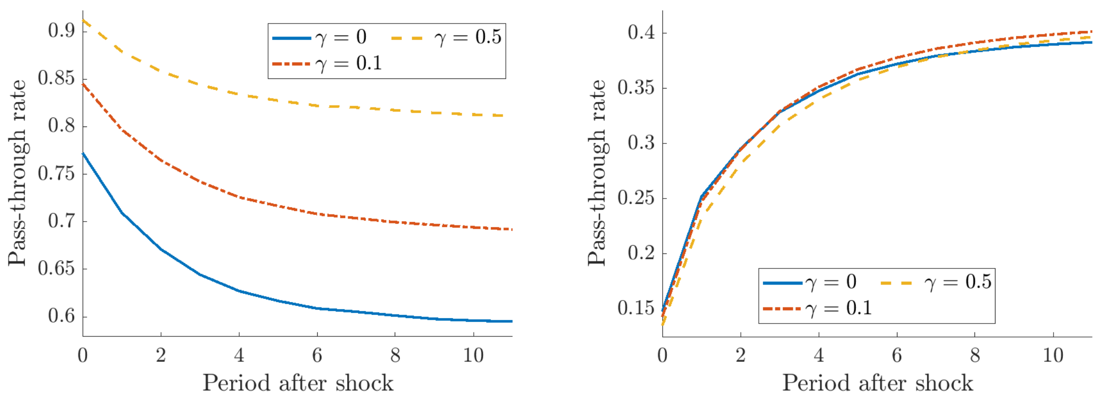
For each log variable $x \in \{\tau, e\}$, the coefficient β_l^x measures the pass-through rate of the l-lag of a change in the variable into the import price. $\sum_{l=0}^{L} \beta_l^x$ measures the cumulative pass-through rate over the duration L. This regression equation has a structural interpretation that arises from equations (1.3.22)-(1.3.23).

We compare results from the simulated model to the findings in Cavallo et al. (2021). It should be emphasized that the model is calibrated to pre-2017 (before the 2018-2019 tariffs) moments of U.S. import price adjustment, and does not target exchange rate pass-through or tariff pass-through. Table 1.2 presents the estimates from the BLS data alongside four specifications of the model: three with the baseline Kimball aggregator parameterization and varying levels of TPU (no TPU,

[47] Note that unlike Cavallo et al. (2021), we do not include a firm-level fixed effect, since all the variation in the model is coming from $a_{\omega,t}$ which has the same mean and variance for all firms. Therefore there are no time-invariant differences between the firms. In a robustness check, we estimate the regression while also controlling for L lags of $a_{\omega,t}$. This does not affect the estimates of β_l^{τ} or β_l^{e} in a meaningful way.

[48] We also estimate the regression with $L = 23$, but since almost all of the adjustment happens within the first year after a change in either tariff or the exchange rate, we relegate the results with $L = 23$ to an online appendix. .

Figure 1.9: Tariff and exchange rate cumulative pass-through into the tariff-inclusive import price estimation in the simulated model



(A) Tariff pass-through estimation, $\sum_{l=0}^{11} \hat{\beta}_l^{\tau}$ (B) Exchange rate pass-through estimation, $\sum_{l=0}^{11} \hat{\beta}_l^{e}$

Note: Estimation of regression equation (1.5.1) in the simulated data.

intermediate TPU, and high TPU), and one without TPU but with CES demand. The model can generate incomplete exchange rate pass-through rate well, as evident from the model columns (1)-(3). Column (1) highlights how this standard model, absent TPU, yields counterfactually low tariff pass-through rate. The presence of TPU raises tariff pass-through significantly, and it increases beyond 80%. Column (4) shows that CES demand can lead to very high tariff pass-through in the simulated data, but at the cost of counterfactually high exchange rate pass-through, almost double its estimated rate in the data. This paper does not claim that the presence of TPU was the sole contributor to the high observed tariff pass-through during 2018-2019, but rather that it was one important, and overlooked, contributing factor. Other important factors beyond the scope of this model could be related to the level of differentiation of Chinese exports to the U.S. and the unique role that China plays in the global supply chain as the production powerhouse of the world.

Figure 1.9(a) presents the estimator of $\sum_{l=0}^{11} \hat{\beta}_l^{\tau}$ as it evolves over one year after the tariff increase. Tariff pass-through into the import price is highest on impact ($l = 0$). Then, as more firms adjust their border price, pass-through decreases until it reaches its desired level, approximately 11 months after the initial increase. Tariff pass-through increases significantly with the uncertainty level, γ. When there is no uncertainty about the future level of tariff, $\gamma = 0$, firms pass-through 59.5% of the tariff increase into the import price after one year. This rate increases to 69.2% when $\gamma = 0.1$, and to 81.1% when $\gamma = 0.5$.

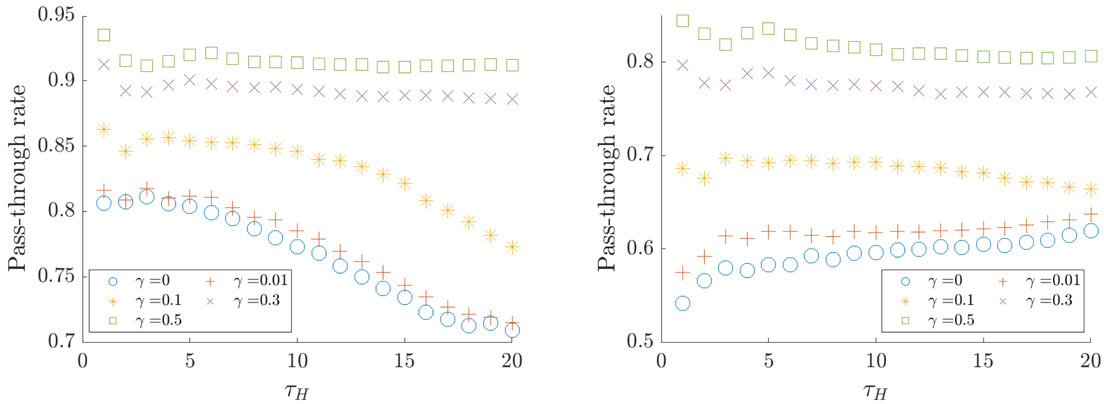
These large differences in tariff pass-through as a result of increase in uncertainty have only a marginal effect on exchange rate pass-through. Figure 1.9(b) presents the estimator of $\sum_{l=0}^{11} \hat{\beta}_l^e$ during the comparable period. When the real exchange rate depreciates (an increase in e), the firm's marginal cost in Home currency increases, which leads the firm to increase its border price. On impact, a real depreciation is passed-through at an average low rate. Then, as more firms adjust their prices over time, the average pass-through rate reaches its desired level. The estimated real exchange rate pass-through into the import price is on average 39%-40% after one year, regardless of the level of uncertainty about the tariff. The fact the exchange rate pass-through is almost unaffected by the level of tariff uncertainty is not surprising. Since the desired level of exchange rate pass-through is determined mostly by the parameters that govern demand and by expectations about future levels of the exchange rate, TPU has only an indirect effect on exchange rate pass-through. Since higher TPU is associated with higher import prices after the tariff increase, and a higher markup, this will affect the (variable) price elasticity of the markup. However, this effect is not large enough to change the desired level of exchange rate pass-through drastically. Therefore, TPU can increase tariff pass-through substantially without affecting the low and incomplete exchange rate pass-through.

1.5.3 Calibration of TPU parameter γ

The estimation results presented above indicate that when TPU reaches its highest level, $\gamma = 0.5$, tariff pass-through increases significantly, relative to the no-TPU case, $\gamma = 0$. However, even this substantial increase to over 80% pass-through is not enough to replicate the observed near 100% tariff pass-through in the 2018-2019 data. For this reason, we do not use the pass-through estimates to calibrate γ, since it is clear that there are other factors affecting pass-through that are not captured in this simple model.

However, qualitatively, $\gamma = 0.5$ should not be seen as an extreme or unrealistic value. $\gamma = 0.5$ assigns a 50% chance every period that the tariff will go back down to 0%. While this is a very high probability, it is entirely plausible. Recall that TPU levels according to several empirical indices

Figure 1.10: Tariff pass-through into the tariff-inclusive import price estimation in the simulated model, variation in τ^H and γ



(A) Tariff pass-through estimation, contemporaneous $\hat{\beta}_0^\tau$

(B) Tariff pass-through estimation, one year $\sum_{l=0}^{11} \hat{\beta}_l^\tau$

Note: Estimation of regression equation (1.5.1) in the simulated data for different levels of the tariff increase to τ^H, and for different levels of uncertainty, γ.

during this period were at an all-time high, as depicted in Figure 1.1. Given the volatile news and tweets emanating from the Trump administration during some months in 2018 immediately after the first couple of tariff waves, at the time it seemed entirely possible that the tariffs would be lifted shortly if a deal were reached. As a matter of fact, the steel and aluminum tariffs on Canada followed a highly volatile path during the same period, being lifted and then re-imposed several times. During the first half of 2019, trade negotiations between the U.S. and China started with the goal of reaching a deal. These trade talks advanced quickly and were about to culminate in an agreement, but on the eve of signing the agreement in May 2019, the talks collapsed and the trade war resumed in full force. These events point towards a very high probability of resolution of the trade war and a decrease in tariff before May 2019, in a way that is consistent with γ close to $1/2$.

1.5.4 Variation in the size of tariff increase and in uncertainty

Next, we explore whether changes in the expected level of the tariff affect the pass-through rate. For a given level of $\mathbb{E}\tau$, an increase in γ is a mean-preserving spread, since the transition matrix is symmetric. Thus the unconditional mean of tariff remains the same when γ changes. In a subsequent section, we show that an alternative specification which ensures that the conditional mean of tariff is held constant when γ increases yields similar results. To show the effect of different values of τ^H, which determine the unconditional mean of tariff $\mathbb{E}\tau$, we solve the model separately for each combination of τ^H and γ. For each combination, we use the same 1,000 simulated economies as in the baseline case. In each economy we estimate the pass-through regression 1.5.1.

Figure 1.10(a) presents the tariff pass-through estimator on impact, β_0^τ. That is, during the same period of the tariff and TPU increase. Figure 1.10(b) presents the cumulative tariff pass-through over one year, $\sum_{l=0}^{11} \beta_l^\tau$. When the tariff increases from 0% to τ^H and the change is perceived to be permanent ($\gamma = 0$), pass-through on impact into the import price decreases with the level of τ^H, from 80.7% when $\tau^H = 1\%$ to 70.9% when $\tau^H = 20\%$. The larger is the tariff increase, the more likely it is to trigger an adjustment of the border price immediately, which leads to lower pass-through into the import price on impact. After one year, however, the effect is opposite, where tariff pass-through increases with the size of τ^H, from 54.2% when $\tau^H = 1\%$ to 61.9% when $\tau^H = 20\%$. There are two reasons for this pattern. First, pricing complementarities play an important role. When the tariff increase is small, the effect on the sectoral price level is very small and domestic firms barely react to the increase. This puts pressure on foreign exporters to absorb more the of (small) tariff increase in their border price. When the tariff increase is larger, there is a more pronounced increase in the sectoral price index. This incentivizes domestic producers to increase their untaxed prices. As a result, foreign exporters actually face less pressure to reduce their border price. Second, with the Kimball demand structure, firms have a "choke price". They can choose to set the border price at a level that leads to 0 demand and 0 profits, rather than set the border price at a lower level which would lead to positive demand but negative profits. The number of firms who choose to "opt out" of selling a positive quantity increases with the size of the tariff increase, where fewer firms find it optimal to reset an increasingly lower border price. As a result, pass-through into the tariff-inclusive import price rises with τ^H. The latter is of lesser quantitative importance, as removing firms with zero quantity from the regression does not change the results dramatically.

This pattern diminishes as γ increases. When uncertainty is fairly low but the tariff is perceived to be transitory ($\gamma = 0.01$), the pass-through rate on impact and after one year is close to its level when $\gamma = 0$. But the more γ increases, a different pattern emerges. For all values of τ^H, an increase in γ increases tariff pass-trough–both on impact and over one year. When $\gamma = 0.1$, the decrease in pass-through rate on impact as τ^H increases is clear (from 86.3% when $\tau^H = 1\%$ to 77.7% when $\tau^H = 20\%$). But after one year instead of an increase in pass-through rate with the level of τ^H, there is now overall a stability of the pass-through rate across levels of τ^H, albeit with a slight decline (from 68.6% when $\tau^H = 1\%$ to 66.4% when $\tau^H = 20\%$). This pattern is even more pronounced when γ increases to higher levels. When $\gamma = 0.5$, there is a very slight decline with τ^H on impact (from 93.5% when $\tau^H = 1\%$ to 91.2% when $\tau^H = 20\%$), and over one year (from 84.4% when $\tau^H = 1\%$ to 80.7% when $\tau^H = 20\%$). The effect of the increase in TPU and the high γ leads to higher border prices. The combined effect of both the "wait-and-see" motive and the precautionary markup motive is strong across all levels of τ^H for a given large γ, and leads to roughly the same pass-through rate at all levels. At every given level of τ^H, however, the increase in tariff pass-through with γ is clear and pronounced.

1.5.5 Alternative tariff process specification

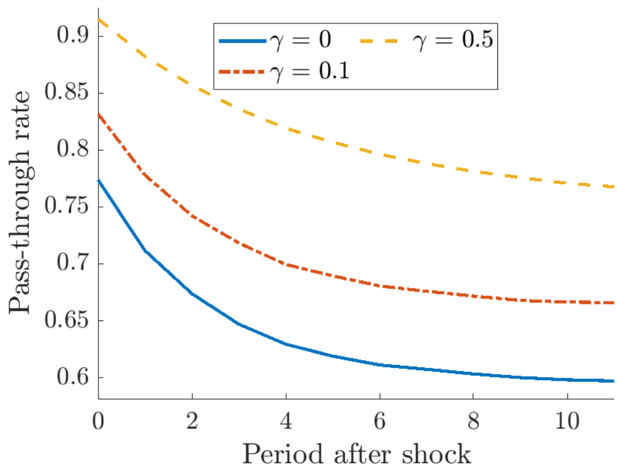
The tariff process and TPU formulation presented in Section 1.3.2 follow the conventional setup of TPU in the literature. It maintains a constant unconditional expected value of tariff, $\mathbb{E}\tau$, as γ changes (and therefore, as $Var\left(\tau_t - \mathbb{E}_{t-1}\tau_t\right)$ changes). A potential issue with this setup is that the conditional mean of tariff, $\mathbb{E}\left[\tau_{t+1}|\tau_t\right]$, changes when γ changes - even as the unconditional mean remains constant. This might mean that results are driven by a conditional expected mean effect rather than the increase in uncertainty.

To address this concern, we alter the tariff process in the following way. We keep $\tau^L = 0$ as before, but instead of a symmetric transition matrix as in (1.3.17), we allow the low state to be absorbing. That is, the transition matrix is now

$$\Lambda^*\left(\gamma\right) = \begin{bmatrix} 1 & 0 \\ \gamma & 1-\gamma \end{bmatrix} \tag{1.5.2}$$

such that the firm perceives a switch from τ^L to τ^H as an unexpected regime change. If $\gamma > 0$, the

Figure 1.11: Tariff pass-through into the tariff-inclusive import price estimation, $\sum_{l=0}^{11} \hat{\beta}_l^{\tau}$, in the simulated model with alternative tariff process



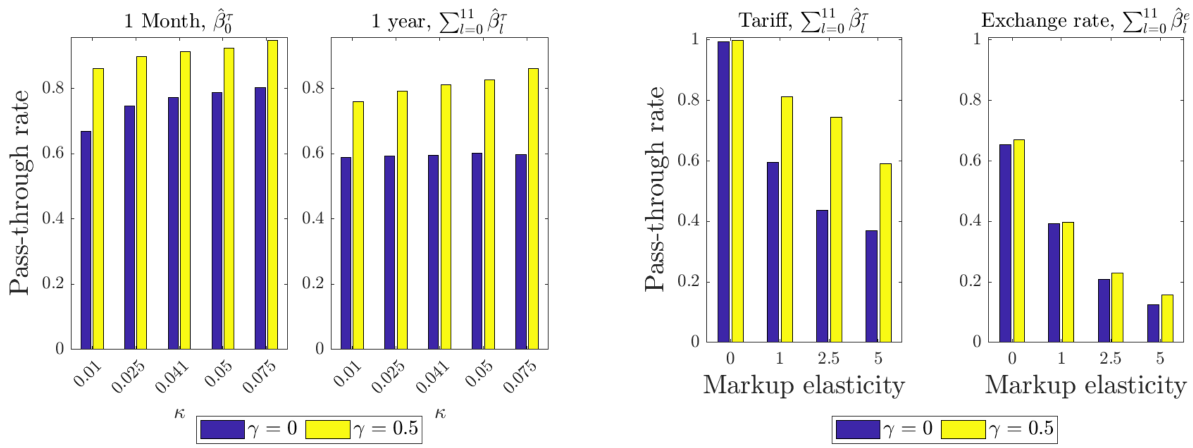
Note: Estimation of regression equation (1.5.1) in the simulated data with the alternative tariff process presented in Section 1.5.5.

firm expects the tariff to revert back to the low state in the future, and when it does the firm expects the tariff to remain low indefinitely. This setup is based on the process in Handley & Limão (2017). With this process, the unconditional mean of tariff is always $\mathbb{E}\tau = 0$, and the conditional mean, upon observing τ^H today, is $\mathbb{E}\left[\tau_{t+1}|\tau_t = \tau^H\right] = (1-\gamma)\,\tau^H$. We choose γ and τ^H jointly to keep the unconditional mean at 10%.[49] The conditional variance, $Var\left(\tau_{t+1}|\tau_t = \tau^H\right) = (1-\gamma)\left(\tau^H\right)^2$, increases with γ. Therefore, any effect that an increase in γ has in this setup is due to a pure risk effect since there is no expected mean effect (conditional or unconditional).

Figure 1.11 presents the estimation results of tariff pass-through into import prices in the simulated data with the alternative tariff process. Keeping the conditional expected level of tariff constant does not change the results in a meaningful way. An increase in γ still increases tariff pass-through substantially. Tariff pass-through after one year increases from 59.7% when $\gamma = 0$ to 66.6% when $\gamma = 0.1$, and 76.8% when $\gamma = 0.5$.

[49]For example, when $\gamma = 0.1$ the tariff increase that keeps the unconditional mean at 10% is $\tau^H = 11.1\%$.

Figure 1.12: Tariff pass-through into the tariff-inclusive import price estimation in the simulated model: variation in price adjustment cost and in strength of price complementarities



(A) Price adjustment cost, κ

(B) Price complementarities, ε

Note: Estimation of regression equation (1.5.1) in the simulated data. Panel (a): selected levels of κ (in the baseline model $\kappa = 0.041$); panel (b): selected levels of $\varepsilon \in \{0, 4, 10, 20\}$ that correspond to markup elasticity level $\Gamma \in \{0, 1, 2.5, 5\}$ (in the baseline model $\varepsilon = 4$).

1.5.6 The role of costly price adjustment and price complementarities

Two key elements in the model capture important characteristics of price setting considerations of exporters. The fixed price adjustment cost, κ, makes the price setting problem a dynamic one. Firm's expectations about future realizations of shocks and their persistence matter for current price setting decisions. The superelasticity parameter, ε, determines how much the price elasticity of demand for the firm's variety is affected by the firm's tariff-inclusive relative price. It therefore captures how variable markups are, and as a result how strong pricing complementarities are. In this subsection we explore how these parameters affect the results.

Variation in price adjustment cost κ We solve the model and estimate the pass-through regression with different levels of $\kappa \in \{0.01, 0.025, 0.041, 0.05, 0.075\}$. First, an increase in κ intuitively affects the extensive margin of price adjustment since it makes price adjustment more costly. This is apparent in the left panel of Figure 1.12(a), where immediately after a tariff increase, tariff pass-through into the import price rises with κ as the frequency of price adjustment decreases. Second, an increase in κ also has an effect on the intensive margin of price adjustment since it affects the optimal reset border price (conditional on price adjustment). This is shown in the one year cumulative tariff pass-through in the right panel of Figure 1.12(a). In line with the analysis of policy functions with different levels of κ in Section 1.4, when $\gamma = 0$ there is no effect of the value of κ on the optimal reset border price. Tariff pass-through after one year remains stable around 59% even as κ increases. This is intuitive, since if there is no uncertainty about the tariff then the price setting problem with respect to the tariff is in fact static. Conversely, when $\gamma > 0$ then an increase in κ increases the optimal reset border price due to precautionary markup. The greater is κ, the more costly it is to adjust the price, and thus firms would like to avoid making multiple costly price adjustments by setting a higher border price today in anticipation of a decrease in tariff in the future.

Variation in strength of price complementarities ε Next, we solve the model for different levels of $\varepsilon \in \{0, 4, 10, 20\}$. These values correspond to stochastic steady state price elasticity of the markup $\Gamma \in \{0, 1, 2.5, 5\}$, where the case of $\Gamma = 0$ is CES. Figure 1.12(b) shows estimation results of tariff and exchange rate pass-through over one year in the simulated data. Changes in the price elasticity of the markup do not affect the extensive margin, but they do affect the intensive margin of price adjustment. As mentioned above, with CES demand there are no price complementarities since the price elasticity of demand is unaffected by changes in the relative price of the firms. In this case, an increase in tariff has no effect on the constant markup that a firm charges and tariff pass-through into the import price is nearly complete, very close to 100%. However, as discussed before, exchange rate pass-through is counterfactually high at 65%. For the other levels of positive markup elasticity, there is a large effect of TPU on tariff pass-through and very small effect on exchange rate pass-through (if at all). When Γ increases, price complementarities strengthen. The size of the decrease in the border price in response to a tariff increase is greater as the firm tries to keep its price closer to the sectoral price level. As a result, tariff pass-through into the import price decreases with Γ. The effect of an increase in TPU from $\gamma = 0$ to $\gamma = 0.5$ on tariff pass-through is sizable in all cases of $\Gamma > 0$: an increase of 21.6 percentage points when $\Gamma = 1$, 30.8 percentage points when $\Gamma = 2.5$, and 22.2 percentage points when $\Gamma = 5$. The effect of an increase in γ on exchange rate pass-through remains very small in all cases. This result is quite interesting, as it demonstrates that the marginal profit function remains convex in tariff even for large values of ε, and therefore there is a precautionary markup motive for exporters over a wide range of parameterizations of the Kimball aggregator. This is an important result, since Gopinath & Itskhoki (2010) and Amiti et al. (2022) show that exporters differ in their markup variability. This plays an important role in rationalizing observable patterns of exchange rate pass-through and of currency of invoicing choice in international trade. We demonstrate here that even as exporters differ in the strength of pricing complementarities, the effect of TPU on their price setting decision is the same.

1.5.7 Tariff on imported intermediate inputs and retaliation

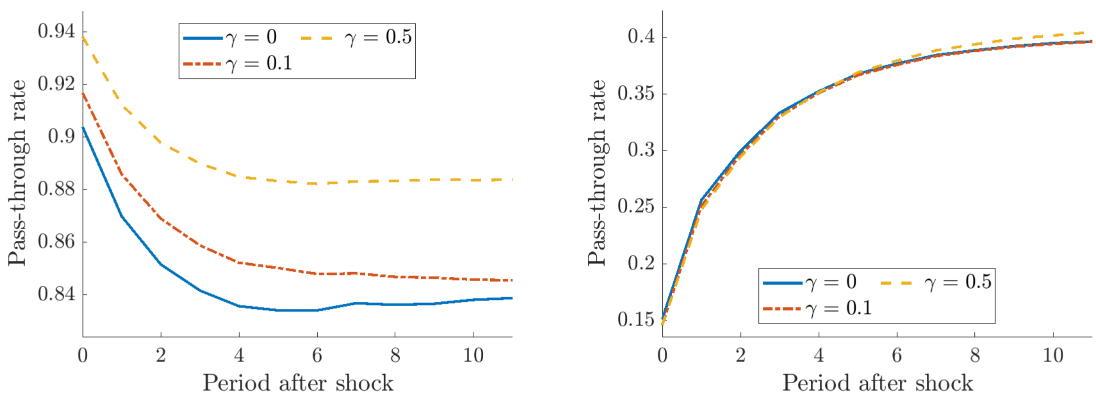
The tariff considered so far is imposed on final goods purchased by Home importers. However, the early waves of the 2018-2019 tariffs were imposed mostly on imported intermediate inputs before subsequent waves expanded the tariffs to final goods. Furthermore, China imposed retaliatory tariffs on U.S. imports in each wave. Tariffs on imported inputs are different from tariffs imposed on final goods since they increase a firm's cost of production rather than the output price paid by the consumer. We now address this type of tariffs.

In the short-run, it is costly and difficult to change the mix of inputs used in production by the firm. Thus, when a tariff is imposed on imported inputs, a firm cannot necessarily switch to domestic or third country inputs instead (Handley et al. 2020). For this reason, we introduce tariffs on imported inputs in a rather simplistic way: The same tariff τ_t is now imposed not only on imported final varieties, but also on the intermediate input X_t^* used by Home firms. In retaliation, the Foreign country imposes a similar size tariff, $\tau_t^* = \tau$, on Home inputs used by Foreign producers, X_t. This setup is in line with the findings of Flaaen & Pierce (2019) who find that the 2018-2019 U.S. tariffs increased the cost of imported inputs for American firms, which led to an increase in producer prices. As a result, the marginal cost of Home and Foreign producers is now

$$MC^*_{\omega,t} = \tilde{\phi}^* e^{-a^*_{\omega,t}} \left(\left(1+\tau_t\right)/\mathcal{E}_t\right)^{\phi^*} \tag{1.5.3}$$

$$MC_{\omega,t} = \tilde{\phi} e^{-a_{\omega,t}} \left(1+\tau_t\right)^{\phi} \tag{1.5.4}$$

Figure 1.13: Tariff and exchange rate pass-through into the tariff-inclusive import price estimation in the simulated model: tariff on final goods, imported inputs, and retaliatory tariff



(A) Tariff pass-through estimation, $\sum_{l=0}^{11} \hat{\beta}_l^{\tau}$ (B) Exchange rate pass-through estimation, $\sum_{l=0}^{11} \hat{\beta}_l^{e}$

Note: Estimation of regression equation (1.5.1) in the simulated data with tariffs on final goods, imported inputs, and retaliatory tariff.

The increase in tariff on both final goods and imported inputs affects prices through different channels. First, the import price of Foreign varieties increases as it did before. However, now the marginal cost of both Foreign and Home producers increases as well, by approximately $\phi\tau$. In the case of a 10% tariff increase, this is roughly an increase of 2.5%. Foreign exporters now face competing pressures on their reset border price. On the one hand, the relative import price increases because of the final good tariff, which pushes exporters to decrease their border price. On the other hand, the marginal cost increases (albeit by a lower amount since only a small share of inputs are imported), which pushes exporters to raise the border price. At the same time, Home producers now face an increase in their marginal cost, which pushes them to raise their prices. This elevates some of the price complementarity pressure on Foreign exporters to reduce their border prices. As we show next, the overall effect is a smaller decrease in the border price, relative to the case of tariff imposed on the final good alone. This leads to even higher tariff pass-through.

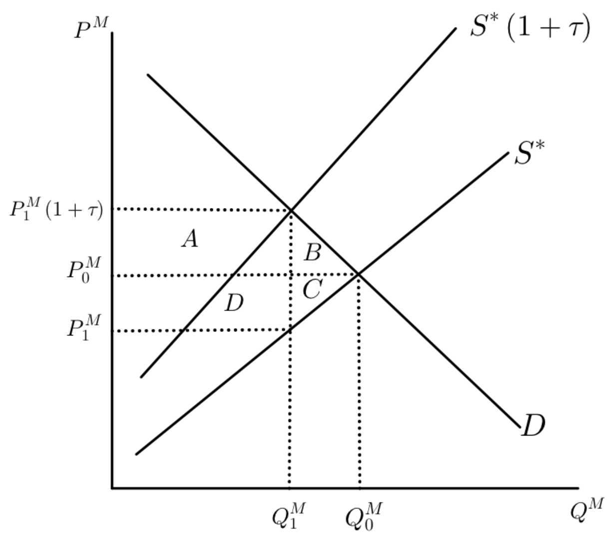
Figure 1.13 presents pass-through estimation results from the simulated model. The 10% tariff increase now affects final imported varieties, and imported inputs. Additionally, there is a parallel retaliatory tariff on imported inputs used by Foreign exporters. Panel (a) presents cumulative tariff pass-through estimates through one year after the tariff increase. In all cases, tariff pass-through into the import price is higher relative to the baseline case. The effect of TPU is clear and present when a tariff is imposed on imported inputs as well. However, the size of the increase in tariff pass-through that results from an increase in TPU is smaller, since the rate of tariff pass-through when there is no uncertainty is quite high to begin with. Immediately after the tariff increase, tariff pass-through into the import price is 90.4% when $\gamma = 0$, and when TPU is present this rate increases to 91.7% and 93.8% (for $\gamma = 0.1$ and $\gamma = 0.5$, respectively). After one year, tariff pass-through is 83.8% when $\gamma = 0$, 84.5% when $\gamma = 0.1$, and 88.4% when $\gamma = 0.5$. Panel (b) shows that exchange rate pass-through is unaffected by changes in TPU, and remains around 39% after one year in all cases.

To understand why an increase in TPU has a smaller effect on tariff pass-through in this case, we have to take into account how TPU affects Home producers' prices when there is a tariff on imported inputs. Tariff pass-through into Home producers' prices decreases with TPU due to the same mechanism described earlier. Home producers are more hesitant to adjust the price when TPU is present because price adjustment is costly. When they do reset, they take future profits into account, and the probability that the tariff will go back to its low level and their marginal cost will decrease. As a result, tariff pass-through into the Home producers' prices decreases from 30.6% when $\gamma = 0$ to 21.1% when $\gamma = 0.5$. Therefore, with a tariff on imported inputs the pressure on Foreign exporters' to decrease the border price is greater when TPU is present. This counteracting force is not enough, however, to offset the other channels in which TPU pushes exporters to curb their border price decrease. The overall result is that tariff pass-through increases with TPU.

1.6 Policy implications

In the last part of the paper, we conduct a simple exercise to gauge the effect of TPU on deadweight loss created by a tariff increase. In the canonical framework for analyzing the effects of tariffs on welfare in a large economy, when a country is large enough to affect the world price then the foreign exporters should bear some of the tariff incidence due to a terms of trade effect. A deadweight loss is still created by the imposition of the tariff in this framework. We use this partial equilibrium framework to illustrate the effect of a tariff increase accompanied by an increase in TPU

Figure 1.14: Stylized market for Foreign imports in the Home country with a tariff increase



on the size of the deadweight loss. It should be stressed that this is not a welfare analysis (which requires a general equilibrium framework), but rather an illustration of the effect that TPU could have on deadweight loss.

Consider the basic aggregate demand and supply for Foreign imports in the Home country. Figure 1.14 presents such a market, with the aggregate quantity of Foreign imports on the horizontal axis, and the sectoral aggregate price index on the vertical axis. D is the demand curve for Home importers of the Foreign good, and S^* is the aggregate supply curve of Foreign exporters.[50] An increase of the tariff by τ decreases the quantity of imports from Q_0^M to Q_1^M, raises the import price from P_0^M to $P_1^M (1+\tau)$, and decreases the border price from P_0^M to P_1^M. As a result, the Home government raises revenue equal to the area $A+D$, and a deadweight loss equal to the area $B+C$ is created. If a terms of trade effect occurs, the area D represents the tariff incidence borne by exporters and transferred to the Home government.

We follow Amiti, Redding & Weinstein (2019) in using this basic framework to sketch the effect of TPU on the deadweight loss created by the tariff. While this is a "back of the envelope" exercise, Amiti, Redding & Weinstein (2019) show that their empirical estimates of the deadweight loss using

[50]For the following analysis of the deadweight loss, it is not crucial if the supply curve is more elastic or upward sloping.

Table 1.3: Deadweight loss, tariff revenue, and tariff incidence in units of consumption of the Home country

	$\gamma = 0$	$\gamma = 0.1$	$\gamma = 0.5$
Deadweight loss	2.66	3.24	4.02
Government revenue	24.73	24.39	23.77
Tariff incidence - importers	14.50	16.64	18.96
Tariff incidence - exporters	10.23	7.75	4.80

Note: Measures of deadweight loss, government revenue, and tariff incidence from an increase of 10% in tariff on imported varieties in the simulated model under three level of TPU from 1,000 simulated economies. The sectoral import price index and the aggregate quantities after the tariff increase are calculated one year after the shock, relative to the last period before the shock. See the text for further details.

this framework are quite close to the welfare loss estimates derived in Fajgelbaum et al. (2020) using a general equilibrium structural model. In the simulated data, we calculate the quantities associated with Q_0^M and Q_1^M, and the sectoral border price index associated with P_0^M and P_1^M.[51] Table 1.3 presents the value of the deadweight loss, total government revenue, and importer and exporter tariff incidence associated with a tariff increase from 0% to 10%, in three different levels of TPU: $\gamma \in \{0, 0.1, 0.5\}$. The values are given in units of consumption in the Home country. An increase in TPU from $\gamma = 0$ to $\gamma = 0.5$ increases the deadweight lost approximately by 51%, while the government revenue remains unchanged. The increase in TPU shifts much more of the tariff incidence to the Home importers than to the Foreign exporters. While the model presented in this paper is not equipped for deep welfare analysis, these preliminary results point towards a potentially important welfare effect of TPU. A tariff increase that is perceived to be a permanent policy change could be associated with a smaller deadweight loss than a similar tariff increase that is perceived to be transitory. This result is in line with previous findings about the adverse welfare consequences policy uncertainty. It is possible that optimal trade policy should take uncertainty into account and consider a form of trade policy forward guidance.

[51]We take period "1" to be one year after the tariff increase, and period "0" to be the last period before the tariff increase. Thus, in period "1" almost all of the price adjustment to the tariff has already occurred.

1.7 Conclusion

In this paper, we incorporate tariffs and trade policy uncertainty (TPU) into a workhorse model of exporting to the U.S. with price rigidities and variable markups. Variable markups are an important channel for explaining low and incomplete exchange rate pass-through into U.S. import prices. At the same time, variable markups also lead to incomplete pass-through of a one-time permanent tariff change into tariff-inclusive import prices, which is at odds with the complete tariff pass-through estimated for the 2018-2019 U.S. tariffs on China. We show that TPU, which was extremely high in 2018-2019, increases tariff pass-through into import prices significantly, even with variable markups.

The effect of TPU on the exporters' tariff-exclusive border price setting decision, and thus pass-through, occurs via two channels. On the extensive margin of price adjustment, an increase in TPU makes costly border price adjustments less likely ("wait-and-see" effect), which increases tariff pass-through into tariff-inclusive import prices immediately after a tariff increase. On the intensive margin, when the exporter chooses to adjust the border price in response to a tariff hike, TPU decreases the size of the border price reduction, due to a precautionary markup motive. The intensive margin effect leads to higher tariff pass-through into the import price even in the medium-run, once the border price is reset.

Quantitatively, TPU increases tariff pass-through into U.S. import prices significantly from 59% up to 81%, without affecting exchange rate pass-through which remains below 40%. Thus, high TPU can explain up to half of the gap between the observed tariff pass-through rate during the trade war and the prediction of the standard model without TPU. Additionally, TPU increases tariff deadweight loss and the tariff incidence on U.S. importers resulting from a tariff increase over one year.

The effect of TPU on exporters' price setting decisions in the short- and medium-run is an important area for future research, as the experience of the U.S.-China 2018-2019 trade war has demonstrated. This paper gives rise to several testable hypotheses. Testing these hypotheses empirically is an important next step. Furthermore, understanding the effect of TPU on import prices is not only crucial for the design of trade policy and the assessment of its welfare effects, but it could also be informative for monetary policy makers. TPU appears to increase price rigidity, and affect import prices even in the medium-run. Therefore, TPU could potentially enhance and affect monetary non-neutralities, in addition to its effect on import price inflation.

Chapter 1 Appendices

1.A Model Solution and Computational Details

The model has no analytical solution, therefore we use numerical methods. For a given sectoral price level, the firm's value functions and policy functions can be found via a standard method of value function iteration. However, the sectoral price level is endogenous and affected by the price setting decision of each firm, which is determined by both an idiosyncratic stochastic process and by aggregate stochastic processes. To find the firm's forecasting rules for the sectoral price level, we use the method introduced by Krusell & Smith (1998).

The firm's problem is solving the following system of Bellman equations:

$$V\left(\mathbf{S}_t, \mathbf{s}\right) = \max\left\{V^A\left(P_{\omega,t}; \mathbf{S}_t, \mathbf{s}\right) - \kappa, V^N\left(\mathbf{S}_t, \mathbf{s}\right)\right\}$$

$$V^N\left(\mathbf{S}_t, \mathbf{s}\right) = \Pi_t\left(P_{\omega,t-1}; \mathbf{S}_t, \mathbf{s}\right) + \beta\mathbb{E}\left[V\left(\mathbf{S}_{t+1}, \mathbf{s}\right)|\mathbf{S}_t\right]$$

$$V^A\left(P_{\omega,t}; \mathbf{S}_t, \mathbf{s}\right) = \max_{P_{\omega,t}}\left\{\Pi_t\left(P_{\omega,t}; \mathbf{S}_t, \mathbf{s}\right) + \beta\mathbb{E}\left[V\left(\mathbf{S}_{t+1}, \mathbf{s}\right)|\mathbf{S}_t\right]\right\}$$

where $\mathbf{S}_t = (P_{\omega,t-1}, a_{\omega,t}, P_t, e_t, \tau_t)$ is a vector of state variables and $\mathbf{s} = (\sigma, \varepsilon, \phi^*, \kappa, \beta, \gamma)$ is a vector of parameters.

We use grid search and iteration methods to solve the value function, where the grid size is $N_{P_\omega} \times N_P \times N_a \times N_e \times N_\tau$. For the firm's price, we set the grid points to be no more than 0.005 log points apart (this implies that $N_{P_\omega} = 187$), and for the sectoral price level we set the grid points to be no more than 0.002 log points apart (which implies $N_P = 51$). The boundaries are set based on the static analytical solution for the optimal border price with maximum values of the shocks. We discretize the idiosyncratic productivity process a_ω using the Tauchen method with $N_a = 11$ grid points. For the exchange rate process e, since the dollar exchange rate follows a highly volatile and persistent process close to a random walk, we discretize the process by letting the exchange rate jump one standard deviation up or down with probability 0.5 every period (a month), in a band of $\pm 7\sigma_e$, as detailed in Gopinath & Itskhoki (2010). The tariff process τ and its transition matrix Λ are constructed as detailed in the main text.

The value function iteration algorithm is as follows:

1. Find static profits for all points on grid of price, state variables, given parameters:

$$\Pi_t^{(i)} = \Pi\left(P_{\omega,t}^{(i_{P\omega})}, a_{\omega,t}^{(i_a)}, P_t^{(i_P)}, e_t^{(i_e)}, \tau_t^{(i_\tau)}; \mathbf{s}\right) \tag{1.A.1}$$

2. This is the initial guess for V^N:

$$V_t^{N(0)} = \frac{1}{1-\beta}\Pi_t \tag{1.A.2}$$

3. Find maximum static discounted profits and the optimal price:

$$\hat{P}_\omega^{(i_{P\omega})}\left(a_{\omega,t}^{(i_a)}, P_t^{(i_P)}, e_t^{(i_e)}, \tau_t^{(i_\tau)}; \mathbf{s}\right) = \arg\max_{i_{P\omega}} \frac{1}{1-\beta}\Pi\left(P_{\omega,t}^{(i_{P\omega})}, a_{\omega,t}^{(i_a)}, P_t^{(i_P)}, e_t^{(i_e)}, \tau_t^{(i_\tau)}; \mathbf{s}\right) \tag{1.A.3}$$

   and use this optimal flexible price to compute the value with adjustment, V^A:

$$V_t^{A(0)} = \frac{1}{1-\beta}\Pi\left(\hat{P}_{\omega,t}\right) \tag{1.A.4}$$

4. Initial guess for V: $V_t^{(0)} = \max\left\{V_t^{A(0)} - \kappa, V_t^{N(0)}\right\}$.

5. While $\sup \|V^{(n)}(\mathbf{S}_t, \mathbf{s}) - V^{(n-1)}(\mathbf{S}_t, \mathbf{s})\| > \epsilon$

   (a) Update expected value function, using given forecasting rule $P_{t+1} = f(P_t, e_t, \tau_t; \mathbf{s})$:

$$\mathbb{E}\left[V_t^{(n)}(\mathbf{S}_t, \mathbf{s})|\mathbf{S}_{t-1}\right] = \sum_{i_P, i_a, i_e, i_\tau} \pi_a(i_a|j_a)\,\pi_e(i_e|j_e)\,\pi_\tau(i_\tau|j_\tau) \times$$
$$V_t^{(n-1)}\left(f\left(P^{i_P}, e^{j_e}, \tau^{j_\tau}; \mathbf{s}\right), \mathbf{S}_t, \mathbf{s}\right)$$

   (b) This gives the optimal value without adjustment:

$$V_t^{N(n)}(\mathbf{S}_t, \mathbf{s}) = \Pi_t\left(\hat{P}_{\omega,t-1}\right) + \beta\mathbb{E}\left[V^{(n)}(\mathbf{S}_{t+1}, \mathbf{s})|\mathbf{S}_t\right] \tag{1.A.5}$$

(c) Find optimal reset price:

$$\overline{P}_{\omega,t}^{(n)} = \arg\max_{P_{\omega,t}} \left\{ \Pi_t \left(P_{\omega,t}; \mathbf{S}_t, \mathbf{s} \right) + \beta \mathbb{E} \left[V^{(n)} \left(\mathbf{S}_{t+1}, \mathbf{s} \right) | \mathbf{S}_t \right] \right\} \tag{1.A.6}$$

which gives the maximum value with adjustment:

$$V^{A(n)} \left(\overline{P}_{\omega,t}^{(n)}; \mathbf{S}_t, \mathbf{s} \right) = \Pi_t \left(\overline{P}_{\omega,t}^{(n)}; \mathbf{S}_t, \mathbf{s} \right) + \beta \mathbb{E} \left[V^{(n)} \left(\mathbf{S}_{t+1}, \mathbf{s} \right) | \mathbf{S}_t \right] \tag{1.A.7}$$

(d) Find optimal price updating indicator:

$$\mathbb{I}^{(n)} \left(\mathbf{S}_t, \mathbf{s} \right) = \mathbf{1} \left\{ V^{A(n)} \left(\overline{P}_{\omega,t}^{(n)}; \mathbf{S}_t, \mathbf{s} \right) - \kappa > V_t^{N(n)} \left(\mathbf{S}_t, \mathbf{s} \right) \right\} \tag{1.A.8}$$

(e) Find policy function:

$$P_{\omega,t}^{(n)} = \mathbb{I}^{(n)} \left(\mathbf{S}_t, \mathbf{s} \right) \overline{P}_{\omega,t}^{(n)} + \left(1 - \mathbb{I}^{(n)} \left(\mathbf{S}_t, \mathbf{s} \right) \right) \hat{P}_{\omega,t-1} \tag{1.A.9}$$

This constitutes the first step of the model solution. Once policy functions are obtained, we use them to execute the Krusell & Smith (1998) method to find the forecasting rule $f\left(P_t, e_t, \tau_t; \mathbf{s}\right)$. Following the literature, we use a linear forecasting rule. We verify that adding higher order terms and lags does not add any meaningful explanatory power, which is evident in the linear regression's $R^2 = 0.999$. The algorithm to find the forecasting rule is as follows:

1. Start with a guess for the forecasting rules $\delta^{(0;\mathbf{s})} = \left(\delta_0^{(0;\mathbf{s})}, \delta_1^{(0;\mathbf{s})}, \delta_2^{(0;\mathbf{s})}, \delta_3^{(0;\mathbf{s})} \right)$ used by firms:

$$\mathbb{E}_{t-1} \ln P_t = \delta_0^{(0;\mathbf{s})} + \delta_1^{(0;\mathbf{s})} \ln P_{t-1} + \delta_2^{(0;\mathbf{s})} e_{t-1} + \delta_3^{(0;\mathbf{s})} \tau_{t-1} + \epsilon_{t-1} \tag{1.A.10}$$

   Thus, we have N_γ forecasting rules for each possible state of current uncertainty level, because this level affects the formation of the aggregate price level. This follows Bloom et al. (2018) in their solution method.

2. Given $\delta^{(0;\mathbf{s})}$, find value and policy functions as detailed above.

3. Use value function and policy function to simulate B panels of N firms over T periods.

4. For each $i_B = 1 \dots B$ estimate (1.A.10). Find the median estimators and update: $\delta^{(n;\mathbf{s})} = \left(\delta_0^{(n;\mathbf{s})}, \delta_1^{(n;\mathbf{s})}, \delta_2^{(n;\mathbf{s})}, \delta_3^{(n;\mathbf{s})}\right)$.

5. Calculate a measure of convergence Δ (we use χ-statistic). If $\Delta < \epsilon$, stop. Otherwise, use $\delta^{(n;\mathbf{s})}$ and repeat steps 2-5.

6. Once converged, use the new forecasting rule $\delta^{(\infty;\mathbf{s})}$ to find value and policy functions.

To compute impulse response function while taking non-linearities into account, we use the following standard algorithm.[52] Let $\omega = 1, \dots, \Omega$ denote heterogenous firms in an economy, let $n = 1, \dots, N$ denote an economy, and let $t = 1, \dots, T$ denote a period in an economy. For each economy n, we simulate a panel of Ω idiosyncratic productivity shocks $\{a_{\omega,t}\}$, an aggregate real exchange rate process $\mathcal{E}_t$, for T periods. For each economy n, the tariff rate is $\tau_t = \tau^L$ and there is no TPU, $\gamma = 0$, for $t < \bar{t}$. Then, consider two cases. First, there is no tariff and TPU shock at period $\bar{t}$, so the economy continues with $\tau_t = \tau^L$ and $\gamma = 0$ for $t \geq \bar{t}$. Denote this first case by τ_t^0. Second, there is a tariff increase and also TPU increase at period $\bar{t}$ so that $\tau_t = \tau^H$ and $\gamma \geq 0$. Denote this second case by τ_t^1. The rest of the shocks $(a_{\omega,t}, \mathcal{E}_t)$ are identical in both cases.

The impulse response of variable Z_t (import price, quantity, etc.) for a tariff increase together with a TPU increase over horizon L is denoted $\hat{z}_t$. It is computed by aggregating the log of Z_t over all relevant firms (exporters, domestic producers, all firms) and averaging over simulations for τ_t^1 and comparing this log variable to the one with τ_t^0. Formally,

$$\hat{z}_t = \frac{\sum_{n=1}^{N} \sum_{\omega=1}^{\Omega} \log Z_l\left(\tau_l^1\right)}{\sum_{n=1}^{N} \sum_{\omega=1}^{\Omega} \log Z_l\left(\tau_l^0\right)}; \text{for } l = \bar{t}, \dots \bar{t} + L \tag{1.A.11}$$

We use $\Omega = 1,440$, $M = 1,000$, $T = 240$, and $L = 24$, with $\bar{t} = 145$.

[52] This procedure is widely used in model with uncertainty shocks, see Gilchrist et al. (2014) and Bloom et al. (2018).

1.B A Static Model of Price Setting Under TPU: Precautionary Markups

In this appendix, we present a simple static model of a competitive monopolist exporter constrained to set its border price before observing the realization of shocks. The model illustrates the effect of tariff uncertainty on a preset (completely sticky) price. This exercise build on Kimball (1989), who showed that when a monopolist must set the price in advance, an increase in demand uncertainty could lead to precautionary markup and a higher price if the marginal profit is convex in the demand shifter.[53]

Convex marginal profit means that the price-setting firm faces the following problem. The price is set today, but the realization of demand next period is unknown. On the one hand, if the price is set too low today, next period the firm must supply more units of its product at a "too low" price, which is not optimal. On the other hand, if the price is set "too high", demand next period would be sub-optimally low. The convexity means that the high price, which compensates for the low demand, leads to smaller losses than the low price, which leads to undesirably high production. This tradeoff arises from price complementarities induced by the demand structure, so that the optimal price is not just a constant markup above marginal cost but also depends on the price of competitors. We show that pricing complementarities and variable markups are necessary for the effect described above, which does not arise in the case of constant elasticity of substation (CES) demand.

Simple stylized model of exporting Consider a Foreign exporter producing a differentiated variety which it sells in the Home country.[54] The exporter takes all aggregate variables as given, and must set its relative border price, P, in advance and exclusive of tariff. All prices are denoted in the Home country's unit of account.

[53] A similar argument has been made by Fernández-Villaverde et al. (2015), Oh (2020), and Born & Pfeifer (2021) about various sources of uncertainty in a general equilibrium framework.

[54] The following setup is based on a standard market structure in international trade (e.g., Gopinath & Itskhoki (2010)).

Demand Q for the firm's variety is given by

$$Q = \psi(\tau P) \tag{1.B.1}$$

where the demand function $\psi(\cdot)$ is continuously differentiable, $\psi'(\cdot) < 0$, $\psi(1) = 1$, and τ is gross ad-valorem tariff which is drawn from some probability distribution with mean $\overline{\tau}$ and variance σ_τ^2.

The firm produces using a constant returns to scale technology. Its marginal cost, $\mathcal{MC}$, is constant in quantity. Assume for simplicity that $\mathcal{MC} = \frac{\sigma-1}{\sigma}$, where $\sigma > 1$ is a constant.

The firm's static profit is then

$$\Pi(P, \tau) = (P - \mathcal{MC})\,\psi(\tau P) \tag{1.B.2}$$

The firm's optimal preset border price solves the problem $\overline{P} = \arg\max_P \mathbb{E}\Pi(P, \tau)$, where the expectation is over the probability distribution of τ. Expected marginal profit is given by

$$\mathbb{E}\Pi_P(P, \tau) = \mathbb{E}\left\{\frac{\psi(\tau P)}{P}\left[(1 - \sigma(\tau P))\,P + \sigma(\tau P)\,\mathcal{MC}\right]\right\} \tag{1.B.3}$$

where $\sigma(\tau P) \equiv -\frac{\partial \log \psi(\tau P)}{\partial \log(\tau P)}$ is the price elasticity of demand. $\overline{P}$ satisfies the first order condition $\mathbb{E}\Pi_P\left(\overline{P}, \tau\right) = 0$.

Marginal profit Π_P is strictly convex in the tariff if its second derivative w.r.t. τ is positive, $\Pi_{P\tau\tau} > 0$. If Π_P is strictly convex, then from Jensen's inequality it follows that $\mathbb{E}\Pi_P(\tau P) > \Pi_P(\mathbb{E}\tau P)$. This leads to precautionary markup when facing a mean-preserving spread around $\mathbb{E}\tau$, and a higher preset border price. Whether Π_P is convex depends on the structure of demand and how it reacts to a change in the tariff.

To illustrate how uncertainty about τ affects the optimal preset price, we consider two cases: constant elasticity of substitution (CES, Dixit-Stieglitz) demand, and a general homothetic Kimball demand.

CES The CES demand function is given by $Q = P^{-\sigma}$, $\sigma > 1$. In this case $\sigma(\tau P) = \sigma, \forall \tau, P$. It is clear that $\overline{P}$ is independent of the expected value of τ, and

$$\overline{P}^{CES} = \frac{\sigma}{\sigma - 1}\mathcal{MC} = 1 \tag{1.B.4}$$

where the markup is constant and unaffected by the realization or the distribution of the tariff. The marginal profit is unaffected by τ, and $\Pi_{P\tau\tau} = 0$. A mean preserving spread around $\overline{\tau}$ would not affect $\overline{P}^{CES}$.

Kimball demand Next, consider the demand function that arises from Kimball (1995) homothetic general aggregator. Under this specification, $\sigma(\tau P)$ varies with both the tariff and the price, so a mean-preserving spread around $\overline{\tau}$ affects the optimal preset border price:

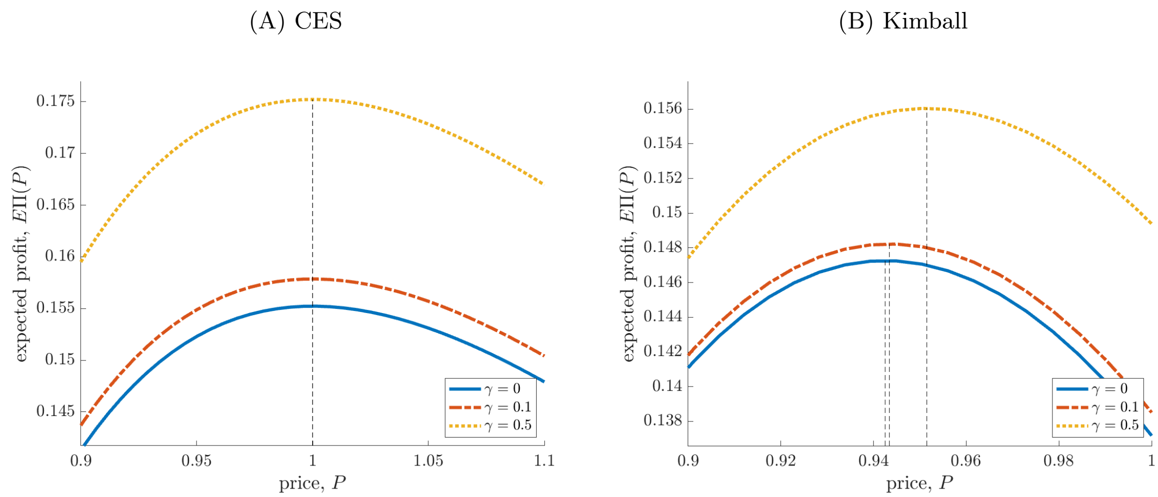
$$\mathbb{E}\left\{\frac{\psi\left(\tau\overline{P}^{KIM}\right)}{\overline{P}^{KIM}}\left[\left(1-\sigma\left(\tau\overline{P}^{KIM}\right)\right)\overline{P}^{KIM}+\sigma\left(\tau\overline{P}^{KIM}\right)\mathcal{MC}\right]\right\} = 0 \tag{1.B.5}$$

Since τ affects the relative border price that the consumer pays for the firm's variety, a mean-preserving spread would affect the optimal markup that the firm sets in advance. Generally, it is not guaranteed that Π_P with this demand structure is convex.[55] We use a numerical illustration of the effect of convex profit for simplicity. As will be clear throughout this paper, convexity of marginal profit in the tariff is the case with plausible parameterization of the Kimball aggregator.

Preset price and uncertainty We use the Klenow & Willis (2016) functional form for the Kimball aggregator, $\psi(\tau P) = [1 - \varepsilon \log(\tau P)]^{\sigma/\varepsilon}$. We set $\sigma = 5$ and $\varepsilon = 4$ so that the level of markup elasticity with $\tau = 1$ is unity. These parameter values are used as the baseline parameterization of the dynamic model. Figure 1.15 illustrates the effect of an increasing mean-preserving spread in tariff on the optimal preset price. The figure depicts three levels of expected profit, $\mathbb{E}\Pi$, with $\overline{\tau} = 1.1$. The first case is that of $\tau = 1.1$ with certainty. The two other cases are mean-preserving spreads around this

[55] The Kimball aggregator function $\Upsilon(\cdot)$ is defined as strictly increasing and strictly concave, $\Upsilon'(\cdot) > 0, \Upsilon''(\cdot) < 0$. The demand function is defined as $\psi(\cdot) \equiv \Upsilon'^{-1}(\cdot)$. Without a further assumption about the sign of the third derivative of the aggregator, $\Upsilon'''(\cdot)$, it is not guaranteed that the demand function will be convex or concave. This is a desirable feature of most functional specifications of the Kimball aggregator.

Figure 1.15: Stylized example of price setting with tariff mean preserving spreads



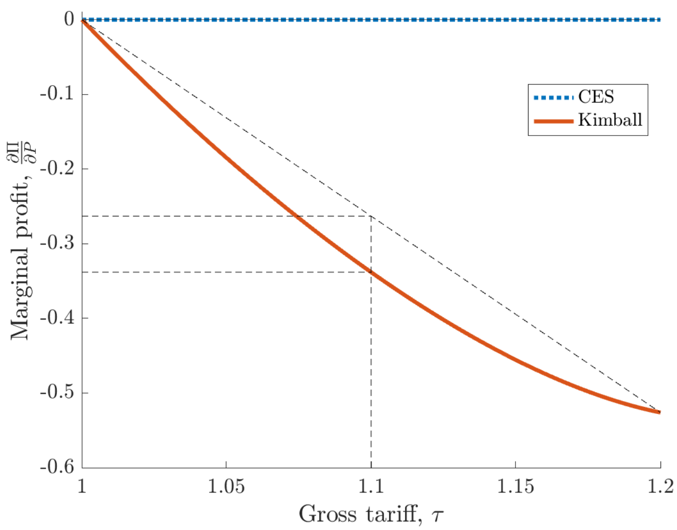
Note: Expected profits of the firm with CES (panel (a)) and Kimball (panel (b)) demand, as a function of the firm's relative price. In all cases, the expected tariff level is $\mathbb{E}\tau = 1.1$ and $\mathbb{E}\delta = 0$. Each line represents expected profits with different level of mean-preserving spread of τ: $\gamma \times 1 + (1-\gamma) \times \tau^H$, where γ and τ^H are chosen to keep $\mathbb{E}\tau = 1.1$. The Klenow & Willis (2016) functional form of the Kimball aggregator is used, $\psi(\tau P) = [1 - \varepsilon \log(\tau P)]^{\sigma/\varepsilon}$, with $\sigma = 5$ and $\varepsilon = 4$. In the CES case, $\varepsilon = 0$. The dashed black lines indicate the optimal preset price for each expected profit function.

expected value of tariff, with $\tau = 1$ with probability γ, and τ^H with probability $1-\gamma$. We set γ and τ^H to maintain $\mathbb{E}\tau = 1.1$. Panel (a) illustrates that the increase in uncertainty does not affect the optimal preset border price with CES demand. Panel (b) illustrates that the preset border price increases with the level of uncertainty, as would be expected since the marginal profit is convex.

Figure 1.16 presents the period marginal profit of the firm, Π_P, for different levels of τ, holding the border price constant at $P = 1$ and the cost shock at $\delta = 0$. The marginal profit with CES demand is flat at 0, and thus there is no effect of uncertainty in τ on the optimal preset border price. However, with Kimball demand the marginal profit is convex, and therefore the optimal preset border price with a mean-preserving spread of τ would be higher. This represents a precautionary markup motive for the firm that stems entirely from uncertainty, as the expected value of τ remains the same.

Finally, Figure 1.17(a) presents the optimal preset border price of the firm as a function of the mean-preserving spread γ around $\mathbb{E}\tau = 1.1$, With CES demand, the preset border price is stable at $\overline{P}^{CES} = 1$. With Kimball demand, if $\gamma = 0$ then $\tau = 1.1$ with certainty. In this case, the firm sets

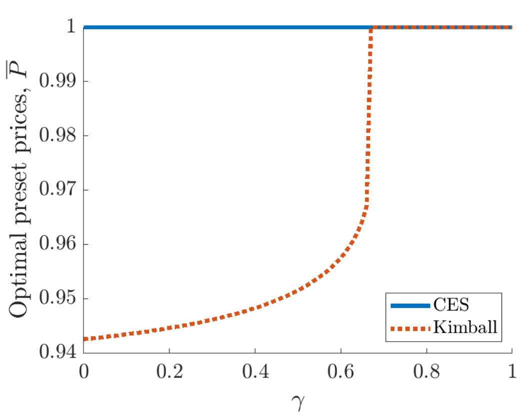
Figure 1.16: Marginal profit for different levels of gross tariff τ, with $P = 1$ and $\delta = 0$



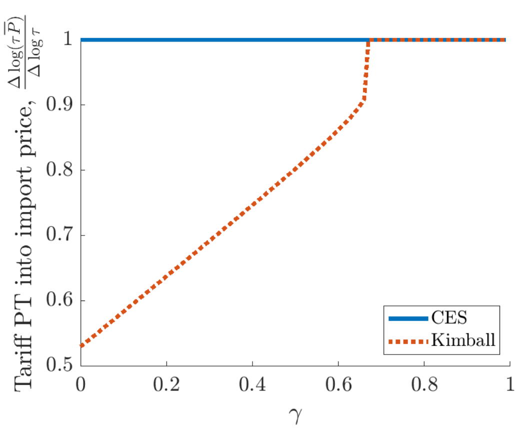
Note: Marginal period profit of the firm with CES and Kimball demand, as a function of gross tariff τ, holding $P = 1$ and $\delta = 0$. The Klenow & Willis (2016) functional form of the Kimball aggregator is used, $\psi(\tau P) = [1 - \varepsilon \log(\tau P)]^{\sigma/\varepsilon}$, with $\sigma = 5$ and $\varepsilon = 4$. In the CES case, $\varepsilon = 0$. The dashed black lines indicate a mean preserving spread of τ with $\mathbb{E}\tau = 0.5 \times 1 + 0.5 \times 1.2 = 1.1$.

Figure 1.17: Optimal preset border price and realized tariff pass-through into import price, different levels of uncertainty γ, and τ^H with $\mathbb{E}\tau = 1$

(A) Optimal preset border price, $\overline{P}$



(B) Realized tariff pass-through into import price with τ^H



Note: Panel (a) presented the optimal preset border price of the firm with CES and Kimball demand, as a function of gross tariff uncertainty γ, holding $\mathbb{E}\tau = 1$. The parameter γ represents and increasing mean preserving spread, $\mathbb{E}\tau = \gamma \times 1 + (1 - \gamma)\tau^H$, where τ^H is chosen to keep $\mathbb{E}\tau = 1.1$. Panel (b) presents the realized tariff pass-through into the tariff-inclusive import price when τ^H is realized, $\Delta \log\left(\tau \overline{P}\right) / \Delta \log \tau$. The Klenow & Willis (2016) functional form of the Kimball aggregator is used, $\psi(\tau P) = [1 - \varepsilon \log(\tau P)]^{\sigma/\varepsilon}$, with $\sigma = 5$ and $\varepsilon = 4$. In the CES case, $\varepsilon = 0$.

the border price at its lowest level, accommodating the reduction in demand caused by the tariff. As γ increases, there is an increasing probability that the realization of the gross tariff would be 1, and a decreasing probability that the realization would be $\tau^H > \mathbb{E}\tau$. As can be seen clearly, the firm's optimal preset border price increases with γ as the probability of low tariff increases.

Figure 1.17(b) presents the implication of this mean-preserving spread for tariff pass-through into the tariff-inclusive import price, $\tau\overline{P}$. Tariff pass-through is constructed from the following exercise. Initially, there is no tariff, $\tau = 1$, and the optimal border price is $P_0 = 1$. Then, the firm learns that a tariff might be imposed. It has to choose a preset border price, $\overline{P}$. After the tariff τ is realized (0 or τ^H), the tariff pass-through rate into the tariff-inclusive import price is

$$\frac{\Delta \log \tau P}{\Delta \log \tau} = \frac{\log \tau + \log \overline{P} - \log P_0}{\log \tau} = 1 + \frac{\log \overline{P}}{\log \tau} \tag{1.B.6}$$

Figure 1.17(b) depicts this tariff pass-through rate into the import price when τ^H is realized. Tariff pass-through into the import price increases with γ, as the preset border price increases with γ.

This simple structure captures the mechanism that leads to precautionary markup when there is uncertainty about tariffs. The basic idea presented here drives the intensive margin effect of TPU on border price resetting in the dynamic model.

Chapter 2

Multiple Invoicing Currencies in a Small Open Economy

2.1 Introduction

Exchange rate movements have considerable implications for open economies: they change the relative prices of domestic and foreign goods, and thus the trade balance and welfare; their pass-through rate into domestic prices affects monetary policy; and they affect the valuation of internationally traded financial assets. The relationship between nominal exchange rate fluctuations and other nominal and real variables depends critically on the currency in which exporters set prices that adjust infrequently. Early models of open economies assumed that exporters set prices in their domestic currency (producer currency pricing, PCP), meaning that the price importers at the destination country pay move one-for-one with the exchange rate before prices are adjusted.[1] Subsequent models, however, acknowledged the stylized fact that many exporters set prices in the destination country's currency (local currency pricing, LCP), which implies that the import price in the destination country is stable and does not react to exchange rate changes in the short run before prices adjust.[2] As new empirical evidence revealed an outsized role of the U.S. dollar as a vehicle currency (VCP)

[1]These works include Obstfeld & Rogoff (1995) and Clarida et al. (2002).

[2]See Engel & Rogers (1996), Betts & Devereux (2000), Devereux & Engel (2003), Chari et al. (2002), and Engel (2011).

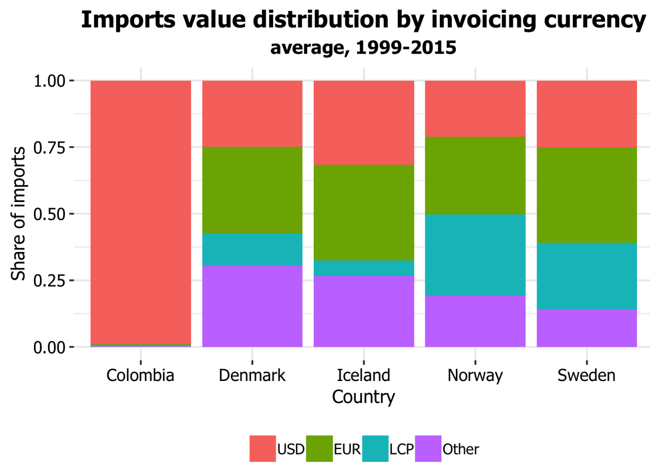


Figure 2.1: Distribution of invoicing currency for Scandinavian countries and Colombia
Source: Gopinath (2015) dataset, own calculations.

in international trade, a new paradigm of the dollar as a dominant currency emerged (dominant currency pricing, DCP).[3] Under this paradigm, the bilateral exchange rate has little effect on the price of goods invoiced in USD, but changes in the USD exchange rate significantly impact the price that importers pay.

The three pricing paradigms are limiting cases helpful in studying the effects of shocks on open economies and optimal monetary and FX policy, where the currency of invoicing plays an important role. For some economies, PCP, LCP, or DCP might be a reasonably accurate approximation of the mix of currencies used to invoice international transactions.[4] But in other economies, the composition of invoicing currencies is more diverse. Specifically, some developed economies use several invoicing currencies in non-negligible shares, such as the Scandinavian countries (see Figure 2.1 for comparison with Colombia), UK, Japan, and Switzerland. Explaining observed exchange rate pass-through rates into import prices and the response of these economies to exogenous shocks requires accounting for the use of multiple invoicing currencies in significant shares.

This paper addresses the case of a small open economy (SOE) with multiple invoicing currencies (MCP). The paper introduces a theoretical framework that builds a New Keynesian SOE model with

[3]See Goldberg & Tille (2008), Gopinath et al. (2010), Gopinath (2015), Gopinath et al. (2020), and Mukhin (2022).
[4]For example, in the US and Columbia nearly 100% transactions are invoiced in USD, while in the eurozone nearly all transactions are invoiced in euros, which is compatible with DCP (Gopinath 2015).

infrequent price and wage adjustments a la Calvo and where different firms set their export prices in either their domestic currency (PCP), the destination currency (LCP), or a vehicle currency (VCP). In the model, the SOE trades with two large open economies. Price rigidities and multiple invoicing currencies lead to deviations from the law of one price and different exchange rate pass-through rates at the firm level in the short run, when prices are sticky: for PCP firms, the law of one price holds, and bilateral exchange rate pass-through into the price paid by importers is high; for LCP firms the law of one price is violated and bilateral exchange rate pass-through into the price paid by importers is low; and for VCP firms bilateral exchange rate pass-through is low, but fluctuations in the exchange rate of the destination currency vis-a-vis the vehicle currency are passed-through into the price paid by the importer. The model also accounts for empirically documented incomplete exchange rate pass-through into import prices in the medium run, even conditional on a price adjustment. Incomplete exchange rate pass-through in the medium run results from domestic and imported intermediate inputs used in production, exposing firms' production cost to exchange rate fluctuations; and price complementarities that arise from the demand structure that yields variable price elasticity of demand, thus creating an incentive for exporters not to deviate too much from the price of competitors, even when faced with exchange rate fluctuations.

The theoretical framework yields testable hypotheses about exchange rate pass-through into import and export prices and the effect of exchange rate changes on the terms of trade. Namely, the effect of a change in the exchange rate on these aggregate price measures crucially depends on the share of goods invoiced in PCP, LCP, or VCP. We test these hypotheses in the data for Sweden, an SOE with large shares of invoicing in each of the three pricing paradigms. We construct export and import price indices and terms of trade for Sweden from UN COMTRADE data and show that bilateral and dollar exchange rate pass-through rates are incomplete but still substantial, in line with large shares of goods invoiced in PCP, LCP, and VCP in USD. A 10% depreciation of the Swedish krone (SEK) against the producer's currency leads to a 5.45% increase in the import price in Sweden after one year. In comparison, a 10% depreciation of the SEK against the USD leads to a 2.31% increase in import prices. The price of exports from Sweden exhibits similar results, where a 10% depreciation of the destination currency against SEK leads to a 3.75% increase in the price of

Swedish exports to the destination country, while a 10% depreciation of the destination currency against the USD leads to an increase of 2.1% in Swedish export prices. We show that exchange rate pass-through rates vary by country: imports from dollarized economies and the eurozone exhibit high rates of bilateral exchange rate pass-through in Sweden, in line with pricing in the producer's currency, but for the rest of the world, pass-through rates of both bilateral and USD exchange rate are much lower, indicating a large share of goods invoiced in SEK.

We estimate the shares of invoicing currencies used in international trade in Sweden by calibrating the model to moments of the Swedish economy and the estimated exchange rate pass-through rates and using the simulated method of moments. The model can match the empirically estimated exchange rate pass-through rates well, and the estimated shares of currencies used in imported goods in Sweden are 55% PCP, 23% LCP (SEK), and 22% USD. We simulate data from the model and show that accounting for this heterogeneity in invoicing currencies is essential, as using any of the three "pure" pricing paradigms lead to counterfactual exchange rate pass-through rates. We then use the calibrated model to derive impulse response functions and study the reaction of the SOE to monetary and financial shocks, comparing the MCP economy to PCP, LCP, and DCP. The MCP economy combines patterns from all three paradigms as firms react differently to shocks based on the currency in which they invoice their exports. Notably, while the response of the terms of trade is relatively small, the terms of trade are only partially stable, a departure from DCP. This finding, together with the overall failure of the law of one price and distortions in relative prices resulting from price rigidities in multiple currencies, could indicate that optimal monetary policy might be different in the MCP than in any of the limiting pricing paradigms, as the economy exhibits different wedges simultaneously. Optimal monetary policy in an SOE with MCP is a topic for further research in the future.

The rest of the paper is structured as follows. Section 2.2 scans the relevant literature and the empirical evidence supporting the inclusion of multiple invoicing currencies in the framework of a small open economy. Section 2.3 presents a small open economy New Keynesian model where prices are sticky in producer, local, and vehicle currencies and defines the equilibrium in that economy. Section 2.4 presents testable empirical hypothesis based on the model and uses Swedish data to examine them. Section 2.5 presents the calibrated model, compares the results of exchange rate pass-through from the simulated model and the data, and analyzes the economy's response to exogenous shocks with multiple invoicing currencies. Finally, section 2.6 offers some concluding remarks.

2.2 Related literature

This paper relates to the vast literature discussing the effects of exchange rate fluctuations on open economies. Producer currency pricing (PCP) rose as an early paradigm in international economics (Fleming 1962, Mundell 1963) and shaped the first generation of New-Keynesian models that assumed prices are sticky in the producer's currency (Obstfeld & Rogoff 1995, Clarida et al. 2002, Gali & Monacelli 2005). In this case, the law of one price holds, and nominal depreciation of the producer's currency raises the price of imports relative to exports (terms of trade). However, empirical evidence indicate that the law of one price often fails (Engel & Rogers 1996). This finding gave rise to a second paradigm: prices are sticky in the local (destination) currency (LCP), which creates a wedge between the price of a good at home and abroad when the exchange rate changes (Betts & Devereux 2000, Chari et al. 2002, Devereux & Engel 2003, Engel 2011). As more disaggregated price data in international transactions became available, a new stylized fact emerged: a large share of international trade is invoiced in a small number of currencies, with the USD playing an outsized role as a vehicle currency for transactions between countries that are not the US, serving as a dominant currency (Goldberg & Tille 2008, Gopinath et al. 2010, Gopinath 2015, Ito et al. 2018, Corsetti et al. 2018, Crowley et al. 2021, Amiti et al. 2022, Corsetti et al. 2022). These findings led to the introduction of a vehicle or dominant currency pricing model (VCP or DCP) (Gopinath et al. 2020, Mukhin 2022). Between the three pricing paradigms, there is now a versatile and flexible framework for analyzing the response of open economies to exogenous shocks.

The currency of invoicing of internationally traded goods is an essential factor in determining the pass-through rate of exchange rate movements into the prices of those goods. The currency in which prices are sticky determines whether exchange rate changes are completely passed-through in the short run before prices adjust. Furthermore, using micro-level data for the US, Gopinath et al. (2010) show that even conditional on a price change, there is a significant difference in the pass-through rate of the average imported good in the US priced in dollars (25%) versus non-dollars (95%). Most open macro models take the invoicing choice of firms as exogenous. Engel (2006), Gopinath et al. (2010), and Mukhin (2022) endogenize this choice and show how the desired exchange rate pass-through determines the currency in which firms price their goods. Mukhin (2022) proves the existence and stability of a DCP equilibrium. Incorporating firm heterogeneity in the choice of invoicing currency seems like a natural next step in this area since there is considerable empirical evidence that local, producer, and vehicle currency pricing all exist in non-negligible shares in open economies (Goldberg & Tille 2008, Gopinath et al. 2010, Burstein & Gopinath 2014, Gopinath 2015, Goldberg & Tille 2016, Corsetti et al. 2018, Ito et al. 2018, Rodnyansky 2018, Gopinath et al. 2020, Corsetti et al. 2022). The aggregate share of local, producer, and dominant currency is relatively stable (Gopinath 2015, Corsetti et al. 2022), but there is considerable volatility at the firm and product level (Corsetti et al. 2022, Ito et al. 2018).

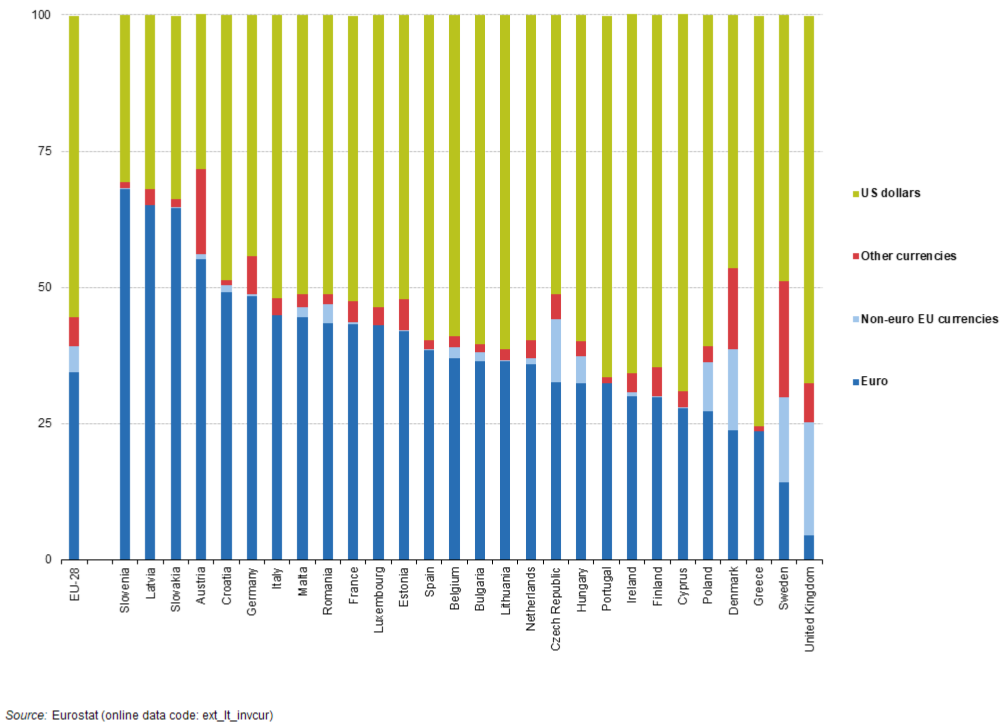
This paper takes the invoicing currency as given. However, it shows that accounting for multiple invoicing currencies (MCP) in large shares is important for small open economies that exhibit such currency of invoicing heterogeneity. Accounting for the MCP case has important macroeconomic implications and is crucial in explaining observed patterns of incomplete exchange rate pass-through into import prices. Several studies have documented SOEs with MCP, which comprise a small but meaningful subset of advanced economies. Corsetti et al. (2018) find that for Chinese exports to the UK in 2010-2016, 71%-78% of import value was invoiced in USD, 16%-22% was invoiced in GBP, and around 5% was invoiced in euro. Corsetti et al. (2022) find that in 2010-2016, 56%-62% of the non-EU export value from the UK was invoiced in GBP, 20%-25% was invoiced in vehicle currencies (mostly USD), and 14.5%-19.5% was invoiced in local currency. For non-EU imports to the UK, Chen et al. (2019) found that in 2010-2017, 27% were invoiced in GBP, 18% were invoiced in the producer's currency, and 55% were invoiced in a vehicle currency, of which the USD is vastly the dominant currency. Goldberg & Tille (2008) examine a cross-section of 24 countries in 1996-2002 and find that the share of exports invoiced in USD or producer currency varies greatly but overall exists in meaningful shares in almost all of the examined countries. Goldberg & Tille (2016) find significant heterogeneity in invoicing currencies of imports in Canada from different origin countries, with the USD playing an outsized role as a vehicle currency and PCP especially prevalent in imports from the Eurozone (23.6%) and Switzerland (21.1%). Ito et al. (2018) find that in Japan, the share of yen-invoiced exports was 33%-41% between 1985-2015, while USD invoicing was about 50% of exports. Finally, looking at a cross-section of extra-EU transactions of EU countries for 2016, we observe a wide heterogeneity in the share of currencies used (Figure 2.2). Thus, ample evidence exists that at least three currencies are frequently used simultaneously for invoicing exports and imports in small open economies.[5]

In conclusion, the literature points to the empirical prevalence of multiple invoicing currencies in various combinations in different economies. These differences arise from firm-level considerations, but they have macroeconomic repercussions. Thus, a study of the effects of shocks on an economy with multiple invoicing currencies can further our understanding of the role that exchange rate fluctuations play in the economy and is vital for explaining observed rates of exchange rate pass-through into import prices in those economies.

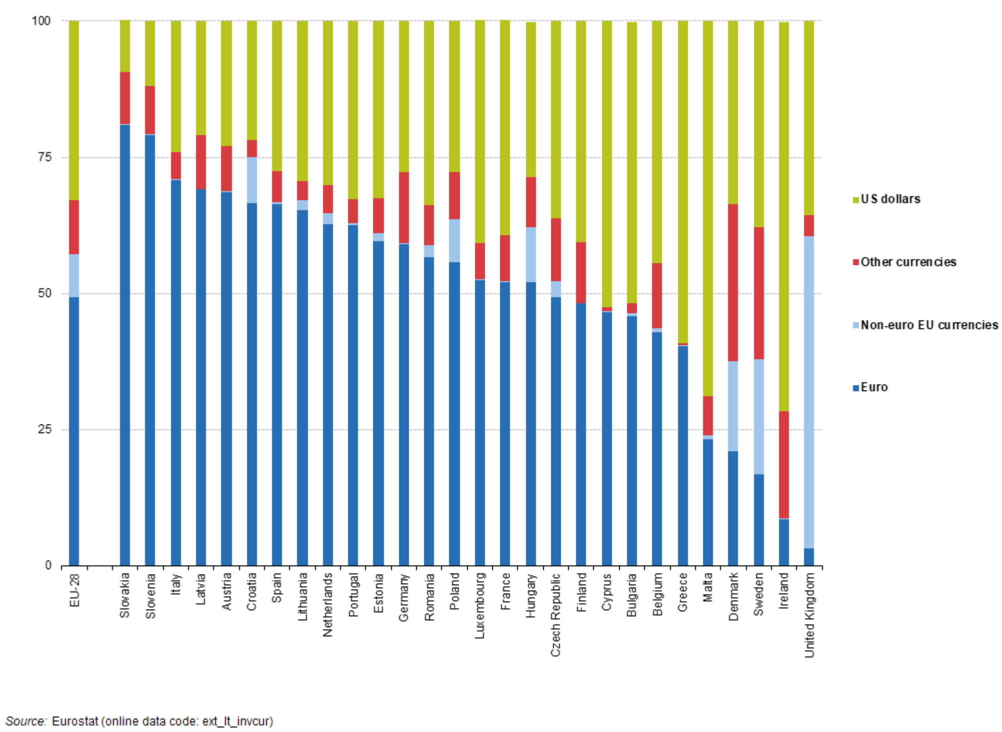
2.3 Theoretical framework

The model depicts a small open economy, H ("Sweden"), that trades with two large open economies, R ("Rest of the world") and U ("USA"), as in Gopinath et al. (2020). The LOEs are taken as exogenous from the perspective of the SOE, as in Galí (2015). Each country has a domestic currency labeled with the same letter as the country. Let $P^k_{ij,t}$ denote the price of a good exported from country i to country j and priced in currency k (e.g., a UK good exported to Sweden invoiced

[5]The causes for the observed heterogeneity in invoicing currencies in some economies (and conversely, the homogeneity observed in others) are at the firm level. The distinction between pricing, invoicing, and settlement is not stressed here, since for an overwhelming share of exports to third parties the price, the invoice and settlement are denominated in the same currency (Friberg & Wilander 2008). Following Friberg & Wilander (2008), we can think of the invoicing decision of firms as follows: price is first set in some currency, at some later point, an invoice is written, and finally, payment is made. Transaction costs and exchange rate variability can affect the currency choice at all these stages, and it is stochastic and unknown at the time of the currency invoicing decision. We can divide the factors affecting the choice of currency into three categories: macro factors, micro/market factors, and firms/transaction factors. Since the source of currency heterogeneity in international transactions is not the focus of this paper, we relegate a survey of these factors to appendix 2.A.



(A) Imports



(B) Exports

Figure 2.2: Extra-EU exports and imports by invoicing currency, 2016 (% of total)

in USD). Domestic goods sold at home are priced in the domestic currency, denoted $P_{HH,t}$, where we drop the currency superscript in this case for simplicity. Internationally traded goods can be priced in one of the three currencies: the producer's currency, local destination currency, or vehicle currency. We make the assumption that only country U's currency is a vehicle currency. This assumption is based on the data, where the use of the USD as a vehicle currency is prevalent while the use of other currencies (most importantly, the euro), is not (Maggiori et al. 2019, Chen et al. 2022). The nominal exchange rate between currency i and currency H, expressed as units of H per one unit of i, is denoted $\mathcal{E}_i$. An increase in $\mathcal{E}_i$ is a depreciation of currency H against currency i.

The model is a full-fledged New Keynesian model of the SOE with price and wage rigidities a la Calvo. The model can generate empirically documented incomplete exchange rate pass-through in the short and medium run. Price rigidities make the firms' price setting problem intertemporal, create deviations from the law of one price if the price is sticky in local or vehicle currency, and lead to low average exchange rate pass-through in the short run before firms can fully adjust their prices. The demand structure yields variable price elasticity of demand and, as a result, price complementarities between goods, and variable markups. These price complementarities lead to incomplete exchange rate pass-through even in the medium run as firms adjust their prices since competition from domestic and third-country producers limits the extent to which exporters can pass-through exchange rate fluctuations into the price that importers pay. On the production side, firms use domestic labor and domestic intermediate inputs, as well as imported intermediate inputs, which are invoiced in producer, local, or vehicle currency, exposing firms' marginal cost to exchange rate fluctuations.

2.3.1 Households

There is a continuum of identical households of measure 1. Household h's per-period utility from consumption of domestic and foreign goods, C_t, and disutility from labor, N_t, is given by

$$U\left(C_t\left(h\right), N_t\left(h\right)\right) = \frac{C_t\left(h\right)^{1-\sigma_c}}{1-\sigma_c} - \kappa \frac{N_t\left(h\right)^{1+\varphi}}{1+\varphi} \tag{2.3.1}$$

where $\sigma_c > 0$ is the relative risk aversion coefficient, $\varphi > 0$ is the inverse of the Frisch elasticity of labor, and $\kappa > 0$ scales the disutility from labor. The index h is omitted whenever possible for simplicity and since households are identical. Households supply a unique labor variety h to domestic firms, facing a demand for labor given by $N_t(h) = \left(\frac{W_t(h)}{W_t}\right)^{-\vartheta} N_t$ (to be derived later).

Consumption C_t is an aggregate of differentiated varieties, indexed by ω, produced domestically and abroad, defined implicitly by a homothetic Kimball (1995) aggregator:

$$\int_{\omega} \gamma_H \Upsilon\left(\frac{C_{HH,t}(\omega)}{\gamma_H C_t}\right) d\omega + \int_{\omega} \gamma_R \Upsilon\left(\frac{C_{RH,t}(\omega)}{\gamma_R C_t}\right) d\omega + \int_{\omega} \gamma_U \Upsilon\left(\frac{C_{UH,t}(\omega)}{\gamma_U C_t}\right) d\omega = 1 \tag{2.3.2}$$

where $C_{iH,t}(\omega)$ is consumption of variety ω produced in country $i \in \{H, R, U\}$, $\gamma_i \geq 0$ is a preference parameter for goods from country i that captures home-bias and satisfies $\gamma_H + \gamma_R + \gamma_U = 1$. The function $\Upsilon(\cdot)$ satisfies $\Upsilon(1) = 1$, $\Upsilon' > 0$, $\Upsilon'' < 0$.

As will be shown later, using this general homothetic aggregator (that also nests the constant elasticity of substitution case at the limit) is a straightforward way of inducing variable elasticity of substitution between varieties and, as a result, variable price elasticity of demand. When the price elasticity of demand depends on the relative price of the variety, firms have an incentive not to deviate too much from the price of competitors. Price complementarities limit the extent to which firms desire to pass through cost shocks into the price paid by consumers.

Households can trade in a complete set of domestic state contingent claims $B_t(s)$ with price $Q_t(s)$. Additionally, households can trade internationally in a risk-free bond denominated in currency U, B_t^U, with discount rate R_{t-1}^U. Returns on this bond are subject to a financial (UIP) shock, ζ_t, that follows the AR(1) process, $\zeta_t = \rho\zeta_{t-1} + \epsilon_{\psi,t}$.[6] The source of the shock might be due the supply of the bond by intermediates and market makers, currently not modeled, and it is a simplistic way for generating deviations from UIP.

Households maximize the discounted utility subject to a budget constraint,

$$\max_{C_t(h), W_t(h), B_{t+1}(s'), B_{t+1}^U} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t(h), N_t(h)\right) \qquad \text{s.t.} \tag{2.3.3}$$

[6]This type of UIP shock is used, for example, in Itskhoki & Mukhin (2021).

$$P_tC_t(h)+\sum_{s'}Q_t(s')\,B_{t+1}(s')+\frac{\mathcal{E}_{U,t}B^U_{t+1}(h)}{e^{\zeta_t}R^U_t}\leq W_t(h)\,N_t(h)+B_t(s)+B^U_t(h)\,\mathcal{E}_{U,t}+\Pi_t(h) \quad (2.3.4)$$

where P_t is the CPI of country H, $W_t(h)$ is the wage set by the household h for all firms, and $\Pi_t(h)$ are domestic firms' profits payed to the household as lump sum.

The optimization problem yields the Euler equations

$$1=\beta R_t\mathbb{E}_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma_c}\left(\frac{P_t}{P_{t+1}}\right)\right] \quad (2.3.5)$$

$$1=\beta e^{\zeta_t}R^U_t\mathbb{E}_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma_c}\left(\frac{P_t}{P_{t+1}}\right)\left(\frac{\mathcal{E}_{U,t+1}}{\mathcal{E}_{U,t}}\right)\right] \quad (2.3.6)$$

where $R_t\equiv\left[\sum_{s'\in\mathcal{S}}Q_t(s')\right]^{-1}$. The stochastic discount factor is therefore

$$\Theta_{s,t}\equiv\beta^{s-t}\mathbb{E}_t\left[\left(\frac{C_s}{C_t}\right)^{-\sigma_c}\left(\frac{P_t}{P_s}\right)\right] \quad (2.3.7)$$

The households are subject to a Calvo friction in wage setting, where every period a household can adjust the wage with probability $(1-\delta_w)$ or maintain the same wage level as the previous period with probability δ_w. The wage setting problem is therefore

$$\max_{C_s(h),W_s(h)}\mathbb{E}_t\sum_{s=t}^{\infty}\Theta_{s,t}\delta_w^{s-t}\left[\frac{C_s(h)^{1-\sigma_c}}{1-\sigma_c}-\kappa\frac{N_s(h)^{1+\varphi}}{1+\varphi}\right] \qquad \text{s.t.} \quad (2.3.8)$$

$$N_s(h)=\left(\frac{W_s(h)}{W_t}\right)^{-\vartheta}N_s \quad (2.3.9)$$

$$P_sC_s(h)=W_s(h)\,N_s(h) \quad (2.3.10)$$

resulting in the optimal reset wage

$$\overline{W}_t(h)^{1+\vartheta\varphi}=\frac{\vartheta}{\vartheta-1}\frac{\mathbb{E}_t\sum_{s=t}^{\infty}\Theta_{s,t}\delta_w^{s-t}W_t^{\vartheta\varphi}P_s\kappa N_s^{\varphi-1}C_s^{\sigma_c}}{\mathbb{E}_t\sum_{s=t}^{\infty}\Theta_{s,t}\delta_w^{s-t}N_s} \quad (2.3.11)$$

Households choose consumption of specific varieties by minimizing expenditure given aggregate consumption level, C_t. This results in the demand function for a specific variety ω

$$C_{iH,t}(\omega) = \gamma_i \psi \left(D_t \frac{\mathcal{E}_{k,t} P^k_{iH,t}(\omega)}{P_t} \right) C_t \tag{2.3.12}$$

where where $\psi(\cdot) \equiv \Upsilon'^{-1}(\cdot) > 0$ so that $\psi(\cdot) < 0$, and $D_t \equiv \sum_i \int_\omega \Upsilon' \left(\frac{C_{iH,t}(\omega)}{\gamma_i C_t} \right) \left(\frac{C_{iH,t}(\omega)}{C_t} \right) d\omega$ is an aggregate consumption variable that results from cost minimization and is exogenous from the household's perspective. Let $Z_{iH,t}(\omega) \equiv D_t \frac{P_{iH,t}(\omega)}{P_t}$ denote the relative price of variety ω, then this demand structure gives rise to a variable price elasticity of demand, $\sigma_{iH,t}(\omega) \equiv -\frac{\partial \log C_{iH,t}(\omega)}{\partial \log Z_{iH,t}(\omega)} > 0$, variable price markup $\mathcal{M}_{iH,t}(\omega) \equiv \frac{\sigma_{iH,t}(\omega)}{\sigma_{iH,t}(\omega)-1}$, and the variable price elasticity of the markup $\Gamma_{iH,t}(\omega) \equiv \frac{\partial \log \mathcal{M}_{iH,t}(\omega)}{\partial \log Z_{iH,t}(\omega)}$. That is, price elasticity of demand and the markup depend on the relative price of variety ω, and the price elasticity of demand increases with the relative price. This induces price complementarities between varieties, since firms do not want to deviate too much from the price of competitors.

2.3.2 Producers

There is a continuum of measure 1 of domestic firms, indexed by ω and producing a differentiated variety. Goods can be used for consumption or as intermediate inputs in production. Firms produce using a Cobb-Douglas production function with labor and intermediate goods:

$$Y_{H,t} = e^{a_t} {L_t}^{1-\alpha} X_t^\alpha \tag{2.3.13}$$

where a_t is aggregate productivity that follows an AR(1) process, $a_t = \rho_a a_{t-1} + \epsilon^a_t$.

L_t is labor used by the firm which is aggregated from the different households by a CES aggregator

$$L_t = \left[\int_0^1 L_t(h)^{\frac{\vartheta-1}{\vartheta}} \, dh \right]^{\frac{\vartheta}{\vartheta-1}} \tag{2.3.14}$$

where $\vartheta > 0$ is the elasticity of substitution between labor varieties.

X_t is aggregated from domestic and foreign varieties by the same homothetic aggregator as consumption goods:

$$\int\limits_{\omega} \gamma_H \Upsilon\left(\frac{X_{HH,t}(\omega)}{\gamma_H X_t}\right) d\omega + \int\limits_{\omega} \gamma_R \Upsilon\left(\frac{X_{RH,t}(\omega)}{\gamma_R X_t}\right) d\omega + \int\limits_{\omega} \gamma_U \Upsilon\left(\frac{X_{UH,t}(\omega)}{\gamma_U X_t}\right) d\omega = 1 \qquad (2.3.15)$$

Markets are segmented, and therefore the per-period profit maximization problem of the firm is separable between destinations. We assume that the currency in which a variety's price abroad is set is exogenous and constant. While this is a strong assumption, it aligns with empirical evidence that the share of invoicing currencies at the aggregate level is stable over time (Gopinath 2015, Corsetti et al. 2022). Therefore, a firm ω that exports to countries R, U and sets its prices in currency $k \in \{H, R, U\}$ has the profit function

$$\Pi_t(\omega) = \sum_{i \in \{R,U\}} \mathcal{E}_{k,t} P^k_{Hi,t}(\omega) Y^k_{Hi,t}(\omega) + P_{HH,t}(\omega) Y_{HH,t}(\omega) - \mathcal{MC}_t Y_t(\omega) \qquad (2.3.16)$$

where $Y^k_{Hi,t}(\omega)$ is the output sold at country i and priced in currency k, $\mathcal{MC}_t$ is the marginal cost, and $Y_t(\omega)$ is total output defined as $Y_t(\omega) = \sum_{i \in \{R,U\}} Y^k_{Hi,t}(\omega) + Y_{HH,t}(\omega)$.

From the firm's cost minimization problem we obtain the marginal cost (which is constant and identical for all firms) and the demand for intermediate inputs and labor:

$$(1-\alpha)\frac{Y_t}{L_t} = \frac{W_t}{\mathcal{MC}_t} \qquad L_t(h) = \left(\frac{W_t(h)}{W_t}\right)^{-\vartheta} L_t \qquad (2.3.17)$$

$$\alpha\frac{Y_t}{X_t} = \frac{P_t}{\mathcal{MC}_t} \qquad X_{iH,t}(\omega) = \gamma_i \psi\left(D_t \frac{\mathcal{E}_{k,t} P^k_{iH,t}(\omega)}{P_t}\right) X_t \qquad (2.3.18)$$

$$\mathcal{MC}_t = \frac{1}{(1-\alpha)^{1-\alpha}\alpha^\alpha} \frac{W_t^{1-\alpha} P_t^\alpha}{e^{a_t}} \qquad (2.3.19)$$

where the aggregate wage index is $W_t \equiv \left[\int_0^1 W_t(h)^{1-\vartheta} dh\right]^{\frac{1}{\vartheta-1}}$.

2.3.3 Pricing

Firms set prices for goods sold at home (in domestic currency) and abroad (given their assigned currency k) to maximize profits subject to demand for final and intermediate goods. Firms are subject to a Calvo pricing friction, where a firm can reset its price, $\overline{P}^k_{Hi,t}(\omega)$, with probability $(1-\delta_P)$ or has to keep its price from the previous period, $P^k_{Hi,t-1}(\omega)$, with probability δ_P.

The firm's optimization problem is given by

$$\max_{\left\{\overline{P}^k_{Hi,t}(\omega)\right\}_i,\overline{P}_{HH,t}(\omega)} \mathbb{E}_t \sum_{s=t}^{\infty} \Theta_{s,t}\delta_P^{s-t} \times \Bigg[\sum_{i\in\{R,U\}} \mathcal{E}_{k,s}\overline{P}^k_{Hi,t}(\omega)\, Y^k_{Hi,s}(\omega) + \overline{P}_{HH,t}(\omega)\, Y_{HH,s}(\omega) - \mathcal{MC}_s Y_s(\omega)\Bigg]$$

$$\begin{aligned}
\text{s.t.} \qquad Y^k_{Hi,s}(\omega) &= C^k_{Hi,s}(\omega) + X^k_{Hi,s}(\omega), \quad \forall i \in \{H,R,U\} \\
Y_s(\omega) &= \sum_{i\in\{H,R,U\}} Y^k_{Hi,s}(\omega) \\
X^k_{Hi,s}(\omega) &= \gamma_i \psi \left(D_{i,s}\frac{\overline{P}^k_{Hi,t}(\omega)}{P^k_{i,s}}\right) X_{i,s} \\
C^k_{Hi,s}(\omega) &= \gamma_i \psi \left(D_{i,s}\frac{\overline{P}^k_{Hi,t}(\omega)}{P^k_{i,s}}\right) C_{i,s}
\end{aligned}$$

where $P^k_{i,s}$ is the CPI in country i at time s expressed in units of currency k.[7]

Profit maximization leads to the optimal reset price for exports to country i set in currency k,

$$\mathbb{E}_t \sum_{s=t}^{\infty} \delta_p^{s-t}\Theta_{s,t}Y^k_{Hi,s}(\omega)\left(\sigma^k_{Hi,s}(\omega)-1\right)\left\{\mathcal{E}_{k,s}\overline{P}^k_{Hi,t}(\omega) - \mathcal{MC}_s\frac{\sigma^k_{Hi,s}(\omega)}{\sigma^k_{Hi,s}(\omega)-1}\right\} = 0 \qquad (2.3.20)$$

where in the case of domestic price, $\mathcal{E}_{H,s} \equiv 1, \overline{P}^H_{HH,t}(\omega) \equiv \overline{P}_{HH,t}(\omega)$.

For a country j exporting to country i, the total share of firms setting their price in currency k is denoted θ^k_{ji}, such that $\sum_{k\in\{H,R,U\}}\theta^k_{ji} = 1$. We can thus define the price index for exports from country j to country i, expressed in the destination currency i, as

$$P^i_{ji,t} \equiv \sum_{k\in\{H,R,U\}} \theta^k_{ji}\mathcal{E}_{ki,t}P^k_{ji,t} \qquad (2.3.21)$$

[7] We also make the assumption for simplicity that the preference parameters are symmetric between country pairs. That is, the preference in country H for imports from country i, γ_i, is identical to the preference in country i for import from country H.

where $\mathcal{E}_{ki,t}$ is the exchange rate between currency i and currency k, the price of one unit of currency k in units of currency i.

Given the consumption aggregator and the demand functions, we define the CPI in country H as

$$P_t = \gamma_H P_{HH,t} + \gamma_R P_{RH,t} + \gamma_U P_{UH,t} \tag{2.3.22}$$

where

$$P_{HH,t} \equiv \int_\omega P_{HH,t}(\omega)\,\psi\left(D_t \frac{P_{HH,t}(\omega)}{P_t}\right) d\omega \tag{2.3.23}$$

$$P^k_{iH,t} \equiv \int_\omega P^k_{iH,t}(\omega)\,\psi\left(D^k_t \frac{P^k_{iH,t}(\omega)}{P_t/\mathcal{E}_{k,t}}\right) d\omega, \quad \text{for } i \in \{R, U\} \tag{2.3.24}$$

$$P_{iH,t} \equiv \sum_{k\in\{H,R,U\}} \theta^k_{iH}\mathcal{E}_{k,t}P^k_{iH,t}, \quad \text{for } i \in \{R, U\} \tag{2.3.25}$$

2.3.4 Real exchange rate, terms of trade, and the country resource constraint

The real exchange rate between country i and H is defined as the ratio between the price of consumption in country i expressed in currency H, $\mathcal{E}_{i,t}P^i_{i,t}$, to the price of consumption in country H,

$$\mathcal{Q}_{i,t} \equiv \frac{\mathcal{E}_{i,t}P^i_{i,t}}{P_t} \tag{2.3.26}$$

where $P^i_{i,t}$ is CPI in country i in currency i.

The terms of trade between country i and H are defined as the price ratio of imports to exports, expressed in currency H,

$$\mathcal{S}_{i,t} = \frac{P_{iH,t}}{\mathcal{E}_{i,t}P^i_{Hi,t}} \tag{2.3.27}$$

where $P_{iH,t}$ is the price index of imports to H from i in expressed in currency H, and $P^i_{Hi,t}$ is the price index of exports from country H to country i expressed in currency i, and the export / import price indices are defined by (2.3.25).

Net exports are defined as the difference between the of sum exports to and the sum of imports from countries R and U in all currencies,

$$NX_t \equiv P_{HR,t}Y_{HR,t} + P_{HU,t}Y_{HU,t} - P_{RH,t}Y_{RH,t} - P_{UH,t}Y_{UH,t} \tag{2.3.28}$$

Aggregating over all households' budget constraints and plugging firms' profits, we obtain country H's resource constraint,

$$\frac{\mathcal{E}_{U,t}B^U_{t+1}}{e^{\psi_t}R^U_t} - B^U_t\mathcal{E}_{U,t} = NX_t \tag{2.3.29}$$

2.3.5 Monetary policy

Domestic interest rate $i_t \equiv \log R_t$ follows a simple Taylor rule with inertia that targets inflation and the output gap, given by

$$i_t - i^* = \rho_m\left(i_{t-1} - i^*\right) + \left(1 - \rho_m\right)\left(\phi_M\pi_t + \phi_Y\widetilde{y}_t\right) + v_t \tag{2.3.30}$$

where i^* is the log global interest rate, ρ_M is the inertia parameter, ϕ_M and ϕ_Y are monetary policy weights selected by the monetary authority, $\pi_t \equiv \log\left(\frac{P_t}{P_{t-1}}\right)$ is the CPI inflation rate, $\tilde{y}_t$ is the log of the output gap, and v_t is a monetary policy shock that follows the AR(1) process $v_t = \rho_{\epsilon_M,t}v_{t-1} + \epsilon^M_t$.

Additionally, following Schmitt-Grohé & Uribe (2003), in order to induce stationarity it is assumed that the burrowing rate for the U-denominated bond is a function of external debt

$$R^U_t = R^* + \phi\left(\exp\left(\frac{B^U_{t+1}}{P^U} - \overline{B}^U\right) - 1\right) \tag{2.3.31}$$

where $\phi > 0$ measures the responsiveness of country H's burrowing rate to the level of external debt $\frac{B^U_{t+1}}{P^U}$ (P^U is a price level exogenous from country H's perspective), $\overline{B}^U$ is the steady state level of debt denominated in U.

Finally, the real exchange rate between countries U and R is exogenous from the SOE H's perspective, and assumed to satisfy the following relation (in logs)

$$e_{R,t} + p^R_{R,t} - p_t = \eta\left(e_{U,t} + p^U_{U,t} - p_t\right) + r_t \tag{2.3.32}$$

where $p^i_{i,t}$ is the log CPI in country $i \in \{R, U\}$ in its domestic currency, η is a parameter that captures comovement between the two RERs, and r_t is an exogenous shock that captures changes in the bilateral exchange rate between R and U, following the AR(1) process $r_t = \rho_r r_{t-1} + \epsilon^r_t$.

2.3.6 Equilibrium

A competitive equilibrium in the small open economy is a sequence of allocations $\left\{\{C_{iH,t}\}_i, N_t, B_{t+1}(s'), B^U_{t+1}\right\}$, inputs $\left\{L_t, \{X_{iH,t}\}_i\right\}$, wages set by households $\left\{\overline{W}_t(h)\right\}$, reset prices set by firms $\left\{\overline{P}^k_{ij,t}\right\}$; given exchange rates $\{\mathcal{E}_{U,t}, \mathcal{E}_{R,t}\}$, interest rates $\left\{R_t, R^U_t\right\}$, exogenous shocks $\{\zeta_t, a_t, v_t, r_t\}$, and all the foreign variables in the LOEs which are taken as exogenous, such that

1. Goods market clears $Y_t(\omega) = \sum_{i\in\{H,R,U\}} [C_{Hi,t}(\omega) + X_{Hi,t}(\omega)]$, $\forall\omega$;
2. Labor market clears $N_t(h) = L_t(h)$, $\forall h$;
3. Domestic bond market clears $B_t(s) = 0, \forall s \in S$.

2.3.7 Consumption aggregator functional form

As in Gopinath et al. (2020), the functional form chosen for $\Upsilon(\cdot)$ in the Kimball aggregator is the one suggested in Klenow & Willis (2016),

$$\Upsilon(x) = 1 + (\sigma - 1)\exp\left(\frac{1}{\varepsilon}\right)\varepsilon^{\frac{\sigma}{\varepsilon}-1}\left(\Gamma\left(\frac{\sigma}{\varepsilon}, \frac{1}{\varepsilon}\right) - \Gamma\left(\frac{\sigma}{\varepsilon}, \frac{x^{\frac{\varepsilon}{\sigma}}}{\varepsilon}\right)\right) \tag{2.3.33}$$

where $\Gamma(u, z)$ is the incomplete gamma function $\Gamma(u, z) \equiv \int_z^\infty s^{u-1}e^{-s}ds$, and ε, σ are parameters that govern the elasticity of substitution and the steady state markup. Thus, the derivative of $\Upsilon(\cdot)$ is $\Upsilon'(x) = \frac{\sigma-1}{\sigma}\exp\left(\frac{1-x^{\frac{\varepsilon}{\sigma}}}{\varepsilon}\right)$ and the inverse of the derivative is

$$\varphi(x) \equiv \Upsilon'^{-1}(x) = \left(1 + \varepsilon\log\left(\frac{\sigma-1}{\sigma x}\right)\right)^{\frac{\sigma}{\varepsilon}} \tag{2.3.34}$$

which gives rise to the following individual demand function

$$C^k_{iH,t}(\omega) = \gamma_H \left(1 + \varepsilon \log\left(\frac{\sigma - 1}{\sigma}\right) - \varepsilon \log\left(D_t \frac{\mathcal{E}_{k,t} P^k_{iH,t}(\omega)}{P_t}\right)\right)^{\frac{\sigma}{\varepsilon}} C_t \tag{2.3.35}$$

with the demand elasticity $\sigma_{iH,t}(\omega) = \frac{\sigma}{1+\varepsilon\log\left(\frac{\sigma-1}{\sigma}\right) - \varepsilon\log\left(Z_{iH,t}(\omega)\right)}$, the log markup $\mu_{iH,t}(\omega) \equiv \log\left(\frac{\sigma_{iH,t}(\omega)}{\sigma_{iH,t}(\omega)-1}\right)$, and the elasticity of the markup $\Gamma_{iH,t}(\omega) = \frac{\varepsilon}{\sigma-1-\varepsilon\log\left(\frac{\sigma-1}{\sigma}\right)+\varepsilon\log\left(Z_{iH,t}(\omega)\right)}$.

2.4 Empirical results

The model yields several testable hypotheses about the relationship between exchange rate pass-through and the currency in which import and export prices are sticky. Let $\Delta p_{ij,t}$ denote the change in log price index of exports from country i (e.g., UK) to country j (e.g., Sweden), measured in currency j (e.g., SEK) at time t. $\Delta e_{kj,t}$ is the change in log nominal bilateral exchange rate between currency k and currency j at time t, expressed as units of currency j to one unit of currency k (e.g., $\Delta e_{kj,t} > 0$ is a depreciation of SEK against GBP). The change in the log price index of exports can be decomposed into

$$\Delta p_{ij,t} = \sum_k \theta^k_{ij} \left(\Delta p^k_{ij,t} + \Delta e_{kj,t}\right) \tag{2.4.1}$$

where $\theta^k_{ij} \in [0,1]$ is the share of exports invoiced in currency $k \in \{i,j,u\}$, $\theta^i_{ij} + \theta^j_{ij} + \theta^u_{ij} = 1$, and $\Delta p^k_{ij,t}$ is the change in log price index of exports from country i to country j that are invoiced in currency k. That is, the aggregate export price index is affected by changes in the prices of goods set in the producer i (e.g., GBP), local j (e.g., SEK) or dominant u (e.g., USD) currency, and by the exchange rate between the importer's currency j and the currency of invoicing k (i or u).

The export prices index of goods invoiced in currency k can be expressed as

$$\Delta p^k_{ij,t} + \Delta e_{kj,t} = (1 - \delta_p)\left(\overline{p}^k_{ij,t} - p^k_{ij,t-1}\right) + \Delta e_{kj,t} \tag{2.4.2}$$

where $1 - \delta_p$ is the share of firms updating their price in period t.

Combining both export price indices, we obtain

$$\Delta p_{ij,t} = \theta_{ij}^{i} \Delta e_{ij,t} + \theta_{ij}^{u} \Delta e_{uj,t} + (1 - \delta_p) \sum_{k} \theta_{ij}^{k} \left(\overline{p}_{ij,t}^{k} - p_{ij,t-1}^{k} \right) \tag{2.4.3}$$

That is, the change in the log export price index is affected by exchange rate fluctuations and those fluctuations are scaled by the share of exports invoiced in the specific currency k. Other factors affect the change in export prices to the extent that export prices are adjusted, namely changes in the marginal cost of exporters, demand, etc.

If the price $p_{ij,t}^{k}$ is fully rigid and does not adjust ($\delta_p = 1$), then the changes in the price of exports between country i to country j and the terms of trade are given by

$$\Delta p_{ij,t} = \theta_{ij}^{i} \Delta e_{ij,t} + \theta_{ij}^{u} \Delta e_{uj,t} \tag{2.4.4}$$

$$\Delta p_{ji,t} = \theta_{ji}^{i} \Delta e_{ij,t} + \theta_{ji}^{u} \Delta e_{uj,t} \tag{2.4.5}$$

$$\Delta tot_{ij,t} = \Delta p_{ij,t} - \Delta p_{ji,t} \tag{2.4.6}$$

where the price index of exports from j to i, $p_{ji,t}$, is also expressed in units of currency j for ease of comparison.

Three limiting cases arise from this setup:

- PCP: $\theta_{ij}^{i} = \theta_{ji}^{j} = 1$ and $\theta_{ij}^{j} = \theta_{ji}^{i} = \theta_{ij}^{u} = \theta_{ji}^{u} = 0$, $\Delta p_{ij,t} = \Delta e_{ij,t}$, $\Delta p_{ji,t} = 0$, $\Delta tot_{ij,t} = \Delta e_{ij,t}$
- LCP: $\theta_{ij}^{j} = \theta_{ji}^{i} = 1$ and $\theta_{ij}^{i} = \theta_{ji}^{j} = \theta_{ij}^{u} = \theta_{ji}^{u} = 0$, $\Delta p_{ij,t} = 0$, $\Delta p_{ji,t} = \Delta e_{ij,t}$, $\Delta tot_{ij,t} = -\Delta e_{ij,t}$
- DCP: $\theta_{ij}^{u} = \theta_{ji}^{u} = 1$ and $\theta_{ij}^{i} = \theta_{ji}^{j} = \theta_{ij}^{j} = \theta_{ji}^{i} = 0$, $\Delta p_{ij,t} = \Delta e_{uj,t}$, $\Delta p_{ji,t} = \Delta e_{uj,t}$, $\Delta tot_{ij,t} = 0$

However, in the case of MCP, both the bilateral exchange rate, $e_{ij,t}$, and the exchange rate with currency u, $e_{uj,t}$, will affect import price inflation and the terms of trade:

- MCP: $\theta_{ij}^{k} > 0, \forall k \in \{i, j, u\}$, $\Delta p_{ij,t} = \theta_{ij}^{i} \Delta e_{ij,t} + \theta_{ij}^{u} \Delta e_{uj,t}$, $\Delta p_{ji,t} = \theta_{ji}^{j} \Delta e_{ij,t} + \theta_{ji}^{u} \Delta e_{uj,t}$, $\Delta tot_{ij,t} = \left(\theta_{ij}^{i} - \theta_{ji}^{i} \right) \Delta e_{ij,t} + \left(\theta_{ij}^{u} - \theta_{ji}^{u} \right) \Delta e_{uj,t}$.

This limiting fully rigid prices case serves as the extreme case for the effect of exchange rate changes on economies with different invoicing currency regimes. In the case of a small open economy with

MCP, we expect to find substantial, but incomplete, pass-through rate for both the bilateral exchange rate and the vehicle currency exchange rate vis-a-vis the domestic currency. The effect on the terms of trade is ambiguous, but it is likely to be different than zero, which is the case with DCP.

In light of this hypothesis, we estimate exchange rate pass-through into import and export prices, and terms of trade, for Sweden. We estimate standard pass-through regressions prevalent in the literature (see Campa & Goldberg (2005) and Burstein & Gopinath (2014)), which follow from the model prediction (2.4.3):

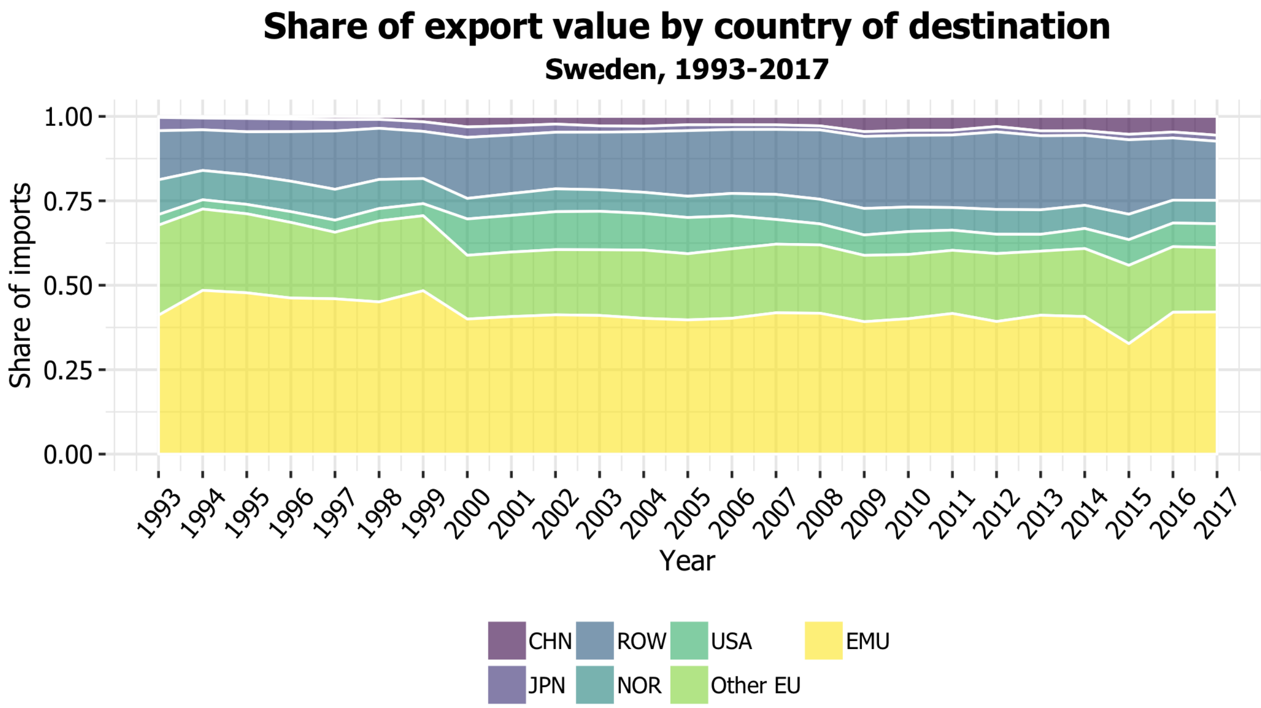
$$\Delta p_{j,t} = \sum_{\ell=0}^{2} \beta_\ell^j \Delta e_{j,t-\ell} + \sum_{\ell=0}^{2} \beta_\ell^\$ \Delta e_{\$,t-\ell} + \sum_{\ell=0}^{2} \alpha_\ell \Delta ppi_{j,t-\ell} + \lambda_j + \varphi_t + \varepsilon_{j,t} \tag{2.4.7}$$

$$\Delta tot_{j,t} = \sum_{\ell=0}^{2} \beta_\ell^j \Delta e_{j,t-\ell} + \sum_{\ell=0}^{2} \alpha_\ell \Delta ppi_{j,t-\ell}^{diff} + \lambda_j + \varphi_t + \varepsilon_{j,t} \tag{2.4.8}$$

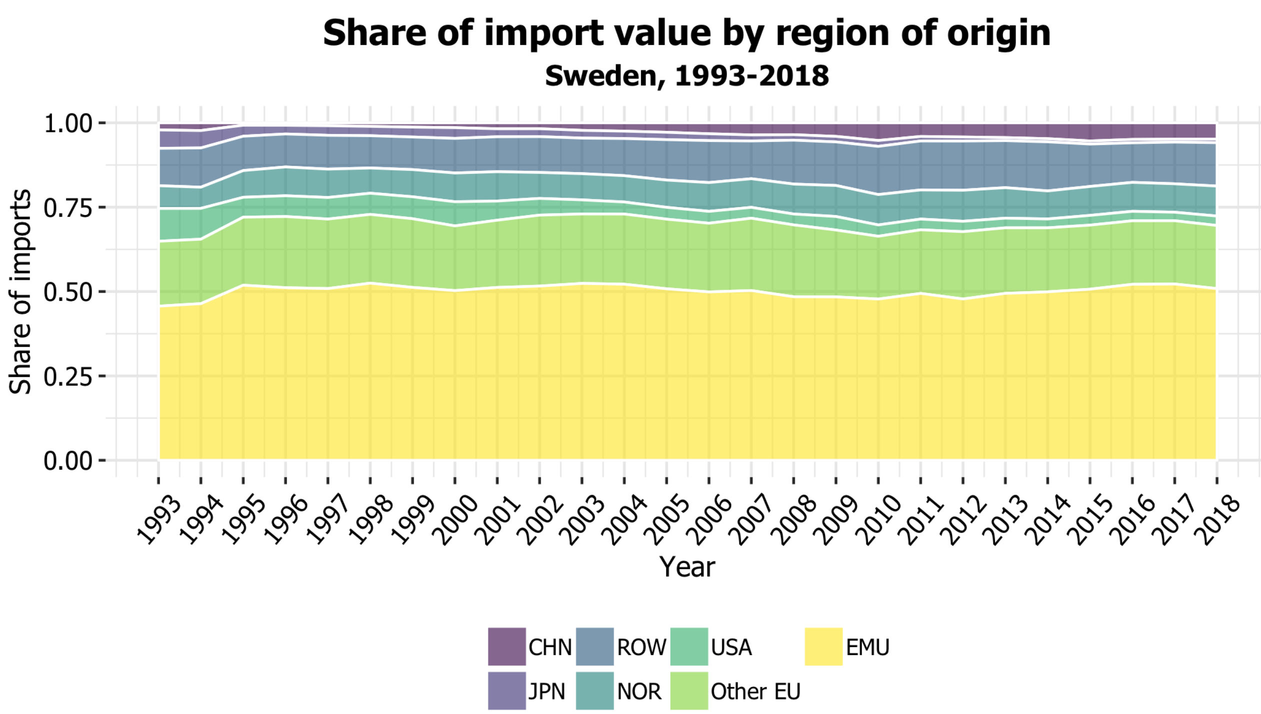
where $\Delta p_{j,t}$ is The import (export) log price change represented by the change in a chained Fisher index for imports (exports) from (to) country j to (from) Sweden, measured in SEK (destination currency j); $\Delta e_{j,t}$ is the change in log nominal bilateral exchange rate between country j and Sweden at time t, expressed as units of currency j to one unit of Swedish krona for exports, and the reciprocal for imports; $\Delta ppi_{j,t}$: The change in log producer price index for country j (Sweden PPI for exports); $\Delta ppi_{j,t}^{diff} = \Delta ppi_{j,t} - \Delta ppi_{SWE,t}$; and λ_j, φ_t are country and time fixed effects.

2.4.1 Data

We collect data for the value and quantity of international trade from the UN COMTRADE database, which includes all international transactions at varying levels of aggregation. The data is available in annual frequency for 1989-2018 at the HS6 level categories of goods, which constitutes 6,406 categories for imports and 6,492 categories for exports. We use the data reported to COMTRADE by the importer country rather than by Sweden for exports, as the reporting importer data is considered more accurate since imports pass through customs in the destination country. We focus on manufacturing goods and omit commodities from the sample. Commodities are defined as HS chapters 1-27 and 72-83.



(A) Exports



(B) Imports

Figure 2.3: Share of Swedish trade value by region of destination, 1993-2017

Source: UN COMTRADE, own calculations.

Figure 2.3 shows the share of the value of exports and imports by destination region. Eurozone countries are the destination of approximately 45.3% of the value of Sweden's international transactions. In comparison, dollarized economies (mainly the US) are 6.9%, the top 15 trading partners in the rest of the world (including the UK, Denmark, Norway, and Switzerland) account for 39.1%, and the rest of the world is 8.7% of the total value. These shares are relatively stable over the period.

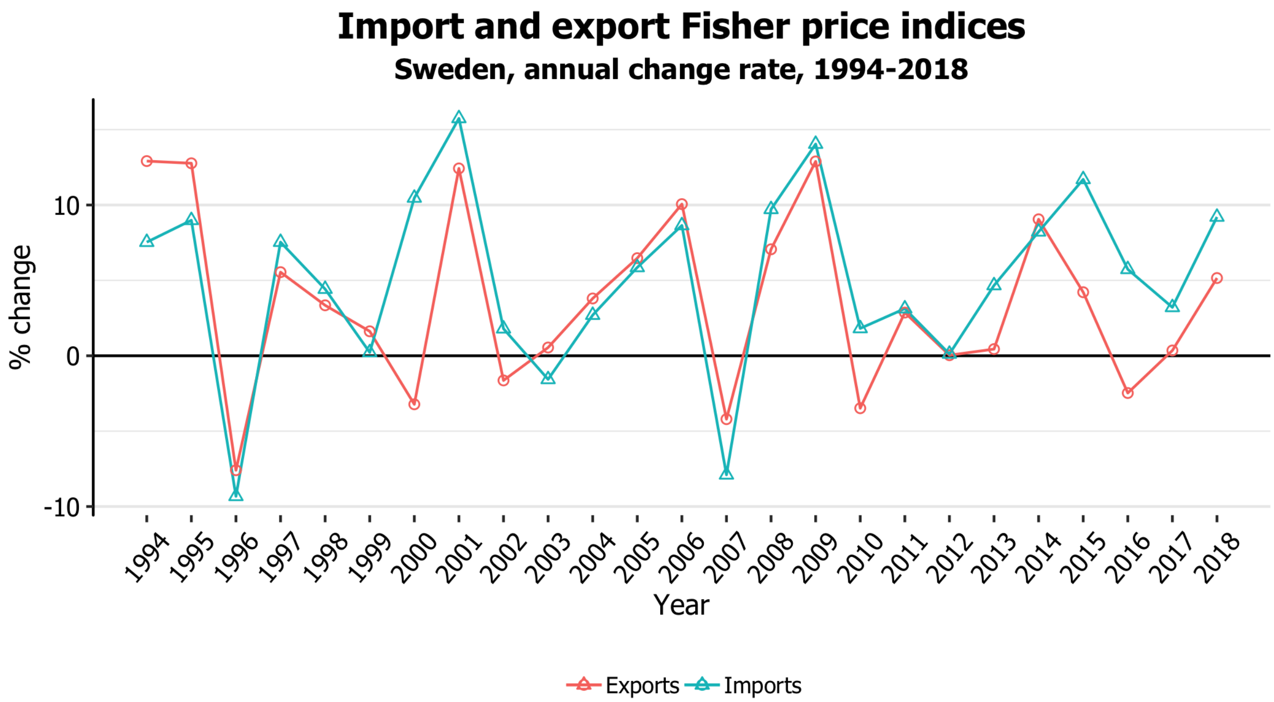
Price indices are constructed following the methodology of Gaulier et al. (2008) for COMTRADE data. The dependent variable $\Delta p_{j,t}$ is the first difference of the log chained Fisher price index, which is constructed from unit values that are calculated using the value of trade and the net weight in kilograms, both of which are available in the data.[8] Observations with missing weight or value account for 6.4% of exports and 5.1% of imports. As some unit values present extreme and unlikely year-on-year changes during the sample period, the criterion for outliers presented in Gaulier et al. (2008) is adopted to deal with them: observations for goods category m from country j are dropped if $\Delta p_{j,m,t}$ is 5 times larger or smaller than the median price change in category m at time t in all countries. These outliers account for 7.4% of exports and 3.4% of imports. Finally, we use the concordance developed by Pierce and Schott (2012) to deal with the change in HS categories every five years, and mitigate these changes in the relevant years. The export and import chained Fisher price indices and the terms of trade are presented in figure 2.4.

Other variables are collected as follows. Bilateral exchange rates are retrieved from the World Bank's alternative conversion factor, a series which accounts for currency changes. The relative change in the PPI, $\Delta ppi^{diff}_{j,t-\ell}$, is calculated using the World Bank's national PPI indices, after converting them into a common currency.

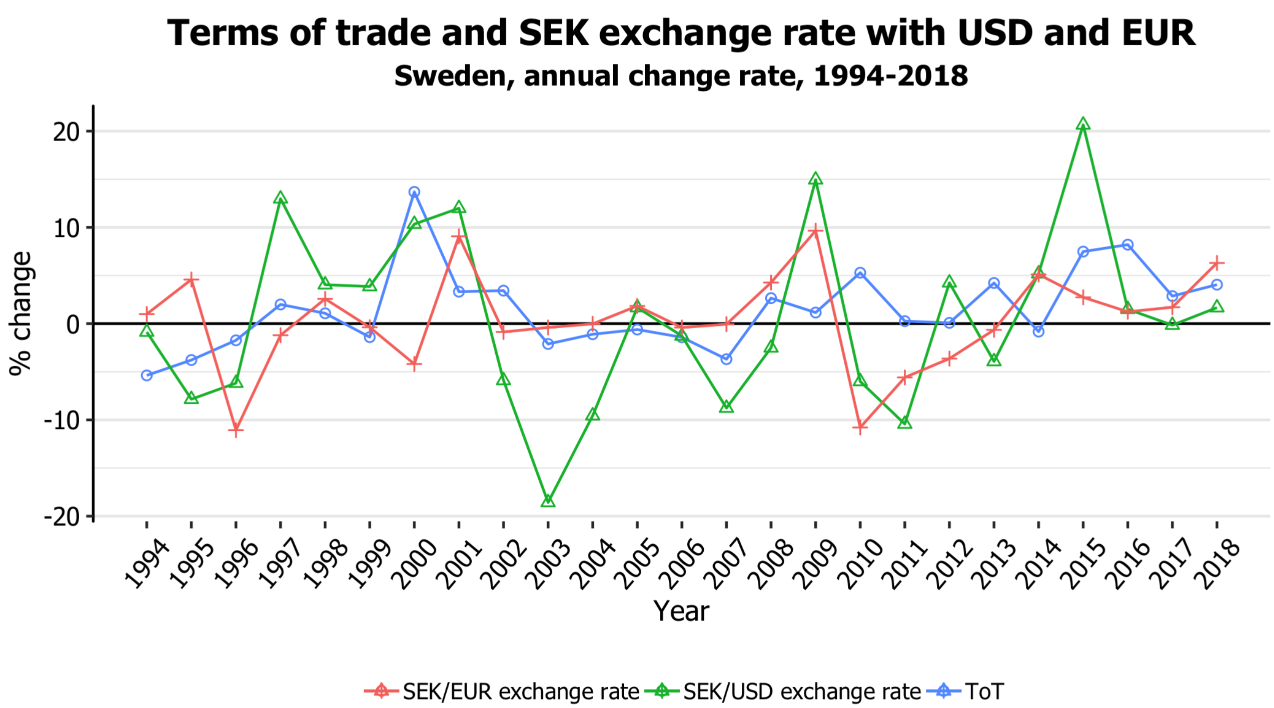
2.4.2 Results

The following results from estimating equations (2.4.7)-(2.4.8) in the data for Sweden point towards an economy with meaningful shares of invoicing in producer, local, and dollar (vehicle)

[8] The Fisher price index, also known as the 'ideal' price index, is constructed as a weighted average of the Laspeyres and Paasche indices and is commonly used to measure import/export prices. While the choice of index may depend on the purpose of the analysis and the data available, using the Laspeyres or Paasche indices separately has little consequence on the results presented herein.



(A) Export and price indices



(B) Terms of trade and SEK exchange rates

Figure 2.4: Sweden: Export and price indices, terms of trade, and exchange rates
Source: UN COMTRADE, World Bank, own calculations.

Table 2.1: Terms of trade and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$
$\Delta e_{j/SEK,t}$	.408***	.594***	.386***	.435***
	(.103)	(.161)	(.0647)	(.127)
Observations	2054	1132	2054	1132
R^2	.615	.811	.967	.973
Trading partners	141	68	141	68
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes
PPI	no	yes	no	yes
Lags	2	2	2	2

Note: Results of estimation of equation (2.4.8). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. Full results are presented in table 2.9. *** p<0.01, ** p<0.05, * p<0.1.

currencies. Table 2.1 presents results from estimating the effect of bilateral exchange rate changes on terms of trade between Sweden and trading partners, specified in equation (2.4.8). The results of the trade-weighted regression, controlling for the change in PPI differentials, indicate that a 10% depreciation of SEK vs. currency j is associated with a 4.35% increase in terms of trade with country j. This result is a stark departure from the predictions of the three pricing paradigms, and is instead in line with an economy with multiple invoicing currencies with a slight tilt towards PCP. This result is in line with the trading and invoicing patterns for Sweden, i.e. major shares of international transactions are invoiced in producer and destination currencies. There is no major difference between the weighted and unweighted regressions.

Table 2.2 presents results from estimating bilateral and dollar exchange rate pass-through into Sweden import prices, specified in equation (2.4.7). The price is measured in SEK, and the exchange rate is units of SEK to 1 unit of trading partner currency. Columns (2) and (4) include the exchange rate between SEK and USD as well as the bilateral exchange rate. Results from the trade-weighted regression in column (4) indicate that a 10% depreciation of SEK against the producer's currency is associated with a 5.45% increase in import prices. A 10% depreciation of SEK vs. USD is associated with a 2.31% increase in import prices. These results deviate from what would be expected with each "pure" pricing paradigm but align with an economy where a meaningful share of transactions is

Table 2.2: Import prices and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$
$\Delta e_{SEK/j,t}$	.377***	.278**	.646***	.545***
	(.106)	(.109)	(.0696)	(.0752)
$\Delta e_{SEK/USD,t}$		.379***		.231***
		(.0808)		(.044)
Observations	1189	1189	1189	1189
R^2	.277	.295	.251	.31
Trading partners	68	68	68	68
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes
Exporter PPI	yes	yes	yes	yes
Lags	2	2	2	2

Note: Results of estimation of equation (2.4.7). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. Full results are presented in table 2.10. *** p<0.01, ** p<0.05, * p<0.1.

priced in USD, producer, and local currency.

Table 2.3 presents results from the same trade-weighted regression analysis conducted for three groups of countries separately: dollarized economies (U.S., Ecuador, and El Salvador), countries in the European Monetary Union, and the rest of the world. A 10% depreciation of SEK relative to USD is associated with an 8.2% increase in import prices from dollarized economies, consistent with the dollar being the currency of invoicing in the overwhelming share of transactions (for example, Gopinath & Rigobon (2008) find that more than 90% of U.S. exports are invoiced in U.S. dollar). In imports from EMU countries, a 10% depreciation of SEK against the euro is associated with an 8% increase in import prices, which again points towards the euro being the primary currency of invoicing. For EMU countries, a 10% depreciation of SEK against USD is associated with only a 1.8% increase in import prices. For the rest of the world, pass-through estimates are in line with significant shares of multiple invoicing currencies, especially the SEK (that is, LCP). A 10% depreciation of SEK against the producer's currency is associated with a 3.4% increase in import prices. In comparison, a 10% depreciation of SEK against USD is associated with a 3% increase in import prices.

Table 2.3: Import prices and exchange rate by country group

	(1) Dollarized	(2) EMU	(3) Rest of World
$\Delta e_{SEK/USD,t}$	.821***	.178***	.3***
	(.244)	(.0548)	(.072)
$\Delta e_{SEK/j,t}$		.798***	.343***
		(.13)	(.0876)
Observations	53	366	770
R^2	.558	.367	.278
Trading partners	3	18	47
Country FE	yes	yes	yes
Time FE	yes	yes	yes
Exporter PPI	yes	yes	yes
Lags	2	2	2

Note: Results of estimation of equation (2.4.7) for three groups of countries: dollarized economies (U.S., El Salvador, and Ecuador), European Monetary Union, and the rest of the world. Regressions are trade-weighted. Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. Full results are presented in table 2.11. *** p<0.01, ** p<0.05, * p<0.1.

Table 2.4 presents results from estimating (2.4.7) for exports from Sweden to the rest of the world, where the prices are measured in the local destination currency, j. The specifications are identical to those in table 2.2. Results in column (4) indicate that a 10% depreciation of the local currency vs. SEK is associated with a 3.75% increase in export prices. In comparison, a 10% depreciation of the local currency vs. USD is associated with a 2.1% increase in export prices. This pattern is similar to the one observed in import prices: it is far from each "pure" pricing paradigm but points towards PCP, LCP, and DCP having large shares in Swedish exports' invoicing.

Table 2.5 presents pass-through estimation results by country group. In dollarized economies (column (1)), a 10% depreciation of SEK against the USD is associated with a 1.5% decrease in export prices, but this estimate is not statistically significant. This finding aligns with Swedish exports to dollarized countries invoiced overwhelmingly in USD.[9] In EMU countries (column (2)), a 10% depreciation of the euro against SEK (USD) is associated with a 1.1% (0.7%) increase in export prices, and both of these estimates are not statistically significant. The estimators' size and lack of

[9] The set of dollarized countries for exports is larger due to data availability and includes U.S., El Salvador, Ecuador, Antigua and Barbuda, Dominica, Grenada, Hong Kong, Saint Kitts and Nevis, Saint Lucia, Panama, Saint Vincent and the Grenadines.

Table 2.4: Export prices and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$
$\Delta e_{j/SEK,t}$	.486***	.314***	.45***	.375***
	(.0541)	(.0667)	(.0525)	(.0559)
$\Delta e_{j/USD,t}$		.371***		.21***
		(.0622)		(.0469)
Observations	2614	2614	2614	2614
R^2	.172	.182	.202	.219
Trading partners	165	165	165	165
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes
Exporter PPI	yes	yes	yes	yes
Lags	2	2	2	2

Note: Results of estimation of equation (2.4.7). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. Full results are presented in table 2.12. *** p<0.01, ** p<0.05, * p<0.1.

statistical significance align with LCP for Swedish exports to the EMU.[10] Finally, for the rest of the world (column (4)), a 10% depreciation of the local currency against SEK (USD) is associated with a 3.8% (2.8%) increase in export prices. This finding indicates considerable shares of different invoicing currencies, with SEK, the local currency, and USD all playing a significant role.

Overall, these results indicate that an economy with a non-negligible share of invoicing currencies displays different patterns of exchange rate pass-through into import prices than the three "pure" paradigms.[11] Next, we calibrate the New Keynesian small open economy model to Sweden and show that significant producer, local, and vehicle currency shares can account for these exchange rate pass-through patterns. We then discuss macroeconomic implications by analyzing impulse response functions.

[10] According to Gopinath (2015), virtually all exports to EMU countries from non-euro EU countries are invoiced in euro.

[11] Additional and extended results are presented in Appendix 2.C.

Table 2.5: Export prices and exchange rate by country group

	(1) Dollarized	(2) EMU	(3) Rest of World
$\Delta e_{SEK/USD,t}$	-.154		
	(.17)		
$\Delta e_{j/SEK,t}$		.106	.481***
		(.111)	(.0687)
$\Delta e_{j/USD,t}$		.0711	.28***
		(.0649)	(.065)
Observations	164	390	2060
R^2	.141	.165	.278
Trading partners	11	18	136
Country FE	yes	yes	yes
Time FE	yes	yes	yes
Exporter PPI	yes	yes	yes
Lags	2	2	2

Note: Results of estimation of equation (2.4.7) for three groups of countries: dollarized economies (U.S., El Salvador, Ecuador, Antigua and Barbuda, Dominica, Grenada, Hong Kong, Saint Kitts and Nevis, Saint Lucia, Panama, Saint Vincent and the Grenadines), European Monetary Union, and the rest of the world. Regressions are trade-weighted. Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. Full results are presented in table 2.13. *** p<0.01, ** p<0.05, * p<0.1.

2.5 Quantitative analysis

The data for Sweden point strongly towards an economy with multiple currencies used in invoicing imports and exports. To discern between the different pricing paradigms and their relevance for the data, we take the data to the model presented in section 2.3. In the model, the Home country, H, is Sweden, the first large economy is the U.S., U, and the second large economy is the rest of the world (ROW), R. Parameter values are taken from the literature, estimated or measured directly in the data, and calibrated using the simulated method of moments. The calibrated model can account well for estimated exchange rate pass-through rates for Sweden, implying significant shares of local, producer, and vehicle currencies used in invoicing of international transactions. We simulate data from the model and compare estimates of exchange rate pass-through in the data and the model, and then compare the economy's response to exogenous shocks under MCP relative to the "pure" pricing paradigms: PCP, LCP, and DCP.

2.5.1 Matching data and model

We solve the model by log linearizing around the symmetric perfect foresight steady state with balanced trade (detailed in appendix 2.B). The parameterization is a combination of parameter values taken from the literature, parameters estimated directly from the data, and parameters calibrated using simulated method of moments. Parameters values taken from the literature (see, e.g., Galí (2015) and Gopinath et al. (2020)) are reported in table 2.6. The discount factor is $\beta = 0.99$ such that the steady state (quarterly) international interest rate is $i^* = \beta^{-1} - 1 = 1.01\%$. The elasticity of demand and the risk aversion coefficient are both assumed to be $\sigma = \sigma_c = 2$, in the midpoint of macro elasticities of substitution between domestic and foreign varieties estimated by Broda & Weinstein (2006) and Feenstra et al. (2018). The Kimball aggregator superelasticity parameter is $\varepsilon = 1$, which implies that the elasticity of the markup is $\Gamma = \varepsilon / (\sigma - 1) = 1$, a value consistent with estimates in Amiti, Itskhoki & Konings (2019). The following parameters are set at standard values in the literature, following Gopinath et al. (2020): the inverse Frisch elasticity of labor supply is $\varphi^{-1} = 0.5$, the elasticity of substitution across labor varieties is $\vartheta = 4$, the disutility from labor

Table 2.6: Parameter values from the literature

Parameter	Value
Households	
Discount factor β	0.99
Risk aversion σ_c	2
Elasticity of demand σ	2
Superelasticity ε	1
Inverse Frisch elasticity of labor supply φ^{-1}	0.5
Disutility from labor κ	1
Wage rigidity δ_w	0.85
Firms	
Share of intermediate inputs α	2/3
elasticity of substitution across labor varieties ϑ	4
Price rigidity δ_p	0.85
Monetary & Financial	
International interest rate i^*	$\beta^{-1} - 1$
Taylor rule inertia ρ_m	0.5
Inflation sensitivity ϕ_M	1.5
Output gap sensitivity ϕ_y	1.5/4
Exogenous processes	
Autocorrelation monetary shock ρ_v	0.5
SD monetary shock σ_ν	0.025
Autocorrelation financial shock ρ_ζ	0.95
SD financial shock σ_ζ	0.025

scaling factor is $\kappa = 1$, the international bond interest rate elasticity is $\phi = 1.0 - e6$, the Calvo price and wage stickiness are set at $\delta_p = 0.75$ and $\delta_w = 0.85$, and the share of intermediates in production is $\alpha = 2/3$. Parameters for the Taylor rule are in line with standard values in Galí (2015): Taylor rule inertia $\rho_m = 0.5$, inflation sensitivity of the Taylor rule $\phi_M = 1.5$, output gap sensitivity $\phi_y = 1.5/4$, autocorrelation of monetary shocks process $\rho_v = 0.5$, and the standard deviation of monetary shocks $\sigma_\nu = 0.025$. Finally, the parameters of the financial (UIP) shocks, are set to values comparable to Itskhoki & Mukhin (2021): autocorrelation of financial shocks $\rho_\zeta = 0.95$, and standard deviation $\sigma_\zeta = 0.025$.

The parameters $\overline{B}^U, \gamma_H, D_U, D_R$ are set to match the following moments in steady state: share of manufacturing exports to dollarized economies to GDP = 2.02%, share of manufacturing exports to ROW to GDP = 28.65%, and debt to GDP ratio = 64.2%.[12] The implied parameter values are reported by table 2.7a. The parameters for the invoicing shares in Swedish exports are measures in the dataset constructed in Gopinath (2015), and are also reported in table 2.7a.[13]

The parameters governing the productivity shocks, the real exchange rate between U and R, and the invoicing shares of imports are calibrated jointly to match data moments. The vector of calibrated parameters is $\mathbf{v} = \left(\rho_a, \sigma_a, \eta, \rho_r, \sigma_r, \theta^U_{UH}, \theta^U_{RH}, \theta^R_{RH}\right)$, and the corresponding vector of differences between the data moments and the simulated moments is $\mathbf{m}\left(\mathbf{v}\right)$. The values of $\mathbf{v}$ are chosen to minimize deviations between data and simulated moments:

$$\mathbf{m}\left(\mathbf{v}\right)\boldsymbol{\Sigma}^{-1}\mathbf{m}\left(\mathbf{v}\right) \tag{2.5.1}$$

where the weighting matrix Σ is a diagonal matrix with the standard errors of the data moments in the diagonal.

The data moments that are targeted are as follows (standard errors in parentheses):

- θ^U_{UH}: 1 year estimate of SEK-USD exchange rate (e_U) pass-through into U.S. import prices $\hat{\beta}^U_{UH,0} = 0.821$ (.244).

- $\theta^U_{RH}, \theta^R_{RH}$: 1 year estimate of SEK-USD and SEK-LC exchange rates (e_U, e_R) pass-through into ROW import prices $\hat{\beta}^R_{RH,0} = 0.545$ (.075), $\hat{\beta}^U_{RH,0} = 0.231$ (.044).

- η, ρ_r, σ_r: estimates of $\hat{\eta} = 0.923$ (0.0047), $\hat{\rho}_r = 0.912$ (0.041), $\hat{\sigma}_r = 0.021$ (0.033) at quarterly frequency using nominal exchange rates data from Sweden's Riksbank, and CPI data from the IMF's International Financial Statistics database. For the US and Sweden, e_U, p^U_U, and p are given in the data. For the rest of the world, nominal effective exchange rate e_R and average CPI p^R_R are calculated using trade-weights for all transactions between Sweden and trading partners. This implies a fairly high level of comovement between the USD RER and ROW

[12]Trade data is obtained from UN COMTRADE and data for macro variables is from the IMF International Financial Statistics database. Steady state moments are calculates as averages over the period 1995 to 2018.

[13]While there is no data on the share of currencies of invoicing in exports from Sweden to the U.S., several studies of U.S. import prices using BLS data from the International Prices Program found that U.S. imports, from developing and advanced economies, are overwhelmingly invoiced in dollars. Therefore, we set the invoicing share of Swedish exports to the U.S. to at 0.95, with 0.05 share of exports invoiced in SEK.

RER, while shocks are also highly persistent.

- ρ_a, σ_a: standard deviation and autocorrelation of Sweden manufacturing value added $\hat{\rho}_a = 0.953$ (0.0088), $\hat{\sigma}_a = 0.031$ (0.0212), estimated using World Bank WDI indicators.[14]

- Additional moments: 1 year estimate of SEK-USD exchange rate (e_U) pass-through into ROW import and export prices $\hat{\beta}^U_{HR,0} = 0.380$ (0.049), $\hat{\beta}^U_{RH,0} = 0.392$ (0.048).

The calibration process results using the simulated method of moments are reported in table 2.7b. The model matches the targeted moments well, especially the targeted estimates of exchange rate pass-through. The calibration implies that MCP is indeed the case for imported goods in Sweden. Imports from the U.S. are overwhelmingly invoiced in dollars (85%), with some U.S. imports invoiced in SEK (LCP, 15%). Imports from the ROW are roughly half invoiced in the producer's currency (55%), a third in the dollar as a vehicle currency (22%), and the rest in the local SEK (23%).

Table 2.8 compares exchange rate pass-through estimates into prices of Sweden's imports from and exports to the non-dollarized countries (ROW) over one year. Columns (1) and (3) estimate the effect of changes in the bilateral exchange rate (e_{RH}) only, while columns (2) and (4) include the SEK-USD exchange rate, e_{UH}, in addition. The calibrated model matches the data quite well, slightly more for export than import prices. In contrast, the three "pure" pricing paradigms fail to match the pass-through rates estimated in the data. Under DCP (dollar pricing in imports and exports), the dollar exchange rate pass-through is 38-40 percentage points too high, while the bilateral exchange rate pass-through is too low by similar magnitudes. Under PCP, the bilateral exchange rate pass-through is very high, around 80%, while the dollar exchange rate is much lower, less than 10%, in contrast to the data. Under LCP, the bilateral and the dollar exchange rate pass-through are very low, under 20% and 15%, respectively. These results are important since they demonstrate that for an economy like Sweden, MCP is the relevant case while assuming either DCP, PCP, or LCP leads to counterfactual exchange rate pass-through rates. MCP is an essential concept for analyzing the effects of shocks on a small open economy since the rate of exchange rate pass-through affects the inflation rate and, therefore, monetary policy, the relative competitiveness

[14]Estimates using data from Statistic Sweden yield roughly similar results.

Table 2.7: Parameter values: estimated and calibrated

A. Measured or estimated in the data			
Parameter	Value	Moment	Value
Steady state NFA $\overline{B}^U$	3.47	Govt. debt / GDP	0.65
Trade preference weights			
γ_H	0.88	EX \$ economies / EX ROW	0.067
$\gamma_U, \gamma_R = 1 - \gamma_H$	0.06		
Foreign demand			
D_U	-3.32	EX to \$ economies / GDP	0.02
D_R	-0.74	EX to ROW / GDP	0.28
Export invoice share			
ROW in \$ θ^U_{HR}	0.27	Gopinath (2015) dataset	
ROW in SEK θ^H_{HR}	0.39	Gopinath (2015) dataset	
ROW in LCP θ^R_{HR}	0.34	Gopinath (2015) dataset	
U.S. in \$ θ^U_{HU}	0.95	Gopinath (2015) dataset	
U.S. in SEKθ^H_{HU}	0.05	Gopinath (2015) dataset	

B. Calibrated				
Parameter	Value	Moment	Data	Model
Autocorrelation TFP ρ_a	0.95	$\hat{\rho}_a$	0.953	0.953
SD TFP σ_a	0.01	$\hat{\sigma}_a$	0.031	0.029
Autocorrelation RER shocks ρ_r	0.95	$\hat{\rho}_r$	0.912	0.912
SD RER shocks σ_r	0.03	$\hat{\sigma}_r$	0.021	0.023
RER comovement η	2.97	$\hat{\eta}$	0.923	0.923
Import invoice share				
U.S. in \$ θ^U_{UH}	0.85	$\hat{\beta}^U_{UH}$	0.821	0.821
U.S. in SEK θ^H_{UH}	0.15	$1 - \theta^U_{UH}$		
ROW in \$ θ^U_{RH}	0.22	$\hat{\beta}^U_{RH}$	0.231	0.227
ROW in SEK θ^H_{RH}	0.23	$\hat{\beta}^R_{RH}$	0.545	0.542
ROW in PCP θ^R_{RH}	0.55	$1 - \theta^U_{RH} - \theta^H_{RH}$		
Additional moments				
		$\hat{\beta}^U_{HU}$	0.838	0.874
		$\hat{\beta}^U_{HR}$	0.380	0.375
		$\hat{\beta}^U_{RH}$	0.392	0.395

Table 2.8: Exchange rate pass-through in the data and in the model

	Exports		Imports	
	(1)	(2)	(3)	(4)
	$\Delta p_{HR,t}$	$\Delta p_{HR,t}$	$\Delta p_{RH,t}$	$\Delta p_{RH,t}$
		Data		
$\Delta e_{RH,t}$	0.55	0.42	0.65	0.55
	(0.052)	(0.056)	(0.69)	(0.075)
$\Delta e_{UH,t}$		0.21		0.23
		(0.047)		(0.044)
		Calibrated model		
$\Delta e_{RH,t}$	0.47	0.38	0.51	0.42
$\Delta e_{UH,t}$		0.27		0.27
		DCP		
$\Delta e_{RH,t}$	0.31	0.18	0.34	0.20
$\Delta e_{UH,t}$		0.59		0.63
		PCP		
$\Delta e_{RH,t}$	0.22	0.19	0.81	0.79
$\Delta e_{UH,t}$		0.14		0.07
		LCP		
$\Delta e_{RH,t}$	0.78	0.77	0.22	0.19
$\Delta e_{UH,t}$		0.05		0.15

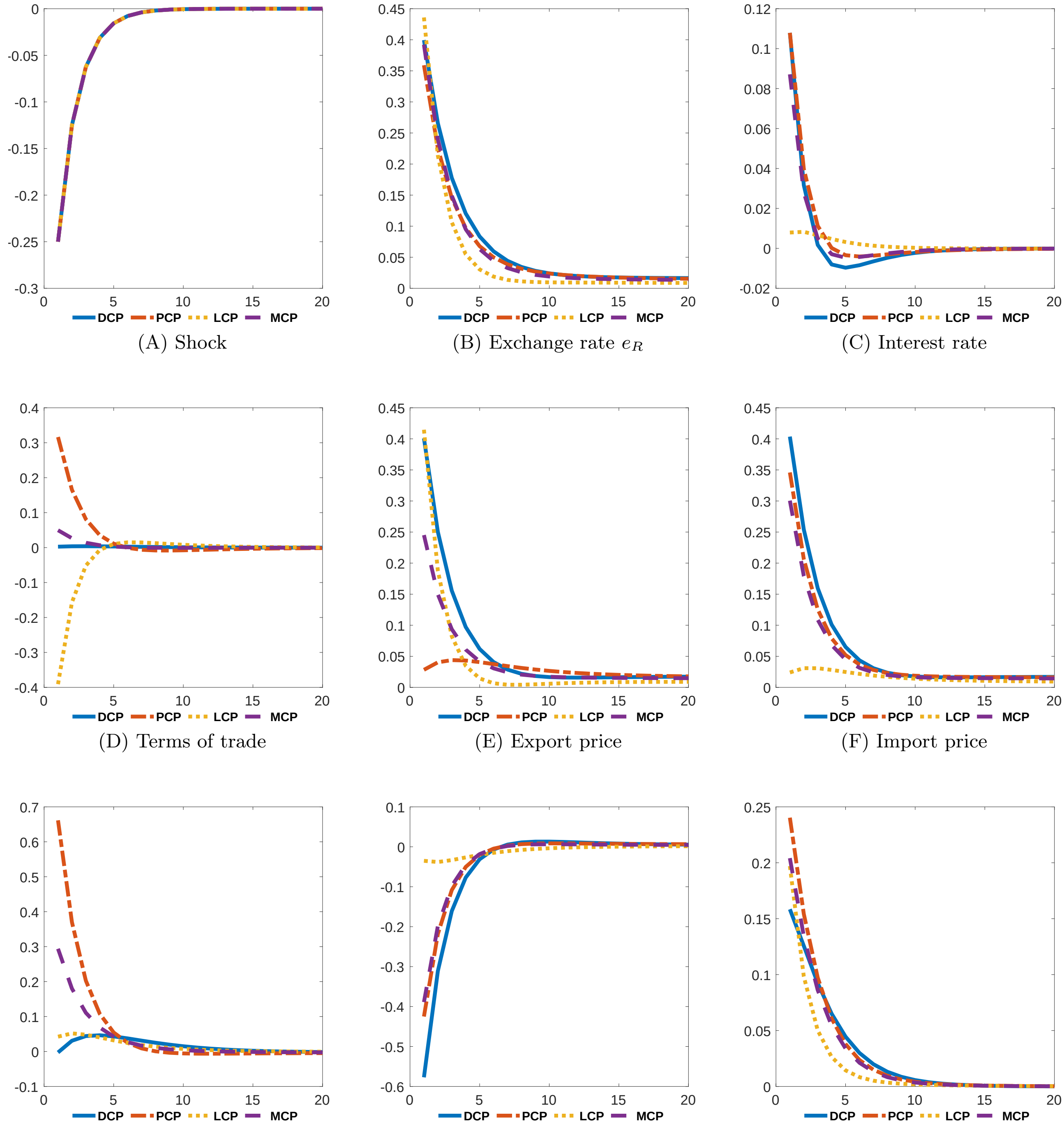
Note: Exchange rate pass-through estimates into Sweden import and export prices (in SEK) over one year, in the data and in the simulated model under different pricing paradigms. Columns (1) and (3) estimate only the effect of bilateral exchange rate, $\Delta e_{RH,t}$, while columns (2) and (4) additionally control for the SEK-USD exchange rate, $\Delta e_{UH,t}$. The data regressions include country and time fixed effects, and robust standard errors are in parentheses. The different pricing paradigms are differentiated by the shares of θ_{ij}^k for $i, j \in \{H, R\}$ and $k \in \{H, R, U\}$.

of domestic industries, and the trade balance. In the following subsection, we analyze the effects of financial and monetary shocks on an SOE with MCP using impulse response functions relative to the other pricing paradigms.

2.5.2 Impulse response functions

In this subsection, we analyze the response of the SOE to two exogenous shocks: a financial UIP shock and a monetary policy shock. The direction of both shocks leads to a depreciation of currency H against both currencies R and U. The first shock analyzed is a 25 basis points UIP deviation (financial shock). This shock results in a decrease in the spread $i_t - i_t^U$ and a depreciation of the domestic currency H vis-a-vis the dominant currency U. As a result of the high level of comovement between U and R, currency H depreciates against R as well. Figure 2.5 presents impulse response functions for this shock, contrasting the pricing paradigms PCP, LCP, and DCP with the case of multiple invoicing currencies (MCP). Since MCP is only prevalent in trade with R (for trade with country U there is DCP in currency U), and the volume of trade with U is small compared to R, we will focus only on variables related to trade with R.

A financial UIP shock leads to a depreciation of currency H. Under MCP, the depreciation leads to a price increase of both exports (measured in currency H) and imports. Inflation rises on impact due to the increase in import prices, but domestic price increases as well–due to the price of imported intermediate inputs increasing and expenditure switching towards domestic goods. The rise in inflation leads to an increase in the interest rate. The quantity of exports increases (since the price paid by importers in R in currency R decreases) while the quantity of imports decreases. GDP rises due to the increase in both exports and domestic production. Note that under MCP, the period-1 depreciation is 0.4% while the increase in export price is 0.25% and the increase in import price is 0.29%. These numbers are in line with the incomplete pass-through predicted by the theory when there is a significant share of firms pricing their goods in currency H (exports) and R (imports). Both prices react strongly under DCP since there was a larger depreciation of currency H versus currency U at the same time. Under MCP, the terms of trade improve slightly, but the effect is quite small, more in line with DCP. This effect on the terms of trade is a result of the combination



(A) Shock (B) Exchange rate e_R (C) Interest rate

(D) Terms of trade (E) Export price (F) Import price

(G) Export quantity (H) Import quantity (I) GDP

Figure 2.5: Impulse response functions of a SOE to a UIP shock

Note: The shock is realized in period 1. All variables except for shock, interest rate, and GDP, are for trade between country H and country R. Interest rate is the domestic interest rate. Parameter values are given in table 2.6.

of pricing in both currencies H and R, canceling their effect on the terms of trade.

Next, we analyze the effect of a 25 basis points negative monetary shock that leads to a decrease in the interest rate, presented in Figure 2.6. The decrease in Home interest rate leads to a decrease in the interest rate spread vis-a-vis country U bonds, which in turn leads to a depreciation of currency H against currencies U and R. Following the depreciation, the prices of exports (measured in currency H) and imports from country R increase. Under MCP, the reaction of export and import prices is milder than under the other "pure" pricing paradigms, since significant shares of exports and imports are invoiced in currencies that stabilize the price to exchange rate fluctuations (currency R for exports and currency H for imports). The inflation rate increases due to the decrease in interest rate and the increase in import and domestic prices. Under MCP, this increase is smaller than under PCP or DCP, but larger than under LCP. As a result, the interest rate declines more under MCP than PCP or DCP, but less than under LCP. Since both export and import prices increase under MCP, the effect on the terms of trade is a slight increase, close to the DCP case but still positive. The quantity of exports increases and the quantity of imports decreases. GDP increases as both exports and domestic production increase.

Overall, an SOE economy with MCP presents more moderate reactions in the different variables to UIP and monetary shocks, relative to the "pure" pricing paradigms. The fact that the MCP economy reacts in a different way indicates that such an economy might have a different optimal monetary policy than a PCP, LCP or DCP economy. Specifically, whether the monetary authority should target the producer price inflation as in PCP (Galí 2015) or DCP (Casas et al. 2017), the CPI as in LCP (Engel 2011), or some type of convex combination of both is an interesting question that should be addressed in future research.

2.6 Conclusion

This paper examines the implications of multiple invoicing currencies for a small open economy. We present a framework for analyzing a small open economy that uses several invoicing currencies and shows that multiple invoicing currencies can mitigate some of the effects of exchange rate fluctuations,

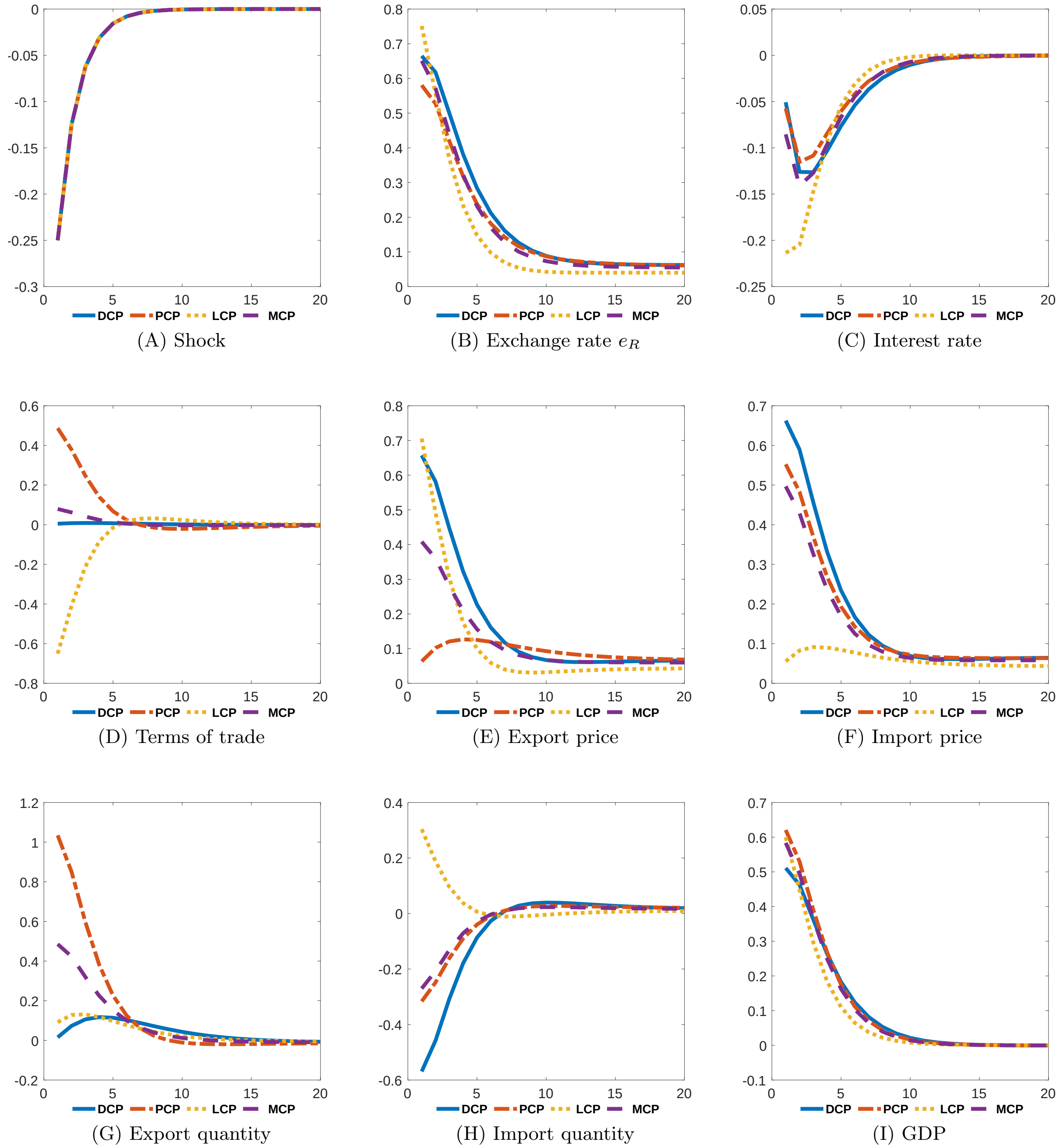


Figure 2.6: Impulse response functions of a SOE to a monetary shock

Note: The shock is realized in period 1. All variables except for shock, interest rate, and GDP, are for trade between country H and country R. Interest rate is the domestic interest rate. Parameter values are given in table 2.6.

as exchange rate pass-through into import and export prices is incomplete when multiple invoicing currencies are used.

We estimate exchange rate pass-through into import and export prices using data for Sweden, a small open economy with substantial shares of several invoicing currencies. We find an incomplete pass-through of exchange rate shocks into import and export prices, much higher than under LCP or DCP, but lower than under PCP. This finding is in line with the hypothesis of an economy with a significant share of PCP.

We calibrate a New Keynesian small open economy model to moments of the Swedish economy, including exchange rate pass-through estimates, and show the importance of accounting for heterogeneity in invoicing currencies, as using any one of the three "pure" pricing paradigms lead to counterfactual exchange rate pass-through rates.

We suggest that further exploration of SOEs with multiple invoicing currencies could shed light on several questions of interest to researchers and policymakers. First, expanding this research using detailed firm-level data to understand better the role of firm-level factors in invoicing decisions and their implications for exchange rate pass-through and monetary policy. An area of active research is how some economies end up with multiple invoicing currencies instead of converging into one of the three limiting paradigms. Second, analyzing the repercussions of multiple invoicing currencies for monetary policy in a small open economy is a relevant and important question for policymakers in such economies that must consider the effect of several exchange rates and distortions created by using different currencies for different internationally traded goods.

Chapter 2 Appendices

2.A Causes for observed heterogeneity in invoicing currencies

Macro-level factors. A major risk factor for exporting firms is exchange rate risk, and specifically volatility.[15] Even relatively small unexpected changes in the exchange rate can affect the firm's profits. Goldberg & Tille (2016) find that higher volatility of the exchange rate of the origin country versus Canadian dollar is correlated with bigger share of the transactions invoiced in vehicle currency and not producer currency. Choosing the currency of invoicing could be viewed as a financial / natural hedge, where the choice of currency is used as a hedging device against volatility risk. This is especially true for choosing a vehicle currency.[16] Ito et al. (2018) conduct an extensive survey of Japanese firms, focusing on currency choice and hedging. They find that hedging costs affects the firm's currency of invoicing choice, as an increase in the cost of hedging increases firms' tendency to invoice in yen.[17] They find that the choice of invoicing currency is apparently a key factor in Japanese firms' decision regarding the use of operational and financial hedges. Namely, firms that invoice in yen hedge less (they are also the smaller firms). Thus, yen invoicing and hedging are supplements.

Micro-level factors. Past studies have found several micro-level factors that affect the currency choice of firms. These mostly relate to the elasticity of demand faced by the firms. Bacchetta & van Wincoop (2005) presented a model of currency choice where the more differentiated the products, the more likely firms are to price in the exporter's currency, as the firm has greater ability to adjust margins for a highly differentiated good. This is supported by the results in Ito et al.

[15] There are several types of risks emanating from the currency risk (Döhring 2008, Ito et al. 2018): Transaction risk, when the exchange rate movements affect the amount of money receivable / payable denominated in a foreign currency; translation risk, when firms that engage in multinational transactions must convert all their finances into one currency for reporting, thus exposing themselves to risk relating to market capitalization; and economic risk, where exchange rate effects on the firm's market value, future cash flows, and market share vs. global competitors.

[16] firms can use two types of mechanisms to hedge against exchange rate risk: Financial hedge (foreign exchange derivatives), such as forward contracts, currency swaps, currency options; natural hedges, such as foreign-currency debt; and operational hedge (medium / long run), such as change production bases overseas or the production capacity of existing bases, change share of imported intermediates, operational matching of revenues and expenditure.

[17] This is evident in bid-ask spreads of the importer's currency, participation in the multi-currency cash settlement system (CLS Bank) which reduces costs of settlement in foreign currency, the fact that larger firms with a larger exposure to more foreign market use more hedging instruments, and firms' limited ability to pass-through exchange rate fluctuations into their prices.

(2018). Goldberg & Tille (2008) and Goldberg & Tille (2016) presented empirical evidence for this hypothesis, by showing that exporters in industries with more homogeneous goods (those that are reference-priced and traded on organized exchange) coalesce on using a dominant currency to limit fluctuations in their relative prices.

Trade in intermediate inputs accounts for as much as two thirds of international trade (Johnson & Noguera 2012), and it plays an important role in invoicing decisions. Most exporting firms employ imported inputs in production, reducing the value added content of exports. Amiti et al. (2014) show that the fact that the largest exporters are simultaneously the largest importers is key to understanding low aggregate pass-through, as well as the variation in pass-through across firms. More import-intensive exporters have significantly lower exchange rate pass-through into their export prices, as they face offsetting exchange rate effects on their marginal costs. Firms are likely to price in the currency of their imported inputs to mitigate the impact of exchange rate fluctuations on marginal costs (Rodnyansky 2018, Corsetti et al. 2022). Ito et al. (2018) found that the trade in intermediate goods decrease yen invoicing and increase USD invoicing for Japanese firms. This suggests that exporters of intermediate goods are different from those of final goods in terms of currency invoicing decisions. Intra firm trade appears to play an important role in invoicing decisions as well, albeit data in this area is very limited. Intra firm trading could be to a subsidiary that acts as a retailer in the local (foreign) market or one that is a production subsidiary that exports its product to other locations. Ito et al. (2018) find that exports to Japanese subsidiaries in Asia tend to be invoiced in USD when the final destination market is the US.

Price linkages between firms (strategic complementarities) have an important part in the formation of VCP equilibrium. It is a well established result of the models that with no intermediates in production and CES consumption aggregator, exporters always choose PCP and no VCP equilibrium exists. Mukhin (2022) shows that price linkages between firms are a necessary condition to rationalize VCP in global trade. The role of strategic complementarities has been studied empirically in Amiti, Itskhoki & Konings (2019).

Country market share is another important factor that also contributes to our understand of why only a small number of currencies are overwhelmingly used in international trade. Bacchetta & van

Wincoop (2005) show that the higher the exporting country's market share in an industry, the more likely firms are to price in the exporter's currency. Goldberg & Tille (2016) show that exporters from a country with a high market share make less use of the destination currency. However, this does not reflect a larger use of the PCP option, unlike what we would expect from the theory, but instead denotes a larger use of the VCP option. Mukhin (2022) formalized this observation and proved that even when all currencies have similar volatility, there is a non-empty region with VCP as a unique equilibrium when the US has a positive size in international trade, and the region increases with the size of the US economy.

Firm/transaction-level factors. Transactions that are large in absolute terms can be associated with lower hedging costs. If hedging through derivatives instruments entails a fixed cost, the average cost is lower for transactions of larger value, and thus exchange rate exposure is less of a concern (Goldberg & Tille 2016). However, Ito et al. (2018) find that greater export amount is associated with USD invoicing by Japanese exporters. The size of the firm also affects invoicing decisions. Ito et al. (2018) find that the smaller (larger) the firm size, the larger is the share of yen (US dollar) invoicing. Larger firms or firms with higher exposure to foreign markets use more currencies. This is in line with the greater costs associated with using foreign currency and managing the exchange rate risk of foreign currencies. In much the same way as the case with a country's market share, firms with a major share of the world market tend to invoice in producer currency (Ito et al. 2018). Devereux et al. (2017) show that exchange rate pass-through and the likelihood of foreign-currency pricing are a U-shaped function of foreign-supplier (exporter) share of the sectoral import market. At the same time, the market share of importing firm is negatively associated with pass-through and positively with LCP. They also find empirical evidence of these relationships in Canadian firms' micro-level data. Firms selling more than one product and to more than one destination are more likely to invoice in vehicle and local (destination market) currencies, rather than invoicing in their own producer's currency (Corsetti et al. 2022).

2.B Steady state

Assume a symmetric perfect foresight steady state with balanced trade. Exogenous shocks are set to $\zeta = a = v = r = 0$. As a result, prices are $P_{iH} = P_{Hi} = P, \forall i \in \{H, R, U\}$. Therefore, $\mathcal{Q}_i = \mathcal{E}_i = \mathcal{S}_i = 1$.

The aggregate demand simplifies to $D = Z_{iH} = Z_{Hi} = \frac{\sigma-1}{\sigma}$, therefore for every pair of countries (i, j)

$$C_{ij} = \gamma_i C \qquad X_{ij} = \gamma_i X$$

$$\sigma_{ij} = \sigma$$
$$\mu_{ij} = \log\left(\frac{\sigma}{\sigma-1}\right)$$
$$\Gamma_{ij} = \frac{\varepsilon}{\sigma-1}$$

Domestic and global interest rates are

$$R = R^U = \frac{1}{\beta} \tag{2.B.1}$$

Real interest rate:

$$\frac{W}{P} = \left(\frac{\vartheta}{\vartheta-1}\right)(\kappa N^{\varphi} C^{\sigma_c}) \tag{2.B.2}$$

Prices for all goods:Prices:

$$P_{ij}^{*k} = \frac{\sigma}{\sigma-1}\mathcal{MC}$$

$$\mathcal{MC} = \frac{1}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}} W^{1-\alpha} P^{\alpha} \tag{2.B.3}$$

Production function:

$$Y = L^{1-\alpha} X^{\alpha} \tag{2.B.4}$$

and the demand for inputs:

$$\frac{X}{Y} = \frac{\alpha \mathcal{MC}}{P} = \alpha e^{-\mu}$$
$$\frac{L}{Y} = \frac{(1-\alpha)\,\mathcal{MC}}{W} = \frac{1-\alpha}{(1-\alpha)^{1-\alpha}\,\alpha^{\alpha}} \left(\frac{W}{P}\right)^{-\alpha}$$

2.C Additional tables

Table 2.9: Terms of trade and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$	$\Delta tot_{j,t}$
$\Delta e_{j/SEK,t}$	.408***	.594***	.386***	.435***
	(.103)	(.161)	(.0647)	(.127)
$\Delta e_{j/SEK,t-1}$	-.00233	-.0466	-.0133	.0441
	(.0719)	(.13)	(.0435)	(.0829)
$\Delta e_{j/SEK,t-2}$	.117	-.0174	.0337	-.0156
	(.0727)	(.12)	(.0331)	(.0667)
$\Delta ppi^{diff}_{j,t}$		.091		.0663
		(.186)		(.118)
$\Delta ppi^{diff}_{j,t-1}$		.0311		.125
		(.135)		(.0831)
$\Delta ppi^{diff}_{j,t-2}$		-.37**		-.0444
		(.151)		(.0815)
Observations	2054	1132	2054	1132
R^2	.615	.811	.967	.973
Trading partners	141	68	141	68
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes

Note: Results of estimation of equation (2.4.8). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. *** p<0.01, ** p<0.05, * p<0.1.

Table 2.10: Import prices and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$
$\Delta e_{SEK/j,t}$	.377***	.278**	.646***	.545***
	(.106)	(.109)	(.0696)	(.0752)
$\Delta e_{SEK/j,t-1}$	.14	.0664	.0885	-.00223
	(.0933)	(.0956)	(.0581)	(.0652)
$\Delta e_{SEK/j,t-2}$	-.363***	-.25**	-.0639	.0588
	(.106)	(.102)	(.0585)	(.0566)
Δppi_t	.343***	.307***	.188**	.348***
	(.114)	(.108)	(.0777)	(.0763)
Δppi_{t-1}	-.0761	-.136	-.0364	-.000796
	(.105)	(.105)	(.0832)	(.0764)
Δppi_{t-2}	-.272**	-.203*	-.153**	-.128*
	(.118)	(.105)	(.0772)	(.0718)
$\Delta e_{SEK/USD,t}$		.379***		.231***
		(.0808)		(.044)
$\Delta e_{SEK/USD,t-1}$		.0643		.106**
		(.0794)		(.0428)
$\Delta e_{SEK/USD,t-2}$		-.114		-.0545
		(.0785)		(.0369)
Observations	1189	1189	1189	1189
R^2	.277	.295	.251	.31
Trading partners	68	68	68	68
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes

Note: Results of estimation of equation (2.4.7). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. *** p<0.01, ** p<0.05, * p<0.1.

Table 2.11: Import prices and exchange rate by country group

	Unweighted			Trade weighted		
	(1) Dollarized	(2) EMU	(3) Rest of World	(4) Dollarized	(5) EMU	(6) Rest of World
$\Delta e_{SEK/USD,t}$	.875*	.0851	.516***	.821***	.178***	.3***
	(.463)	(.068)	(.115)	(.244)	(.0548)	(.072)
$\Delta e_{SEK/USD,t-1}$	.0997	.168**	.0394	.469	.145***	.0143
	(.412)	(.0666)	(.112)	(.309)	(.0545)	(.0554)
$\Delta e_{SEK/USD,t-2}$	-.664	-.0556	-.178	-.0601	-.113**	-.0168
	(.405)	(.0876)	(.11)	(.186)	(.0552)	(.0559)
Δppi_t	1.49	.392**	.218*	1.3*	.36***	.249***
	(.919)	(.155)	(.124)	(.764)	(.135)	(.09)
Δppi_{t-1}	-.351	-.21	-.0543	.119	-.129	-.0204
	(.351)	(.161)	(.131)	(.567)	(.177)	(.074)
Δppi_{t-2}	-.737***	-.0601	-.168*	-.925	-.0369	-.127*
	(.207)	(.141)	(.101)	(.569)	(.172)	(.0767)
$\Delta e_{SEK/j,t}$		.885***	.175		.798***	.343***
		(.168)	(.126)		(.13)	(.0876)
$\Delta e_{SEK/j,t-1}$		-.131	.156		-.183	.129*
		(.122)	(.115)		(.114)	(.072)
$\Delta e_{SEK/j,t-2}$		.274**	-.225**		.246***	-.0996
		(.122)	(.11)		(.0935)	(.0698)
Observations	53	366	770	53	366	770
R^2	.353	.307	.3	.558	.367	.278
Trading partners	3	18	47	3	18	47
Country FE	yes	yes	yes	yes	yes	yes
Time FE	yes	yes	yes	yes	yes	yes

Note: Results of estimation of equation (2.4.7) for three groups of countries: dollarized economies (U.S., El Salvador, and Ecuador), European Monetary Union, and the rest of the world. Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. *** p<0.01, ** p<0.05, * p<0.1.

Table 2.12: Export prices and exchange rate

	Unweighted		Trade weighted	
	(1)	(2)	(3)	(4)
	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$	$\Delta p_{j,t}$
$\Delta e_{j/SEK,t}$	.486***	.314***	.45***	.375***
	(.0541)	(.0667)	(.0525)	(.0559)
$\Delta e_{j/SEK,t-1}$	-.0228	.0498	.114***	.148***
	(.0427)	(.0574)	(.0383)	(.0431)
$\Delta e_{j/SEK,t-2}$	.0679**	.0506	-.0422	-.0647
	(.0336)	(.0567)	(.0354)	(.0529)
$\Delta ppi_{SWE,t}$	-.0849	-.109	.161	.167
	(.211)	(.221)	(.174)	(.182)
$\Delta ppi_{SWE,t-1}$	.117	.0714	.352**	.346**
	(.227)	(.231)	(.17)	(.169)
$\Delta ppi_{SWE,t-2}$	-.723***	-.401*	-.503***	-.341**
	(.225)	(.232)	(.155)	(.158)
$\Delta e_{j/USD,t}$		.371***		.21***
		(.0622)		(.0469)
$\Delta e_{j/USD,t-1}$		-.106*		-.0511
		(.0551)		(.0429)
$\Delta e_{j/USD,t-2}$		-.0181		-.00291
		(.0559)		(.0456)
Observations	2614	2614	2614	2614
R^2	.172	.182	.202	.219
Trading partners	165	165	165	165
Country FE	yes	yes	yes	yes
Time FE	yes	yes	yes	yes

Note: Results of estimation of equation (2.4.7). Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. *** p<0.01, ** p<0.05, * p<0.1.

Table 2.13: Export prices and exchange rate by country group

	Unweighted			Trade weighted		
	(1) Dollarized	(2) EMU	(3) Rest of World	(4) Dollarized	(5) EMU	(6) Rest of World
$\Delta e_{SEK/USD,t}$	.035			-.154		
	(.345)			(.17)		
$\Delta e_{SEK/USD,t-1}$	-.0192			-.0994		
	(.268)			(.162)		
$\Delta e_{SEK/USD,t-2}$	-.135			-.0394		
	(.257)			(.128)		
$\Delta e_{j/SEK,t}$		.0427	.335***		.106	.481***
		(.137)	(.0746)		(.111)	(.0687)
$\Delta e_{j/SEK,t-1}$		-.00364	.0642		.0906	.202***
		(.0966)	(.0659)		(.0852)	(.0574)
$\Delta e_{j/SEK,t-2}$		-.165	.0583		-.299***	-.051
		(.114)	(.0659)		(.111)	(.0696)
$\Delta e_{j/USD,t}$		.0573	.405***		.0711	.28***
		(.0795)	(.0741)		(.0649)	(.065)
$\Delta e_{j/USD,t-1}$		.042	-.131**		.0975*	-.167***
		(.0758)	(.0656)		(.0565)	(.061)
$\Delta e_{j/USD,t-2}$		-.0564	-.0267		-.119**	.0139
		(.0757)	(.0666)		(.0571)	(.0662)
Observations	164	390	2060	164	390	2060
R^2	.0913	.0601	.195	.141	.165	.278
Trading partners	11	18	136	11	18	136
Country FE	yes	yes	yes	yes	yes	yes
Time FE	yes	yes	yes	yes	yes	yes

Note: Results of estimation of equation (2.4.7) for three groups of countries: dollarized economies (U.S., El Salvador, Ecuador, Antigua and Barbuda, Dominica, Grenada, Hong Kong, Saint Kitts and Nevis, Saint Lucia, Panama, Saint Vincent and the Grenadines), European Monetary Union, and the rest of the world. Regressions are trade-weighted. Robust standard errors in parentheses. Includes time and trading partner fixed effects, two lags of $\Delta e_{ij,t}$, PPI used as control variable with 2 lags. The first two columns are unweighted, the last two columns use trade-weights. *** p<0.01, ** p<0.05, * p<0.1.

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