DSGE Models of High Exchange-Rate Volatility and Low Pass-Through[1]

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Abstract

This paper develops a quantitative, dynamic, open-economy model which endogenously generates high exchange rate volatility, whereas a low degree of exchange rate pass-through (ERPT) stems from both nominal rigidities (in the form of local currency pricing) and price discrimination. We model real exchange rate volatility in response to real shocks by reconsidering and extending two approaches suggested by the quantitative literature (one by Backus Kehoe and Kydland [1995], the other by Chari, Kehoe and McGrattan [2002]), within a common framework with incomplete markets and segmented domestic economies. In the short run, a small amount of nominal rigidities — consistent with the evidence in Bils and Klenow [2004] — lowers the elasticity of import prices to 27 percent. Still, exchange rate depreciation worsens the terms of trade – in accord with the evidence stressed by Obstfeld and Rogoff [2000]. In the long run, ERPT coefficients are also below one, as a result of price discrimination. We run a set of regressions adopted by the empirical literature on ERPT, typically plagued by omitted variable bias and measurement errors, on the time series generated by our model. The ERPT estimates are biased, although the bias is often not very large and in most cases the regression model can detect differences between short-run and long-run ERPT.

Keywords: international business cycle, exchange rate volatility, pass-through, international transmission, DSGE models.

JEL Classification Codes: F33, F41.

1 Introduction

Highly volatile exchange rates but stable import prices in local currency are among the most striking features of the international economy. Traditional explanations and a number of recent quantitative papers attribute high exchange rate volatility to noisy behavior of participants in financial and currency markets, and local currency price stability for imports to nominal rigidities.[1] The view that incomplete pass-through is essentially linked to nominal rigidities, however, has been challenged on empirical and theoretical grounds. A large body of both micro and macro literature has shown that, independently of nominal frictions, incomplete exchange rate pass-through can result from price discrimination, i.e. optimal destination-specific markup adjustment by firms, as well as from a large component of non-tradable services and goods in the price of final goods. In the open macro literature, Obstfeld and Rogoff [2000] have argued that models attributing local currency price stability exclusively to nominal rigidities cannot be consistent with the empirical association of exchange rate depreciation and terms-of-trade worsening. Most crucially, recent studies estimating general equilibrium quantitative models adopting the above approach, find that the degree of stickiness is unrealistically larger for the price of imports, than for the price of domestically produced tradables — a result suggesting misspecification (e.g. see Lubik and Schorfheide [2005]). Taken at face value, such result would exacerbate the counterfactual implications for the behavior of the terms of trade pointed out by Obstfeld and Rogoff.

In this paper, we address the general equilibrium link between exchange-rate volatility and the stability of goods prices in a quantitative framework which encompasses both price discrimination and nominal rigidities. Instead of assuming exogenous noise in currency markets, however, we focus on specifications which can endogenously generate large swings of the exchange rate in response to shocks to fundamentals. The literature suggests at least two approaches to modelling endogenous exchange-rate volatility in a rational expectations framework: the first is pursued by Backus, Kehoe, and Kydland [1995], henceforth BKK, — which we label the elasticity approach — the other by Chari, Kehoe and McGrattan [2002] — which we label the risk-aversion approach. We reconsider these approaches in a standard international business cycle framework with traded and nontraded goods (e.g. Stockman and Tesar [1995]), assuming

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[1] See, e.g., Smets and Wouters [2002] and references therein.

incomplete asset markets and a realistic degree of goods-market segmentation. We show that the main properties of the two approaches nicely generalize to our environment, addressing some important issues raised by previous literature.

More precisely, when pursuing the elasticity approach, we run a set of experiments where the impact of productivity shocks on international prices is magnified by a relatively low price elasticity of imports, choosing parameter values on the low end of the range commonly adopted by the literature. In Corsetti, Dedola and Leduc [2004] we have shown that, under this approach, international prices are as volatile as in the data. In this paper we extend this result to a model with price rigidities. Most important, while in the BKK framework the response of import quantities to shocks tends to fall with their price elasticity, we show that in our model with incomplete asset markets the import volatility is not lower than in comparable international DSGE models (though somewhat low relative to the data).

When pursuing the approach by Chari, Kehoe and McGrattan [2002] (henceforth CKM), we exploit the positive and strict link between the ratio of marginal utilities of consumption and the real exchange rate that characterizes economies with high consumption risk sharing. With power utility, if relative risk aversion is sufficiently high, the variability of the ratio of Home to Foreign consumption observed in the data can correspond to large equilibrium movements in the real exchange rate. CKM emphasize nominal rigidities — in their model, as import prices are sticky in local currency, monetary shocks do not spill over to foreign consumption — and show that a similar mechanism works in a large class of models with incomplete markets. A notable result of this paper is to show that the CKM mechanism also works quite well in the absence of nominal rigidities, provided that the national economies are sufficiently insulated from one another by the presence of nontraded goods. In other words, in our model the CKM approach generates exchange rate volatility in response to real shocks both in a flex-price and a sticky price environment.

In either set of experiments, our model allows for markets segmentation and deviations from the law of one price. As in Corsetti and Dedola [2005], market segmentation in the tradable sector of our economies is an implication of the presence of a distribution sector intensive in local inputs. There are at least two advantages in adopting this specification. First, due to distribution, large exchange-rate swings do not translate into large CPI movements even when all prices are fully flexible: retail prices of imported goods reflect only a small proportion of movements in import prices at the border (a point stressed by Burstein, Eichenbaum and Rebelo [2005]). Second, distribution services induce differences in demand elasticity across countries. Thus, with monopolistic producers the law of one price does not hold in general: in a flexible price equilibrium, firms would optimally charge different wholesale prices in the domestic and foreign markets, and would not move prices one-to-one with exchange rate movements. Hence, when we allow for nominal frictions — assuming that foreign exporters face costs in adjusting prices in local currencies — the stability of import prices in local currency does not depend exclusively on price rigidities.

Our quantitative framework yields the following results. *First*, our economies generate highly volatile international prices and can account for persistent and highly correlated movements in real and nominal exchange rates, even for a relatively low degree of nominal rigidity or under flexible prices. What is remarkable about this result is that, contrary to the presumption underlying the vast literature on the PPP puzzle emphasizing nominal shocks, international price volatility and persistence are generated by real shocks.

Second, for a degree of price stickiness consistent with the evidence in Bils and Klenow [2004] that prices are kept unchanged on average for 4.3 months, the real exchange rate is positively correlated with the terms of trade and the price of imports, while it is only very weakly so with the consumer price level. We stress that this result is consistent with the evidence emphasized by Obstfeld and Rogoff [2000]. These authors strongly argue against the hypothesis of 'local currency pricing' (henceforth LCP) on the ground that models assuming it predict a counterfactual negative correlation between exchange rates and terms of trade. Our quantitative analysis shows that some versions of LCP may actually match the empirical evidence, provided that the degree of nominal rigidities is not very high. Indeed, when we increase the average degree of price stickiness from 4.3 months to 3 quarters, the correlation between exchange rates and terms of trade switches sign, and becomes negative.

Third, we find that a reasonably small degree of price stickiness generates a very low elasticity of import and consumer prices to the exchange rate in the short run — or a low degree of exchange-rate pass-through. Using our model we derive an exact (linearized) equation for import prices in the exchange rate, marginal costs in local currency, distribution costs and leads and lags in import prices driven by optimal forward-looking price-setting. This equation underlines nominal and real determinants of exchange-rate pass-through. Assuming that prices are kept unchanged on average for 4.3 months (once again, in line with the evidence in Bils and Klenow [2004]), the short-run exchange-rate pass-through coefficient in this structural equation is as low as 0.27. When our measure of price stickiness is set equal to 3 quarters, this coefficient falls to 0.04. Because of the assumed weight of distribution, exchange-rate pass-through coefficients for imported goods at the consumer-price level are half as large as those for import prices at the borders. The predicted elasticity of the overall CPI with respect to exchange-rate movements is even lower. This is reflected in the generally low correlation between the nominal exchange rate, and inflation and the CPI, across the different model specifications.

These results suggest that, while nominal rigidities may play an important role in determining a high degree of local currency producer- and consumer-price stability in the short run, models that disregard nontradability, distribution, and price discrimination may severely distort the importance of nominal frictions.[2] In our specification, the magnitude of nominal frictions to generate local currency price stability need not be very high, and in any case realistically smaller than in models attributing local currency price stability exclusively to price stickiness. Moreover, consistent with the evidence in Giovannini [1988], Marston [1990], and Campa and Goldberg [2002], our model predicts that imperfect exchange-rate pass-through lasts longer than the period in which prices are sticky on average, generating long-run deviations from the law of one price. Clearly, these deviations cannot be explained by models assuming that pass-through is incomplete because of nominal rigidities.

Additional results follow from an application of our framework to the analysis of regression models of exchange-rate pass-through, with which we conclude our paper. As is well known, empirical estimates of pass-through, purportedly providing useful descriptions of structural features of price dynamics, are extensively used as core inputs in the inflation projections by policy-making institutions. But because of data limitations, regression models typically suffer from omitted-variable bias and measurement errors. Our quantitative models provide us with a useful tool to analyze the implications of these shortcomings for the performance of regression models: we can run standard regressions on the time series generated by artificial economies, in which we fully control the economic structure and the stochastic processes driving shocks to fundamentals, and compare pass-through estimates with the corresponding structural coefficients.

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[2] We should also observe that such models typically ignore the different exchange-rate elasticity of import prices at the border and at the consumer level, downplaying the empirical evidence on the former.

First, based on our theoretical specification, we show that the estimation bias in pass-through regressions is a function of the volatility of the exchange rate and the covariance between the exchange rate and the determinants of import prices. A high volatility of the exchange rate tends to reduce the bias; however, with the exchange rate being endogenously determined in general equilibrium, its covariance with costs and demand can prevent the regression bias from vanishing, even in an environment with very high exchange rate volatility.[3] Indeed, in our environment, a naïve regression of prices on the exchange rate (without any controls) would give a totally distorted picture of prices as being substantially unresponsive to exchange rates at any time horizon.

Second, we consider two representative regression models typically adopted in the literature — that we dub Pricing to Market (PTM) and Exchange Rate Pass-through (ERPT). Both regression specifications rely on proxies of the true marginal costs and ignore distribution costs — evidence on the importance of the latter among the determinants of local currency price stability for imports is provided by Goldberg and Verboven [2001]. According to our experiments, in most cases the PTM and ERPT regression models are able to detect differences in the short- and long-run pass-through coefficients when they are structurally different, while setting the two equal to each other when they are the same. Consistent with our analytical results, point estimates of exchange rate pass-through coefficients are systematically biased, although often not far off their mark. How close they are to their structural counterpart in the model turns out to be sensitive not only to the choice of proxies for marginal costs and demand conditions included in the regression; but also to the set of shocks on which we condition our analysis. Specifically, we show that the overall performance of the PTM and ERPT specifications can vary considerably, depending on whether simulated time series are generated using nominal rather than real shocks.

The paper is structured as follows. Section 2 will describe the model, while the calibration will be discussed in Section 3. Section 4 will discuss the business cycle properties of exchange rates and prices in our model. Section 5 will present an analysis of structural and empirical pass-through equations. The last section concludes.

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[3] A corollary of our analysis is that models attributing exchange rate volatility to exogenous noise would simply downplay the importance of regression bias altogether.

2 The model

The world economy consists of two countries of equal size, H and F. Each country specializes in one type of tradable good, produced in a number of varieties or brands defined over a continuum of unit mass. Brands of tradable goods are indexed by $h \in [0,1]$ in the Home country and $f \in [0,1]$ in the Foreign country. In addition, each country produces an array of differentiated nontradables, indexed by $n \in [0,1]$. Nontraded goods are either consumed or used to make intermediate tradable goods h and f available to domestic consumers.

Firms producing tradable and nontraded goods are monopolistic suppliers of one brand of goods only. These firms combine capital with differentiated domestic labor inputs in a continuum of unit mass. Each worker occupies a point in this continuum, and acts as a monopolistic supplier of a differentiated type of labor input to all firms in the domestic economy. Households/workers are indexed by $j \in [0,1]$ in the Home country and $j^* \in [0,1]$ in the Foreign country. Firms operating in the distribution sector, by contrast, are assumed to operate under perfect competition.[4] They buy tradable goods and distribute them to consumers using nontraded goods as the only input in production.

In our baseline model, prices will be assumed to be perfectly flexible. In alternative specifications, we will introduce nominal price rigidities by assuming that firms face a quadratic cost of adjusting goods' prices. In what follows, we describe our set up focusing on the Home country, with the understanding that similar expressions also characterize the Foreign economy — whereas variables referred to Foreign firms and households are marked with an asterisk.

2.1 The Household's Problem

2.1.1 Preferences

The representative Home agent in the model maximizes the expected value of her lifetime utility, given by:

$$E\left\{\sum_{t=0}^{\infty} U\left[C_t, \frac{M_{t+1}}{P_t}, L_t\right] \exp\left[\sum_{\tau=0}^{t-1} -\nu\left(U\left[C_t, \frac{M_{t+1}}{P_t}, L_t\right]\right)\right]\right\}, \tag{1}$$

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[4] Due to this assumption, we note from the start that the equilibrium allocation studied below would be identical in a vertically integrated economy, where exporters with monopoly power own local retailers.

where instantaneous utility U is a function of a consumption index, C_t, leisure, $(1 - L_t)$, and real money balances $\frac{M_{t+1}}{P_t}$. This recursive specification of preferences, according to which the discount factor is a function of past utility levels, guarantees the existence of a unique invariant distribution of wealth, independent of initial conditions.[5]

Households consume all types of (domestically-produced) nontraded goods, and both types of traded goods. So $C_t(n, j)$ is consumption of brand n of Home nontraded good by agent j at time t; $C_t(h, j)$ and $C_t(f, j)$ are the same agent's consumption of Home brand h and Foreign brand f. For each type of good, we assume that one brand is an imperfect substitute for all other brands, with constant elasticity of substitution θ_{H} and $\theta_{\mathrm{N}} > 1$. Consumption of Home and Foreign goods by Home agent j is defined as:

$$\begin{aligned} C_{\mathrm{H},t}(j) &\equiv \left[\int_0^1 C_t(h,j)^{\frac{\theta_{\mathrm{H}}-1}{\theta_{\mathrm{H}}}} dh\right]^{\frac{\theta_{\mathrm{H}}}{\theta_{\mathrm{H}}-1}}, \qquad C_{\mathrm{F},t}(j) \equiv \left[\int_0^1 C_t(f,j)^{\frac{\theta_{\mathrm{H}}-1}{\theta_{\mathrm{H}}}} df\right]^{\frac{\theta_{\mathrm{H}}}{\theta_{\mathrm{H}}-1}}, \\ C_{\mathrm{N},t}(j) &\equiv \left[\int_0^1 C_t(n,j)^{\frac{\theta_{\mathrm{N}}-1}{\theta_{\mathrm{N}}}} dn\right]^{\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}}. \end{aligned}$$

The full consumption basket, C_t, in each country is defined by the following CES aggregator

$$C_t \equiv \left[a_{\mathrm{T}}^{1-\phi} C_{\mathrm{T},t}{}^{\phi} + a_{\mathrm{N}}^{1-\phi} C_{\mathrm{N},t}{}^{\phi}\right]^{\frac{1}{\phi}}, \qquad \phi < 1, \tag{2}$$

where a_{T} and a_{N} are the weights on the consumption of traded and nontraded goods, respectively and $\dfrac{1}{1-\phi}$ is the constant elasticity of substitution between $C_{\mathrm{N},t}$ and $C_{\mathrm{T},t}$. The consumption index of traded goods $C_{\mathrm{T},t}$ is given by the following CES aggregator

$$C = C_{\mathrm{T}} = \left[a_{\mathrm{H}}^{1-\rho} C_{\mathrm{H}}^{\rho} + a_{\mathrm{F}}^{1-\rho} C_{\mathrm{F}}^{\rho}\right]^{\frac{1}{\rho}}, \qquad \rho < 1. \tag{3}$$

2.1.2 Budget constraints and asset markets

Home and Foreign agents trade an international bond, B_{H}, which pays in units of Home currency and is zero in net supply. Households derive income from working, $W_t L_t$, from renting capital to firms, $R_t K_t$, from previously accumulated units of currency, and from the proceeds from holding the international bond, $(1 + i_t) B_{\mathrm{H},t}$, where i_t is the nominal bond's yield, paid at the beginning of period t in domestic currency but known at time $t - 1$. Households pay non-distortionary

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[5] A unique invariant distribution of wealth under these preferences will allow us to use standard numerical techniques to solve the model around a stable nonstochastic steady state when only a non-contingent bond is traded internationally (see Obstfeld [1990], Mendoza [1991], and Schmitt-Grohe and Uribe [2003]).

(lump-sum) net taxes T, denominated in Home currency and use their disposable income to consume, invest in domestic capital, and buy bonds $B_{\mathrm{H,t+1}}$. Only Home residents hold the Home currency, M_t. The individual flow budget constraint for the representative agent j in the Home country is therefore:

$$\begin{gathered}M_t(j) + B_{\mathrm{H},t+1}(j) \leq M_{t-1}(j) + (1+i_t)B_{\mathrm{H},t}(j) + R_t K_t\,(j) \\ + \int_0^1 \Pi(h,j)dh + \int_0^1 \Pi(n,j)dn + \\ W_t L_t(j) - T_t(j) - P_{\mathrm{H},t}C_{\mathrm{H},t}(j) - P_{\mathrm{F},t}C_{\mathrm{F},t}(j) - P_{\mathrm{N},t}C_{\mathrm{N},t}(j) - P_{\mathrm{INV},t}I_t\,(j)\end{gathered} \tag{4}$$

where $\mathcal{E}_t$ is the nominal exchange rate, expressed as Home currency per unit of Foreign currency and $\int \Pi(h,j)dh + \int \Pi(n,j)dn$ is the agent's share of profits from all firms h and n in the economy. The price indexes as as follows: $\overline{P}_{\mathrm{H},t}$ and $P_{\mathrm{H},t}$ denote the price of the Home traded good at the *producer* and *consumer* level, respectively, $P_{\mathrm{F},t}$ is the consumer price of Home imports; $P_{\mathrm{N},t}$ is the price of nontraded goods; P_t is the consumer price index.

We assume that investment is a Cobb-Douglas composite of tradable and nontradable goods, in line with the evidence in Bems [2005], and that the capital stock, K, can be freely reallocated between the traded (K_{H}) and nontraded (K_{N}) sectors:

$$K = K_{\mathrm{H}} + K_{\mathrm{N}}. \tag{5}$$

Different from the consumption of tradables, we assume that investment is not subject to distribution services, though the tradable component of it is obtained through the same CES aggregator as that of consumption. This way we introduce in the model the notion of intermediate imported inputs that contribute to the formation of capital in the economy. The law of motion for the aggregate capital stock is given by:

$$K_{t+1} = I_t + (1-\vartheta)K_t + \frac{b}{2}\left(\frac{I_t}{K_t} - \vartheta\right)^2, \tag{6}$$

where b is an adjustment cost parameter, as in CKM.

The household's problem then consists of maximizing lifetime utility, defined by (1), subject to the constraints (4) and (6).

2.2 Firms' optimization and optimal price discrimination

International price discrimination is a key feature of the international economy captured by our model. In what follows we show that, even if Home and Foreign consumers have identical constant-elasticity preferences for consumption, the need for distribution services intensive in local nontraded goods implies that the elasticity of demand for the h (f) brand at wholesale level be not generally the same across markets. Firms will thus want to charge different prices at Home and in the Foreign country. We will focus our analysis on Home firms — optimal pricing by Foreign firms can be easily derived from it.

Firms producing Home tradables (H) and Home nontradables (N) are monopolist in their variety of good; they employ a technology that combines domestic labor and capital inputs, according to the following Cobb-Douglas functions:

$$\begin{aligned} Y\left(h\right) &= Z(h)K\left(h\right)^{1-\xi} L\left(h\right)^{\xi} \\ Y\left(n\right) &= Z(n)K\left(n\right)^{1-\zeta} L\left(n\right)^{\zeta}, \end{aligned}$$

where $Z(h)$ and $Z(n)$ are sectoral random disturbance following a statistical process to be determined below. We assume that capital and labor are freely mobile across sectors.

Our specification of the distribution sector is in the spirit of the factual remark by Tirole ([1995], page 175) that "production and retailing are complements, and consumers often consume them in fixed proportions". As in Burstein, Neves and Rebelo [2003], we thus assume that bringing one unit of traded goods to consumers requires η units of a basket of differentiated nontraded goods

$$\eta = \left[\int_0^1 \eta(n)^{\frac{\theta_{\mathrm{N}}-1}{\theta_{\mathrm{N}}}} dn\right]^{\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}}. \tag{7}$$

We note here that the Dixit-Stiglitz index above also applies (with an identical elasticity parameter) to the consumption of differentiated nontraded goods, specified in the next subsection. In equilibrium, then, the basket of nontraded goods required to distribute tradable goods to consumers will have the same composition as the basket of nontradable goods consumed by the representative domestic household.[6]

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[6] For simplicity, we do not distinguish between nontradable consumption goods, which directly enter the agents' utility, and nontraded distribution services, which are jointly consumed with traded goods. This distinction may

With flexible prices, the problem of these firms is standard: they hire labor and capital from households to maximize their profits:

$$\begin{aligned}\pi_t(h) &= \overline{p_t}(h)\,D_t(h) - W_tL_t(h) - R_tK_t(h)\\ \pi_t(n) &= p_t(n)\,D_t(n) - W_tL_t(n) - R_tK_t(n)\end{aligned}$$

where $\overline{p}_t(h)$ is the *wholesale* price of the Home traded good and $p_t(n)$ is the price of the nontraded good. W_t denote the aggregate wage rate, while R_t represents the capital rental rate.

Consider first the optimal pricing problem faced by firms producing nontradables for the Home market. The demand for their product is

$$D(n) + \eta(n) = [p_t(n)]^{-\theta_{\mathrm{N}}} P_{\mathrm{N},t}^{\theta_{\mathrm{N}}} \left[D_{\mathrm{N},t} + \eta\left(\int_0^1 D_t(h)dh + \int_0^1 D_t(f)df\right)\right], \tag{8}$$

where $D_{\mathrm{N},t}$ is the (consumption and investment) aggregate demand for non-traded goods. It is easy to see that their optimal price will result from charging a constant markup over marginal costs:

$$\begin{aligned}p_t(n) &= P_{\mathrm{N},t} = \frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1} MC_{\mathrm{N},t}\\ &= P_{\mathrm{N},t} = \frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}\frac{W_t^{\zeta}R_t^{1-\zeta}}{Z_{\mathrm{N},t}}\end{aligned}$$

Now, let $\overline{p}_t(h)$ denote the price of brand h expressed in the Home currency, at *producer* level. With a competitive distribution sector, the consumer price of good h is simply

$$p_t(h) = \overline{p}_t(h) + \eta P_{\mathrm{N},t}. \tag{9}$$

In the case of firms producing tradables, "pricing to market" derives endogenously from the solution to the problem of the Home representative firm in the sector:

$$Max_{\bar{p}(h),\bar{p}^*(h)} \quad [\bar{p}_t(h)D_t(h) + \mathcal{E}_t\bar{p}_t^*(h)D_t^*(h)] - \frac{W_t^{\xi}R_t^{1-\xi}}{Z_{\mathrm{H},t}}[D_t(h) + D_t^*(h)] \tag{10}$$

where

$$D_t(h) = \left(\frac{P_{\mathrm{H},t}}{\bar{p}_t(h) + \eta P_{\mathrm{N},t}}\right)^{\theta_{\mathrm{H}}} C_{\mathrm{H},t}, \quad D_t^*(h) = \left(\frac{P_{\mathrm{H},t}^*}{\bar{p}_t^*(h) + \eta P_{\mathrm{N},t}^*}\right)^{\theta_{\mathrm{H}}^*} C_{\mathrm{H},t}^*. \tag{11}$$

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however be important in more empirically oriented studies (e.g., see MacDonald and Ricci [2001]). By the same token, we ignore distribution costs incurred in the non-traded good market, as these can be accounted for by varying the level of productivity in the nontradable sector.

Making use of (9), the optimal wholesale prices for the consumption good $\bar{p}(h)$ and $\bar{p}^*(h)$ are:

$$\bar{p}_t(h) = \frac{\theta_{\mathrm{H}}}{\theta_{\mathrm{H}} - 1}\left(1 + \frac{\eta}{\theta_{\mathrm{H}}}\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}} - 1}\frac{Z_{\mathrm{H},t}}{Z_{\mathrm{N},t}}\frac{W_t^{\zeta} R_t^{1-\zeta}}{W_t^{\xi} R_t^{1-\xi}}\right)\frac{W_t^{\xi} R_t^{1-\xi}}{Z_{\mathrm{H},t}} = mk_{\mathrm{H},t}\frac{W_t^{\xi} R_t^{1-\xi}}{Z_{\mathrm{H},t}}, \tag{12}$$

$$\mathcal{E}_t\bar{p}^*(h) = \frac{\theta^*_{\mathrm{H}}}{\theta^*_{\mathrm{H}} - 1}\left(1 + \frac{\eta}{\theta^*_{\mathrm{H}}}\frac{\theta^*_{\mathrm{N}}}{\theta^*_{\mathrm{N}} - 1}\frac{Z_{\mathrm{H},t}}{Z^*_{\mathrm{N},t}}\frac{\mathcal{E}_t W_t^{*\zeta} R_t^{*1-\zeta}}{W_t^{\xi} R_t^{1-\xi}}\right)\frac{W_t^{\xi} R_t^{1-\xi}}{Z_{\mathrm{H},t}} = mk_{\mathrm{H}^*,t}\frac{W_t^{\xi} R_t^{1-\xi}}{Z_{\mathrm{H},t}}, \tag{13}$$

where $\mathcal{E}_t$ is the nominal exchange rate, expressed in units of home currency units, and $mk_{\mathrm{H},t}$ and $mk_{\mathrm{H}^*,t}$ denote the markups. Unlike the case of nontraded goods (9), in this case the markups charged by the Home firms include a state-contingent component — in brackets in the above expression — that varies as a function of productivity shocks, monetary innovations (affecting the exchange rate) and relative wages. Since in general $mk_{\mathrm{H},t}$ will not equal $mk_{\mathrm{H}^*,t}$, even when $\theta^*_{\mathrm{H}} = \theta_{\mathrm{H}}$, the optimal wholesale price of tradable goods will not obey the law of one price ($\bar{p}_t(h) \neq \mathcal{E}_t\bar{p}^*_t(h)$). This result reflects the difference in the elasticity of demand faced by the upstream monopolist at Home and abroad brought about by any asymmetry in relative productivity and/or factor prices.

Finally, notice that since there are no distribution costs in investment, the flexible price of the investment goods will be equal to the standard expression without state contingent component of markups.

Sticky Prices To study the impact of local currency pricing on the degree of exchange-rate pass-through, in alternative specifications of our benchmark model we allow for the possibility that goods prices are sticky. Following Rotemberg [1982] and Dedola and Leduc [2001], firms in the traded and non-traded goods sectors are assumed to face a quadratic cost when adjusting their prices (costs which are set equal to zero in steady state). Firms do not face price-adjustment costs in steady state. Firms pay this adjustment cost by purchasing a CES aggregated basket of all the goods in their sector of the economy. The price-adjustment costs faced by firms in the traded and non-traded goods sector are respectively:

$$AC^{p}_{\mathrm{H},t}\left(h\right) = \frac{\kappa^{p}_{\mathrm{H}}}{2}\left(\frac{\bar{p}_t(h)}{\bar{p}_{t-1}(h)} - \pi\right)^2 D_{\mathrm{H},t}, \qquad AC^{p*}_{\mathrm{H},t}\left(h\right) = \frac{\kappa^{*p}_{\mathrm{H}}}{2}\left(\frac{\bar{p}^*_t(h)}{\bar{p}^*_{t-1}(h)} - \pi\right)^2 D_{\mathrm{H},t}, \tag{14}$$

and

$$AC_t^p(n) = \frac{\kappa_{\mathrm{N}}^p}{2}\left(\frac{p_t(n)}{p_{t-1}(n)} - \pi\right)^2 D_{\mathrm{N},t}. \tag{15}$$

Since firms producing traded goods can price differently according to the destination market, they incur a cost when they change prices in either the Home or the Foreign market. Note that, rather innocuously, we assume that both $AC_{\mathrm{H},t}^{p}(h)$ and $AC_{\mathrm{H},t}^{p*}(h)$ are denominated in units of domestic traded goods.

2.3 Price indexes

A notable feature of our specification is that, because of distribution costs, there is a wedge between the producer price and the consumer price of each good. With competitive firms in the distribution sector, the consumer price of the Home traded good $P_{\mathrm{H},t}$ is simply the sum of the price of Home traded goods at producer level $\overline{P}_{\mathrm{H},t}$ and the value of the nontraded goods that are necessary to distribute it to consumers

$$P_{\mathrm{H},t} = \overline{P}_{\mathrm{H},t} + \eta P_{\mathrm{N},t}. \tag{16}$$

We hereafter write the price index of tradables and the utility-based CPIs:

$$\begin{aligned} P_{\mathrm{T},t} &= \left[a_{\mathrm{H}} P_{\mathrm{H},t}{}^{\frac{\rho}{\rho-1}} + a_{\mathrm{F}} P_{\mathrm{F},t}{}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}} \\ P_t &= \left[a_{\mathrm{T}} P_{\mathrm{T},t}{}^{\frac{\phi}{\phi-1}} + a_{\mathrm{N}} P_{\mathrm{N},t}{}^{\frac{\phi}{\phi-1}}\right]^{\frac{\phi-1}{\phi}}. \end{aligned}$$

Foreign prices, denoted with an asterisk and expressed in the same currency as Home prices, are similarly defined. Observe that the law of one price holds at the wholesale level but not at the consumer level, so that $\overline{P}_{\mathrm{H},t} = \overline{P}_{\mathrm{H},t}^{*}$ but $P_{\mathrm{H},t} \neq P_{\mathrm{H},t}^{*}$.

3 Calibration

Table 1 reports our benchmark calibration, which we assume symmetric across countries. Several parameter values are standard in the international business cycle literature, e.g. similar to those adopted by Stockman and Tesar [1995], who calibrate their models to a set of OECD countries, and CKM. Throughout the exercise, we will carry out some sensitivity analysis and assess the robustness of our results under the benchmark calibration.

Productivity shocks Let the vector $\mathbf{Z} \equiv \{Z_j, Z_j^*\}$ represent sector j's technology shocks in the domestic and foreign economies. We assume that sectoral disturbances to technology follow a trend-stationary AR(1) process

$$\mathbf{Z}^{'} = \boldsymbol{\lambda}\mathbf{Z} + \mathbf{u}, \tag{17}$$

whereas $\mathbf{u} \equiv (u_j, u_j^*)$ has variance-covariance matrix $V(\mathbf{u})$, and $\boldsymbol{\lambda}$ is a $2x2$ matrix of coefficients describing the autocorrelation properties of the shocks, that are the same for both sectoral shocks. Since we assume a symmetric economic structure across countries, we also impose symmetry on the autocorrelation and variance-covariance matrices of the above process. Because of lack of sectoral data on productivity, we posit that sectoral shocks follow a simple and rather conventional process.[7] First, in line with most of the international business cycle literature — e.g., BKK — we assume that these shocks are very persistent, and set their autocorrelation to 0.95. Second, the standard deviation of the innovations is set to 0.007 and their correlation across countries to 0.25, while the correlation across sectors is set to zero (see bottom panel of Table 1). Finally, we assume that there are no spillovers across countries and sectors. As a consequence of this choice, it can be anticipated that the model will have a hard time in replicating the pattern of international comovements, for which sizable shock correlations are required. Thus, in judging this aspect of the model we will focus on one meaningful statistic, the difference between the cross-correlations of output and consumption, which, as argued by BKK, is a good indicator of the ability of a model to generate a transmission mechanism that can escape the "quantity puzzle."

Monetary policy In characterizing monetary policy, we assume that in the benchmark systematic policy follows a Taylor-type rule setting the short-term nominal interest rate as a function of the deviations of expected inflation and GDP from steady state values:

$$R_t = \rho R_{t-1} + \chi(1-\rho)E(\pi_{t+1} - \pi^{ss}) + \gamma(1-\rho)(y_t - y^{ss}). \tag{18}$$

We parameterize the policy rule using the estimates in Lubik and Schorfheide [2004]: $\rho = 0.84$, $\chi = 2.19$, $\gamma = 0.3$. To emphasize that our results do no depend on monetary shocks, in the

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[7] In Corsetti, Dedola and Leduc [2004] we estimated this vector process with annual data, the only frequency for which sectoral productivity is available for several OECD countries. If we use a quarterly version of that process we get broadly similar results to those reported here.

exercises reported below we assume that there is no stochastic component to monetary policy. We observe here that our results are unchanged when we add plausible monetary shocks. Likewise, we document that our results remain largely unchanged when we assume that systematic monetary policy is such that money growth remains constant at the steady state level (k-rule), or current inflation is perfectly stabilized (inflation-targeting rule).

Preferences and production We posit that the period-by-period utility function has the following form:

$$U\left[C_t, \frac{M_{t+1}}{P_t}, \ell_t\right] = \frac{C_t^{1-\sigma}}{1-\sigma} + \chi \frac{\left(\frac{M_{t+1}}{P_t}\right)^{1-\sigma}}{1-\sigma} + \alpha \frac{(1-\ell_t)^{1-\upsilon}}{1-\upsilon}, \qquad \sigma > 0, \tag{19}$$

we set α so that in steady state, one third of the time endowment is spent working. In our benchmark calibration, we set υ equal to σ (risk aversion). Since the utility function is separable in consumption and real money balances, money demand is determined residually and does not play any role in our results. We therefore set χ arbitrarily to 0.1. Following Schmitt-Grohe and Uribe [2003], we assume that the endogenous discount factor depends on the average per capita level of consumption, C_t, real money balances, $\frac{M_{t+1}}{P_t}$, and hours worked, ℓ_t, and has the following form:

$$\nu\left(U\left[C_t, \frac{M_{t+1}}{P_t}, \ell_t\right]\right) = \begin{cases} \ln\left(1 + \psi\left[C_t + \chi \frac{M_{t+1}}{P_t} + \alpha(1-\ell_t)\right]\right) & \sigma \neq 1 \\ \ln\left(1 + \psi\left[\ln C_t + \chi \ln \frac{M_{t+1}}{P_t} + \alpha \ln(1-\ell_t)\right]\right) & \sigma = 1 \end{cases}, \tag{20}$$

whereas ψ is chosen such that the steady-state real interest rate is 1 percent per quarter, i.e. equal to 0.006. This parameter also pins down the (very low) speed of convergence to the nonstochastic steady state.

The value of ϕ for the elasticity of substitution between traded and nontraded goods is selected based on the available estimates. We use the estimate by Mendoza [1991] referred to a sample of industrialized countries and set that elasticity equal to 0.74, a value on the higher side of those estimated.

According to the evidence for the U.S. economy in Burstein, Neves and Rebelo [2003], the share of the retail price of traded goods accounted for by local distribution services ranges between 40 percent and over 50 percent, depending on the industrial sector. We follow their calibration and set it equal to 50 percent.

As regards the weights of domestic and foreign tradables in the tradables consumption basket (C_{T}), a_{H} and a_{F} (normalized $a_{\mathrm{H}}+a_{\mathrm{F}}=1$) are chosen such that exports are 10 percent of aggregate output in steady state, roughly in line with the average ratio for the U.S. in the last 30 years. The weights of traded and nontraded goods, a_{T} and a_{N}, are chosen as to match the share of nontradables (i.e. services) in the U.S. consumption basket, which is around 50 percent when energy goods are excluded. The weights of tradables and nontradables inputs in capital formation are set to 0.4 and 0.6, respectively, in line with the evidence in Bems [2005].

We calibrate ξ and ζ, the labor shares in the production of tradables and nontradables, based on the work of Stockman and Tesar [1995]. They calculate these shares to be equal to 61 percent and 56 percent, respectively. Finally, we set the depreciation rate of capital equal to 10 percent annually.

A key role in our model is played by the markup in the tradable sector. Note, however, that in the presence of distribution costs, the sectoral markups will not be equal in steady state across sectors for symmetric values of θ_{H} and θ_{N}. In the nontraded-goods sector, the markup is the standard constant $\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}$. In the traded-good sector, the markup is:

$$mk_{\mathrm{H}} = \frac{\theta_{\mathrm{H}}}{\theta_{\mathrm{H}}-1}\left(1+\frac{\eta}{\theta_{\mathrm{H}}}\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}\frac{MC_{\mathrm{N}}}{MC_{\mathrm{H}}}\right), \tag{21}$$

where MC_{N} and MC_{H} are the marginal costs in the non-traded and traded-goods sector, respectively. We set the gross steady-state markup for domestic goods to 1.15. This implies that θ_{N} (and θ^*_{N}) is equal to 7.7. We then parametrize the elasticity of substitution of traded goods varieties, θ_{H} and θ_{F}, so that the steady-state markup is identical across sectors, for the given calibrated value of the distribution margin.

In our specification with nominal price rigidity, we calibrate the price-adjustment cost parameters, κ^p_{H}, κ^{*p}_{H}, and κ^p_{N}, by noting that a typical Calvo price-setting model implies a (log-linearized) stochastic difference equation for inflation of the form $\pi_t = \beta E_t \pi_{t+1} + \widetilde{\lambda} mc_t$, where mc_t is the firm's real marginal cost of production, and $\widetilde{\lambda} = \frac{(1-q)(1-\beta q)}{q}$, with q being the constant probability that a firm must keep its price unchanged in any given period and β the subjective discount factor (see Galí and Gertler [1999]). The quadratic adjustment-cost model gives a similar (log-linearized) difference equation for inflation, but with $\widetilde{\lambda} = \dfrac{\theta_{\mathrm{J}}-1}{\kappa^p_{\mathrm{J}}\pi^2}$, J=H,N. In line with the evidence reported by Bils and Klenow [2004] for the U.S., showing that the average duration between price changes is 4.3 months, we set the values of κ^p_{H}, κ^{*p}_{H}, and κ^p_{N} equal to 8.6, 3.7, and

4.0, respectively. These values imply that the reduced form coefficient multiplying real marginal costs λ is the same across all goods. Moreover, we also simulate our model assuming that prices are set for three quarters, since this is a value commonly used in the sticky-price literature. Note also that in the experiments below, we have abstracted from wage stickiness, although it may be an important determinant of the response (or lack thereof) of consumer prices to exchange rates.

Setting the elasticity of substitution between Home and Foreign tradables and risk aversion Above, we have discussed the set of parameters whose calibration will remain identical across our experiments, or vary only for robustness checks. We now discuss parameters which play a crucial role in differentiating between the two approaches to modeling real exchange rate volatility suggested by the DSGE literature, that we follow in our quantitative exercises.

The focus of the 'risk-aversion approach,' pursued by CKM, is on the strict positive link between relative consumption and the real exchange rate in complete market economies, as well as in a large class of economies with incomplete markets with comparablu high consumption risk sharing. With power utility, if relative risk aversion is sufficiently high, the variability of the ratio of Home to Foreign consumption observed in the data can correspond to large equilibrium movements in the real exchange rate. We reconsider the CKM modeling strategy in a different framework, including nontradables and distribution costs which create goods-market segmentation and deviation from the law of one price, even in the absence of nominal rigidities. In our set of experiments, following CKM, we will study an economy in which $\sigma = 5$, setting the investment adjustment cost, b, to match the standard deviation of consumption relative to that of output in the United States. The elasticity of substitution between imported and domestic tradables in both consumption and the intermediate input to investment, ω, is set to 1.5 as in CKM.

The 'elasticity approach' has been discussed early on by BKK in the framework of a complete market model, and recently reconsidered in a model with incomplete markets in previous work of ours (Corsetti, Dedola and Leduc [2004]). The idea is that the impact of shocks on international prices is magnified by a relatively low price elasticity of imports – within the range of values adopted by the literature. Following this approach, we also study an economy in which we set

$\sigma = 2$ and $\omega = 0.5$, the lowest value used by BKK.[8] Under the elasticity approach, we calibrate the investment adjustment cost, b, to match the standard deviation of U.S. investment relative to that of U.S. output.

4 Business cycle properties of exchange rates and prices

In this section, we discuss our main quantitative results regarding the general equilibrium properties of exchange rates and prices in economies characterized by endogenously high volatility of the exchange rate. Tables 2A and 2B report the H-P–filtered statistics for the data and for three versions of our economy, one with flexible prices and the other two with a low and a high degree of local currency price stickiness (LCP), corresponding to an average length of prices equal to 1.43 and 3 quarters, respectively. Tables 3A and 3B, instead, report the results for the case of a low degree of price stickiness assuming three different monetary rules: a Taylor rule, a money growth rule, and inflation targeting. Tables 2A and 3A refer to the specification with a relatively low elasticity, while Tables 2B and 3B refer to the parametrization with a high risk aversion. The empirical statistics are all computed with the United States as the home country and the rest of the world as the foreign country.[9] Standard deviations are normalized by the standard deviation of U.S. output. Throughout our exercises, we take a first-order Taylor series expansion around the deterministic steady state and solve our model economy using the DYNARE suite of MATLAB programs (see Juillard [2005]). We compute the model's statistics by logging and filtering the model's artificial time series using the Hodrick and Prescott filter and averaging moments of a long time-series simulation of 5500 periods, of which we discard the first 500 observations.

Consider first Table 2. Overall, we find that the economies displayed in Tables 2A and 2B display a striking ability to account broadly for the main features of exchange rates and

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[8] There is considerable uncertainty regarding the true value of trade elasticities, directly related to this parameter. For instance, Taylor [1993] estimates the value for the U.S. to be 0.39, while Whalley [1985], in the study used by Backus et al. [1995], reports a value of 1.5. For European countries most empirical studies suggest a value below 1. For instance, Anderton et al. [2004] report values between 0.5 and 0.81 for the Euro area.

[9] Thus, import and export prices, the CPI and so on are from U.S. data, while the real exchange rate, for example, refers to the trade-weighted exchange rate for the United States (deflated with CPIs) relative to its trading partners, based on data reported by the OECD and the IMF.

international prices in the data: international price movements are volatile, persistent, and highly correlated — a good qualitative match of the data. Moreover, the correlation of the nominal exchange rate with consumer prices is generally low. A notable result is that the mechanism proposed by CKM to generate volatility works quite well in our framework with traded and non traded goods, irrespective of nominal rigidities, in response to *productivity* shocks. The two economies in Table 2A and 2B, however, differ in one important respect, which is their ability to match the correlation between international prices and quantities. The economy with a low elasticity in Table 2A can account for the negative correlation between relative consumption and the real exchange rate observed in the data, addressing the so-called Backus-Smith anomaly.[10] The mechanism underlying this result is that, with a relatively low price-elasticity of imports, equilibrium movements in international relative prices magnify the consumption risk due to productivity fluctuations. In particular, in response to technology shocks in Home tradables, the equilibrium terms of trade (and the real exchange rate) movements leads to large divergences in relative wealth (and thus consumption) across countries. Conversely, models of exchange rate volatility relying on the mechanism highlighted by CKM predict a virtually perfect correlation between relative consumption and the real exchange rate, a feature that is at odds with the data. This is true in our experiments as well, as reported in Table 2B.

The following results are worth stressing. *First*, the volatility of the nominal exchange rate and international prices is as high or even higher than in the data for both parameterizations. Observe that the addition of price stickiness indeed tends to amplify the volatility of exchange rates. But while raising the degree of nominal rigidities makes international prices more volatile under the elasticity approach, the relationship between price stickiness and volatility is non linear under the risk aversion approach.

Second, for a degree of nominal rigidity consistent with the evidence in Bils and Klenow [2004], we find that the real exchange rate is positively correlated with both the nominal exchange rate and the terms of trade (a weaker currency is associated with a worsening of the terms of trade). Positive comovements between the exchange rate and the terms of trade are stressed by Obstfeld and Rogoff [2000] as evidence against the idea that import prices in local currency

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[10] The analysis of a similar economy with flexible prices is fully developed in Corsetti Dedola and Leduc [2004]. Relative to the flexible prices benchmark, in this paper we highlight that this important feature of our model also characterizes specifications with nominal price rigidities.

do not react to exchange rates, because of nominal rigidities. In light of the debate following Obstfeld and Rogoff [2000], we provide an important qualification to these authors' argument. In a model where firms face costs of adjusting prices in local currency, the correlation between the terms of trade and the exchange rate depends on the degree of nominal rigidities. In our setup, prices can change in the period in which firms are hit by a shock, provided they find it convenient to bear the adjustment costs. Hence, in contrast to the environment adopted by Obstfeld and Rogoff [2000], in which prices are preset for one period, our model does not predict that a depreciation will automatically improve the terms of trade, unless the adjustment cost is relatively high. Indeed, as shown in both Tables 2A and 2B, the correlation between these two variables switches from positive to negative when we raise the degree of nominal rigidities (see the last two columns in the tables).

Third, traditional models with price rigidities and high pass-through predict that the correlation between the exchange rate and the import price index is almost perfect: a depreciation of the currency translates into "imported inflation" for the domestic economy approximately one-to-one. In our simulations, instead, the above correlation is positive but much below one, as in the data: in Table 2A the highest correlation is 0.91 (for the flexible price economy), the lowest correlation is 0.69 (for the economy with 3-quarter price rigidities), against 0.45 in the data (excluding oil imports). Along this dimension, the specification of Table 2B is closer to the data — especially for the low LCP case.

Fourth, distributive trade and a low (endogenous) import price elasticity imply that consumer prices are only tenuously correlated with the nominal exchange rate across all specifications — broadly in accord to the evidence. In particular, the correlation with the CPI (excluding energy) across all specifications with nominal rigidities is low but generally positive in levels, against -0.17 in the data.

Fifth, while the relative volatility of imports falls short of that in the data in all specifications, is comparably high across the two economies in Table 2. It is actually higher in panel 2A, corresponding to the parameterization with a low ω, than in panel 2B. This is remarkable in light of the analysis by BKK, who show that, in a complete market setting, lowering the elasticity of substitution leads to a strong fall in the volatility of imports.

Finally, we observe that the economies in Table 2A are consistent with two key features of the data emphasized in the international business cycle literature: (i) net exports are countercyclical;

and, addressing the so-called ‘quantity puzzle’, (ii) the cross-country correlation of output is larger than that of consumption. Under the elasticity approach, net exports are countercyclical because positive productivity shocks in the Home tradable sector raises their international price (i.e. the terms of trade appreciates), lowering net exports. In contrast, under the risk-aversion approach, productivity improvements in the Home tradables cause their international price to fall, raising net exports. When we assume a low trade elasticity, consumption risk sharing is low, consistent with a negative Backus-Smith correlation. Likewise, under the elasticity approach the model is not subject to the quantity puzzle, as the cross-country correlation of output is higher than that of consumption because of the negative spillovers.

In Tables 3A and 3B, we turn to experiments testing the sensitivity of our results to different monetary policy rules. Overall, these tables show that the results discussed above are broadly independent of the particular monetary policy reaction function assumed in our exercises. The qualitative features of our model being substantially unaffected, different policy reaction functions mainly impinge on the quantitative properties of nominal variables, as should be expected. Namely, in our quantitative results, the CPI becomes progressively smoother when we move from the k-percent rule to our benchmark specification of monetary policy rules (Taylor), and from this to inflation targeting. With a smoother path for the consumer price, the nominal exchange rate tends to become more similar to the real exchange rate. Under inflation targeting (last column in each panel of Table 3), the volatility of the two variables is the same, and their correlation is perfect.

In Table 3B (the economy with high risk aversion), we can detect a second implication of varying monetary rules. In this economy, making monetary policy more responsive to fluctuations in inflation raises the correlation between the CPI and the nominal exchange rate. With inflation targeting, such correlation is as high as 0.68, against 0.15 in the benchmark. In this dimension, the low-elasticity economy of Table 3A does better: when monetary authorities pursue inflation targeting, the predicted correlation is -0.25, against -0.17 in the data.

5 Structural and empirical pass-through equations

Exchange rate pass-through (henceforth ERPT) is defined as the percentage change in import prices denominated in local currency resulting from a one percent change in the bilateral exchange rate between the exporting and the importing country, *other things equal.* A large empirical literature has been providing estimates of (structural) pass-through coefficients using regression analysis. As is well understood, however, constraints on data availability raise potentially serious problems of omitted variable bias and measurement errors in virtually all empirical models in this area.

In this section, we make use of our model to generate artificial data so to assess, in a controlled, quantitative environment, the performance of regression models commonly found in this literature. From our analytical framework, we derive structural expressions for pass-through coefficients in the short and the long run — expressions which are useful towards the specification of empirical regression models consistent with alternative theoretical views of pass-through. Building on these expressions, we analytically characterize the bias in estimates of pass-through coefficients. We then run stylized regression models motivated from the empirical literature on pass-through on the time series generated by our models, deriving a quantitative assessment of the regression bias. We obtain two notable results. While our analytical study suggests that a high volatility of the nominal exchange rate tends to reduce the size of the bias, in general equilibrium the covariance of the exchange rate with demand and marginal costs may prevent this bias from vanishing even for very high values of such volatility. Second, the quality of regression proxies for marginal costs and demand is sensitive to the type of shocks hitting the economy: changing the weight of real and monetary disturbances affect the relative performance of alternative specifications.

5.1 Inspecting the mechanism(s): structural ERPT equations

5.1.1 ERPT and price discrimination

Let us consider first our specifications with flexible prices. The log-linear expression for the price of imports is:

$$\widehat{\widehat{P}}_{\mathrm{F},t} = \frac{1}{1+\mu\left(mk_{\mathrm{F}}-1\right)}\left(\widehat{\mathcal{E}}_t + \widehat{MC^*}_{\mathrm{F},t}\right) + \frac{\mu\left(mk_{\mathrm{F}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)}\widehat{MC}_{\mathrm{N},t} \tag{22}$$

where mk_{F} is the steady state markup and μ is the distribution margin in the home import sector. As long as μ is strictly above zero, the coefficient on the exchange rate will be less than one, and so will be ERPT.

In our benchmark calibration, plausible markups and structural parameter values imply that the ERPT coefficient is equal to 0.93. Because of the presence of distribution services, the impact of changes in the nominal exchange rate on the prices that consumers pay for import will be lower:

$$\widehat{P}_{\mathrm{F},t} = (1-\mu)\widehat{\overline{P}}_{\mathrm{F},t} + \mu \widehat{P}_{\mathrm{N},t} \tag{23}$$

With a distribution margin as high as 50 percent, pass-through to consumer prices (of imports) falls to 46 percent. As noted by the literature, the implications of distributive trade for local currency price stability is quite remarkable even in models with flexible prices and wages.

5.1.2 ERPT and local currency price stickiness

In our model, we have assumed a quadratic price-adjustment cost for Foreign export prices in Home currency, in the form $\frac{\kappa_{\mathrm{F}}^{p}}{2}\left(\frac{\overline{P}_{\mathrm{F},t}(f)}{\overline{P}_{\mathrm{F},t-1}(f)} - \pi\right)^{2} \overline{P}_{\mathrm{F},t} D^{*}_{\mathrm{F},t}$. Solving for optimal pricing, imposing symmetry and log-linearizing around a steady state , we obtain:

$$\begin{aligned}
\widehat{\overline{P}}_{\mathrm{F},t} \quad = \quad & \frac{\left(\widehat{\mathcal{E}}_t + \widehat{MC^{*}}_{\mathrm{F},t}\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)+\kappa_{\mathrm{F}}^{p}\pi^{2}\left(mk_{\mathrm{F}}-1\right)(1+\beta)} + \\
& \frac{\mu\left(mk_{\mathrm{F}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)+\kappa_{\mathrm{F}}^{p}\pi^{2}\left(mk_{\mathrm{F}}-1\right)(1+\beta)}\widehat{P}_{\mathrm{N},t} + \\
& \frac{\kappa_{\mathrm{F}}^{p}\pi^{2}\left(mk_{\mathrm{H}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)+\kappa_{\mathrm{F}}^{p}\pi^{2}\left(mk_{\mathrm{F}}-1\right)(1+\beta)}\left(\beta E_t \widehat{\overline{P}}_{\mathrm{F},t+1} + \widehat{\overline{P}}_{\mathrm{F},t-1}\right),
\end{aligned}$$

whereas the nominal marginal cost $MC^{*}_{\mathrm{F},t} = \frac{\left(W_t^{*}\right)^{\zeta}\left(R_t^{*}\right)^{1-\zeta}}{Z_{\mathrm{F},t}}$, and as before mk_{F} denotes the total markup (including both distribution and standard markup) in the imported Home tradable sector.

The above equation highlights the two mechanisms of imperfect pass-through embedded in our analysis. In the short run, even if prices are fully flexible – corresponding to $\kappa_{\mathrm{F}}^{p} = 0$ – the pass-through coefficient is less than 1 per effect of distributive trade, corresponding to $\mu > 0$. When there are no distribution costs ($\mu = 0$), the short-run pass-through coefficient is less than 1 only when there are nominal rigidities.

The low pass-through coefficient in the short run mostly reflects nominal price rigidities. Calibrating the model according to the evidence in Bils and Klenow [2004], for an average nominal price rigidities of 4.3 months, the short-run coefficient turns out to be 0.27. In turn, assuming that prices are, on average, fixed for three quarters lowers this value to 4 percent. In the long run, nominal rigidities are obviously irrelevant, and imperfect pass-through can only be attributed to the implications of distribution for the price elasticity of imports. Depending on the degree of monopolistic distortions, in our model the long-run EPRT is 93 percent. Recall that, as shown above with a distribution margin of 50 percent, pass-through onto consumer prices will be half the degree of pass-through onto prices at the dock.

When bringing our model to the data, our analysis above makes it clear that an empirical specification of the regression model consistent with theory should include marginal costs in the tradable sector, marginal costs or prices in the distribution sector (which in our analysis are the same as nontradable goods) — to account for the effect of distributive trade on the price elasticity and markup — as well as the expected value of $E_t\widehat{\overline{P}}_{\mathrm{F},t+1}$ — to account for the dynamic dimension of optimal pricing with forward-looking price setters. Omitting any of these variables would likely result into biased estimates.

5.2 Regression bias in empirical models of ERPT: an assessment using simulated time series

5.2.1 Regression bias and endogenous exchange rate volatility

Empirical research on ERPT focuses on the adjustment of prices to an exchange rate change for transactions between an exporting and importing country. According to the taxonomy in Goldberg and Knetter (1997), the typical ERPT regression framework can be written as

$$\mathcal{P}_t = \alpha + \gamma\mathcal{E}_t + \beta\mathcal{C}_t + \delta\mathcal{D}_t + u_t, \tag{24}$$

where all variables are in logs: $\mathcal{P}_t$ is the import price denominated in local currency, $\mathcal{C}_t$ is a measure of exporter's marginal costs, $\mathcal{D}_t$ may include controls for shifts in import demand (like prices of competing goods or income in the importing country), as well as lagged values of the dependent variable to capture dynamics, and $\mathcal{E}_t$ is the nominal exchange rate (importer's currency per unit of exporter's currency). The coefficient γ is referred to as the pass-through coefficient. ERPT — conditional on controls $\mathcal{D}_t$ and $\mathcal{C}_t$ — is full or complete if $\gamma = 1$ and is incomplete if $\gamma < 1$. Provided one can find an accurate measure of marginal cost $\mathcal{C}_t$, the coefficient γ measures the variable markup component of the textbook definition of pass-through.

The typical pass-through regression treats marginal costs as directly observable, but includes cost indices. These indices may be reasonable measures of average costs incurred domestically, but are unlikely to be good measures of marginal costs, which is the relevant concept in specifying optimal pricing by profit-maximizing firms. Furthermore, measurement errors in cost indices may be correlated with exchange rates in ways that bias the coefficients toward finding incomplete pass-through and excess markup adjustment.

The research on pricing-to-market (henceforth PTM) has addressed this issue including prices in both the origin and the destination markets, as well as costs, in the empirical regressions. In terms of (24), $\mathcal{P}_t$ is the export price, $\mathcal{C}_t$ is the domestic price of the same good, while $\mathcal{D}_t$ includes other cost factors and demand shifters in both markets. Costs, and thus errors in costs, influence the export price relative to the domestic price only when there is a difference in the convexity of demand in the two markets (e.g., see Marston [1990]).[11]

To shed light on the quantitative importance of different potential sources of biases in empirical studies of pass-through, in the next subsection we will present and analyze the results from running regressions on the (log of the) artificial data simulated using our theoretical economies. Here, we set the stage for our quantitative analysis by emphasizing an important advantage of using a general equilibrium model where exchange-rate volatility is not attributed to 'exogenous noise.' For simplicity, consider a simple empirical specification where import prices are regressed on the contemporaneous exchange rate only. Using the log-linearized expressions derived above, it is easy to derive the following expression for the bias in estimating γ[12]

$$bias = \frac{Cov\left(\mathcal{E}_t, \frac{1}{1+\mu(mk_{\text{F}}-1)} MC^*_{\text{F},t} + \frac{\mu(mk_{\text{F}}-1)}{1+\mu(mk_{\text{F}}-1)} MC_{\text{N},t}\right)}{Var\left(\mathcal{E}_t\right)} \tag{25}$$

This expression makes clear that the size of the bias is crucially affected by the volatility of the exchange rate: *other things equal*, an economy with a highly volatile exchange rate would provide a relatively better environment for empirical analysis. The regression bias, however,

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[11] Most studies of PTM use international price data which do not reveal the invoice currency. For instance, since he compared Japanese export and domestic prices, Marston [1990] had to allow for possible effects of foreign currency invoicing, distinguishing between short run and long run PTM. Although sticky prices in the foreign currency contribute to PTM in the short run, for Japanese exports Marston [1990] finds that substantial PTM persists beyond the period in which prices are sticky.

[12] Note that the expression is also a reasonable approximation of the more general case of regressions in which the available controls are very poor instruments for the omitted variables $MC_{\text{N},t}$ and $MC^*_{\text{F},t}$.

also depends on the covariance between $\mathcal{E}_t$ and the productivity shocks $Z_{\mathrm{F},t}$ and $Z_{\mathrm{N},t}$ affecting marginal costs in the two economies. In general equilibrium, exchange rate volatility is no guarantee of accuracy in pass-through estimates.

Note that, if marginal costs are basically uncorrelated across border (the case of country-specific shocks), the sign of the bias above will depend on the 'international transmission' of productivity shocks. If (depending on parameters' value) a positive Home shock depreciates the Home nominal exchange rate, the regression bias will be *negative*: pass-through estimates will be *lower* than the true coefficient $\frac{1}{1+\mu(mk_{\mathrm{F}}-1)}$. If instead a positive Home productivity shock brings about a nominal appreciation, the opposite will occur. In theory, both effects are possible (see Corsetti, Dedola and Leduc [2004]).

5.2.2 Quantitative results

We analyze two types of empirical models, which we dub 'ERPT regressions' and 'PTM regression'. The first one is specified as follows:

$$\overline{P}_{\mathrm{F},t} = \alpha + \gamma\mathcal{E}_t + \beta W_t^* + \delta_1 Y_t + \delta_2 \overline{P}_{\mathrm{F},t-1}. \tag{26}$$

In terms of (24), the ERPT regression includes Foreign nominal wages, W_t^*, to control for marginal costs in the exporting country, and Home real GDP, Y_t, to control for demand conditions in the importing country. We also include one lag of the dependent variable to capture differences between short-run and long-run pass-through that are relevant in the economies with nominal rigidities. Thus, the exchange-rate coefficient γ represents the estimate of the short-run ERPT coefficient, while $\dfrac{\gamma}{1-\delta_2}$ will be the estimate of the long-run ERPT coefficient.

The 'PTM regression', instead, has the following specification:

$$\overline{P}_{\mathrm{F},t} = \alpha + \gamma\mathcal{E}_t + \beta \overline{P}^*_{\mathrm{F},t} + \delta_1 \overline{P}_{\mathrm{H},t} + \delta_2 \overline{P}_{\mathrm{F},t-1}, \tag{27}$$

In line with the insights from the PTM literature, this regression includes the domestic price of Foreign exports, $\overline{P}^*_{\mathrm{F},t}$, to control for marginal cost in the exporting country, and the Home PPI of tradables, $\overline{P}_{\mathrm{H},t}$, to control for demand conditions in the importing country. As above, we also include the lagged dependent variable, so that γ represents the short-run ERPT coefficient, while $\dfrac{\gamma}{1-\delta_2}$ will be our estimate of the long-run ERPT coefficient. Moreover, in line with the PTM literature we impose the homogeneity constraint $\beta = \gamma$ (e.g., see Anderton [2003]), reflecting the theoretical a-priori that the exchange-rate pass-through should be equal to that of marginal costs.

Both regressions are clearly misspecified in the context of our theoretical models, as they do not control for the effect of the cost of distribution on demand elasticities, and suffer from measurement error problems, as they rely on proxies of the generally unobservable marginal costs. Precisely, (26) only includes nominal wages, but omit the price of capital and measures of technology shocks. By the same token, the inclusion of the Foreign price of Home imports among the regressors in (27) is a potential source of bias, as this price includes a Foreign market time-varying markup.[13]

Tables 4A through 5B present the results from running our regressions on our simulated time series. The estimated coefficients in these tables are computed using the same 5000 observation used to calculate the business-cycle statistics under the Taylor rule.[14] For each theoretical economy, the table shows the true value of the short-run and long-run coefficients γ and $\frac{\gamma}{1-\delta_2}$ in the two rows under the heading *Structural*. As shown above, these coefficients reflect the value of the structural parameters in the log-linearized first order conditions of the monopolistic Foreign exporter. Thus, the short-run and long-run coefficients coincide in the benchmark model with flexible prices, and their level, equal to 0.93, is fully determined by the steady state level of the markup in the import sector, mk_{H}, and the distribution margin, μ. Conversely, the short-run and long-run coefficients differ in the sticky price model. Because of the destination-specific price adjustment cost, the short-run coefficient is equal to either 0.27 or 0.04 depending on the degree of price stickiness, while the long-run coefficient is 0.93, as in the benchmark. Notably, the values for the short-run coefficients are well in the range of the estimates for the U.S. and in general the industrialized countries (e.g., see Anderton [2003] for the euro area and Campa and Goldberg [2002] for a large set of OECD countries, respectively).

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[13] Interestingly, however, the restrictions on coefficients embedded in this specification are true in our model of price discrimination driven by distribution costs, provided one includes the true structural variables in the regression, that is, the Foreign marginal cost in the tradable sector and the price of distribution in the Home country.

[14] In additional experiments, not reported in the tables, we find that the regression results are not very sensititive to changes in the policy reaction functions, i.e. on whether we generate time series by assuming inflation targeting, the Taylor rule or a money growth rule. Taylor [2000] argues that changes in systematic monetary policy should affect the pass-through coefficient.

As a useful benchmark, all tables begin with a control regression in which the import price is regressed only on its lag and the exchange rate — we dub this specification "naïve". According to such specification, even with flexible prices the estimated short-run ERPT is always less than 1 percent — namely, a 10 percent domestic currency depreciation should lead to only a 0.1 percent increase in import prices. Moreover, the long-run estimates are reasonably close to the structural coefficient only in the case of high price stickiness. The reason to include the naïve specification is apparent: it clearly shows that the problem of omitted variables can be very serious even in a setting characterized by high exchange rate volatility.

It is remarkable that the inclusion of some controls, albeit imperfect, significantly improves the performance of the regression models. Focus at first on Tables 4A and 4B. The PTM regression does particularly well at distinguishing between short- and long-run coefficients when they are truly different, and correctly equates their estimates when they are the same – the case of flexible prices. In contrast, the ERPT specification incorrectly estimates a different value of the short- and long-run coefficients when prices are flexible. With sticky prices, the PTM regression in Table 4A basically recovers the correct value of the long-run structural coefficient, but displays an upward bias in the estimates of the short-run coefficient. In contrast, the estimated long-run coefficient from the ERPT regression show a small upward bias, while the short-run coefficient is closer to the structural one than in the case of the PTM regression. Similar results emerge from table 4B, although the size of the bias here is larger.

What can account for the different performance of the two regressions? In order to address this question we run an hybrid specification (ERPT (2)), equal to the ERPT specification, except that we replace the domestic GDP with $\overline{P}_{\mathrm{H},t}$ in Table 4A and wages with $\overline{P}^{*}_{\mathrm{F},t}$ in Table 4B. In our experiments, the hybrid specification ERPT (2) does better than the ERPT specification, suggesting that the PTM regression include better proxies for marginal costs and demand conditions. We note that, since in our model firms price discriminate, the price variables included in PTM and ERPT (2) have good theoretical foundations — consistently, their use improves the performance of the regressions.

An interesting question is to what extent regression results are sensitive to the driving forces behind exchange rate volatility.[15] To address this question, Tables 5A and 5B report results for

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[15] We thank Pat Kehoe for suggesting this exercise to us.

the model with sticky prices conditional on monetary shocks only. The shocks are appended to the interest-rate rules and are assumed to have a standard deviation equal to 0.2 percent and to be uncorrelated across countries. Notably, relative to table 4, the performance of the PTM regression model deteriorates markedly. In particular, with monetary shocks only, the ERPT regression model seems to perform better than the PTM one. Now, one possible reason for the reversal in the performance of the two regression models is that, with monetary shocks only, the nominal wage (which is flexible in our model) is a better proxy for marginal costs than product prices, whose adjustments are constrained by nominal rigidities. In the absence of frictions in the labor market, equilibrium nominal wages follows closely the monetary stance in the economy. However, in the case of low price rigidity, it turns out that prices are quite responsive to wages, and therefore closely follow marginal costs. A better explanation points to the quality of the proxy for domestic demand. Indeed, when we run a hybrid PTM regression model (dubbed PTM (2)), including the level of domestic output in the place of domestic prices, this tends to perform much better than the original PTM model.

Our experiments in Table 5 suggest that the quality of available empirical proxies for marginal costs and demand (determining the performance of different empirical models) is likely to depend on the type of disturbances affecting the economy. Thus, assessing the sensitivity of pass-through estimates to the inclusion of alternative proxies for marginal costs and import demand is crucial for the reliability of these estimates.

6 Concluding remarks

Understanding the relative importance of different factors causing high exchange rate volatility, on the one hand, and low pass-through and local currency price stability, on the other, is crucial for both model building and policy analysis. As is well known, a core implication of low pass-through is that high exchange-rate volatility will systematically drive apart cross-borders prices of otherwise identical goods — i.e. there will be deviations from the law of one price. In the absence of nominal rigidities, such deviations correspond to optimal pricing strategies by firms with monopoly power. In the presence of nominal rigidities, instead, they correspond to suboptimal fluctuations of firms' profits, with important implications for the design of stabilization policy rules in open economies. Moreover, in the presence of large swings in the exchange rate, lack of risk sharing opportunities imply large fluctuations of relative wealth and consumption. These considerations raise the question of whether exchange-rate movements play the stabilizing role attributed to them by the received wisdom, either as a substitute for relative price adjustment or as mechanism reducing the consumption risk of productivity and nominal shocks.

This paper develops a quantitative, dynamic, open-economy framework which generates high exchange rate volatility, and analyzes the role of nominal rigidities (in the form of local currency pricing) in determining a low degree of ERPT. Because of the presence of distribution services, retail prices have a significant nontradable component. Moreover the elasticity of demand is market specific, which leads firms to price-discriminate across countries. In our model, the combination of distribution services, price discrimination and local currency pricing with nominal rigidity can account for the variable degree of ERPT over different horizons. In the short run, we find that a small amount of nominal rigidities can lower the elasticity of import prices at border and consumer level to a value between 4 and 27 percent. In addition, as a result of price discrimination, our model predicts exchange-rate pass-through coefficients that are lower than one also in the long run.

We stress that in our benchmark economy a limited degree of LCP delivers structural short-run exchange rate pass-through coefficients which are not far from empirical estimates in the literature; for instance Campa and Goldberg [2002] find that on average across OECD countries, exchange rate pass-through into import prices is 46% after one year; estimates are even lower for the US. Relative to these empirical results, our results suggest that an amount of nominal rigidities consistent with the evidence in Bils and Klenow [2004]) may be enough to make our theoretical economies consistent with this dimension of the data.

Yet, regression models commonly used in the empirical literature on exchange rate pass-through are likely to be plagued by measurement errors and omitted variable bias. We use our model as a controlled environment whereas to assess the potential consequences of these problems in empirical analysis. We first characterize the bias analytically and then run two regression models typically adopted by the literature, on artificial time series generated using different shocks to fundamentals. Consistent with theory, regression estimates are biased, but in most cases the regressions can detect differences between short and long run pass-through. While a high exchange rate volatility alleviates the bias, in a general equilibrium environment where the exchange-rate volatility is endogenous this does not guarantee estimates' accuracy. The covariance between the exchange rate and marginal costs, on the one hand, and demand, on the other hand, will tend to prevent the bias from vanishing. Most interestingly, we have shown that the quality of different regressors as proxies for marginal costs and demand conditions depend on the set of shock we condition our estimates on. Shifting importance from real to monetary shocks affects the relative performance of alternative specifications. Thus, assessing the sensitivity of pass-through estimates to the inclusion of alternative proxies for marginal costs and import demand seems to be crucial for the reliability of these estimates.

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Table 1. Parameter values

Benchmark Models	
Preferences and Technology	
Risk aversion	$\sigma = 2, 5$
Disutility of labor	$\alpha = 1.13$
Velocity parameter	$\chi = 0.1$
Elasticity of substitution between:	
Home and Foreign traded goods	$\frac{1}{1-\rho} = 0.5, 1.5$
traded and non-traded goods	$\frac{1}{1-\phi} = 0.74$
Home non-traded goods	$\theta_{\mathrm{N}} = 7.7$
Home traded goods	$\theta_{\mathrm{H}} = 15.3$
Elasticity of the discount factor	
with respect to C and L	$\psi = 0.006$
Distribution margin	$\mu = 0.5 \quad (\eta = 1.22)$
Labor share in tradables	$\xi = 0.61$
Labor share in nontradables	$\zeta = 0.56$
Depreciation rate	$\vartheta = 0.025$
Monetary Policy	
Lagged interest-rate coefficient	$\rho = 0.84$
Weight on inflation	$\chi = 2.19$
Weight on output gap	$\gamma = 0.3$
Sectoral productivity shocks	
Sectoral autocorrelation matrix	$\lambda = \begin{bmatrix} 0.95 & 0.0 \\ 0.0 & 0.95 \end{bmatrix}$
Sectoral variance-covariance matrix (in percent)	$\Omega = \begin{bmatrix} 0.7 & 0.00123 \\ 0.00123 & 0.7 \end{bmatrix}$

Table 2A. Exchange rates and prices in the theoretical economies[a]

Statistics	U.S. Data	*Economy with $\sigma = 2, \omega = 0.5$*		
		Flexible prices	Sticky prices low LCP	Sticky prices high LCP
Standard deviation (relative to GDP)				
Real exchange rate (CPI based)	3.04	3.36	4.12	7.87
Nominal exchange rate	3.26	4.40	5.17	8.68
Terms of trade	1.71	2.93	3.29	6.89
Imports	3.28	2.38	2.29	2.41
Auto-correlation				
Real exchange rate	0.81	0.72	0.79	0.87
GDP	0.87	0.73	0.74	0.72
Correlation with real exchange rate				
Nominal exchange rate	0.96	0.92	0.95	0.98
Terms of trade	0.35	0.82	0.39	-0.43
Cross-country consumption ratio	-0.45	-0.66	-0.77	-0.88
Correlation with nominal exchange rate				
Import prices	0.45	0.91	0.88	0.69
CPI level	-0.17	0.42	0.40	0.30
Difference between cross-correlation of				
GDP and consumption	0.22	0.33	0.40	0.56
Correlation with GDP				
Net exports	-0.51	-0.43	-0.36	-0.27

[a] See main text for a description of the different model economies.

Table 2B. Exchange rates and prices in the theoretical economies[a]

Statistics	U.S. Data	*Economy with $\sigma = 5, \omega = 1.5$*		
		Flexible prices	Sticky prices low LCP	Sticky prices high LCP
Standard deviation (relative to GDP)				
Real exchange rate (CPI based)	3.04	3.40	3.53	3.72
Nominal exchange rate	3.26	3.09	2.81	3.22
Terms of trade	1.71	2.68	2.34	2.29
Imports	3.28	2.35	1.92	1.41
Auto-correlation				
Real exchange rate	0.81	0.71	0.76	0.82
GDP	0.87	0.71	0.72	0.81
Correlation with real exchange rate				
Nominal exchange rate	0.96	0.62	0.63	0.65
Terms of trade	0.35	0.54	0.33	-0.19
Cross-country consumption ratio	-0.45	1.00	1.00	1.00
Correlation with nominal exchange rate				
Import prices	0.45	0.58	0.53	0.45
CPI level	-0.17	0.15	0.15	0.19
Difference between cross-correlation of				
GDP and Consumption	0.22	-0.35	-0.26	-0.18
Correlation with GDP				
Net exports	-0.51	0.66	0.63	0.57

Table 3A. Exchange rates and prices in the theoretical economies, under alternative monetary policies[a]

Statistics	U.S. Data	*Economy with* : $\sigma = 2, \omega = 0.5$, low LCP Benchmark	k-percent rule	Inflation-targeting
Standard deviation (relative to GDP)				
Real exchange rate (CPI based)	3.04	4.12	4.00	3.72
Nominal exchange rate	3.26	5.17	4.51	3.72
Terms of trade	1.71	3.29	3.19	2.88
Imports	3.28	2.29	2.26	2.20
Auto-correlation				
Real exchange rate	0.81	0.79	0.74	0.71
GDP	0.87	0.74	0.77	0.74
Correlation with real exchange rate				
Nominal exchange rate	0.96	0.95	0.99	1.00
Terms of trade	0.35	0.39	0.44	0.46
Cross-country consumption ratio	-0.45	-0.77	-0.76	-0.76
Correlation with nominal exchange rate				
Import prices	0.45	0.88	0.88	0.86
CPI level	-0.17	0.40	0.48	-0.25
Difference between cross-correlation of				
GDP and consumption	0.22	0.40	0.41	0.40
Correlation with GDP				
Net exports	-0.51	-0.36	-0.35	-0.39

[a] See main text for a description of the different model economies.

Table 3B. Exchange rates and prices in the theoretical economies[a]

Statistics	U.S. Data	*Economy with :* $\sigma = 5, \omega = 1.5$, low *LCP* Benchmark	k-percent rule	Inflation targeting
Standard deviation (relative to GDP)				
Real exchange rate (CPI based)	3.04	3.53	3.54	3.66
Nominal exchange rate	3.26	2.81	1.80	3.66
Terms of trade	1.71	2.34	2.26	2.46
Imports	3.28	1.92	1.91	1.82
Auto-correlation				
Real exchange rate	0.81	0.76	0.76	0.72
GDP	0.87	0.72	0.73	0.66
Correlation with real exchange rate				
Nominal exchange rate	0.96	0.63	0.99	1.00
Terms of trade	0.35	0.33	0.29	-0.03
Cross-country consumption ratio	-0.45	1.00	1.00	1.00
Correlation with nominal exchange rate				
Import prices	0.45	0.53	0.58	0.71
CPI level	-0.17	0.15	-0.54	0.68
Difference between cross-correlation of				
GDP and Consumption	0.22	-0.26	-0.26	-0.20
Correlation with GDP				
Net exports	-0.51	0.63	0.63	0.60

Table 4A. Estimates of ERPT coefficients for Import Prices in artificial data[a]

	Economy with $\sigma = 2, \omega = 0.5$		
Specifications	Flexible prices	Sticky prices low LCP	Sticky prices high LCP
Structural			
Short run	0.93	0.27	0.04
Long run	0.93	0.93	0.93
Naïve: $\overline{P}_{\mathrm{F},t} = \alpha + \gamma E_t + \delta_2 \overline{P}_{\mathrm{F},t-1}$			
Short run	<0.01	<0.01	<0.01
Long run	1.59	1.46	1.11
PTM: $\overline{P}_{\mathrm{F},t} = \alpha + \gamma E_t + \beta \overline{P}^*_{\mathrm{F},t} + \delta_1 \overline{P}_{\mathrm{H},t} + \delta_2 \overline{P}_{\mathrm{F},t-1}$			
short run	0.92	0.50	0.20
Long run	0.93	0.94	0.96
ERPT (1): $\overline{P}_{\mathrm{F},t} = \alpha + \gamma E_t + \beta W^*_t + \delta_1 Y_t + \delta_2 \overline{P}_{\mathrm{F},t-1}$			
Short run	0.17	0.13	0.10
Long run	1.00	1.00	1.00
ERPT (2): $\overline{P}_{\mathrm{F},t} = \alpha + \gamma E_t + \beta W^*_t + \delta_1 \overline{P}_{\mathrm{H},t} + \delta_2 \overline{P}_{\mathrm{F},t-1}$			
Short run	0.39	0.27	0.17
Long run	0.88	0.90	0.92

[a] See main text for a description of the different model economies and the specification of the regression models.

Table 4B. Estimates of ERPT coefficients for Import Prices in artificial data[a]

	Economy with $\sigma = 5, \omega = 1.5$		
Specifications	Flexible prices	Sticky prices low LCP	Sticky prices high LCP
Structural			
Short run	0.93	0.27	0.04
Long run	0.93	0.93	0.93
Naïve: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \delta_2 \overline{P}_{\text{F},t-1}$			
Short run	<0.01	<0.01	<0.01
Long run	0.26	0.36	1.15
PTM: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^*_{\text{F},t} + \delta_1 \overline{P}_{\text{H},t} + \delta_2 \overline{P}_{\text{F},t-1}$			
Short run	0.92	0.60	0.24
Long run	0.93	0.88	0.74
ERPT (1): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta W^*_t + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$			
Short run	0.08	0.06	0.06
Long run	1.00	1.00	1.00
ERPT (2): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^*_{\text{F},t} + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$			
Short run	0.90	0.51	0.18
Long run	0.99	1.00	1.00

[a] See main text for a description of the different model economies and the specification of the regression models.

Table 5A. Estimates of ERPT coefficients for Import Prices in artificial data (Monetary shocks only)[a]

	Economy with $\sigma = 2, \omega = 0.5$	
Specifications	Sticky prices low LCP	Sticky prices high LCP
Structural		
Short run	0.27	0.04
Long run	0.93	0.93
Naïve: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	<0.01	<0.01
Long run	90.3	1407
PTM (1): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^{*}_{\text{F},t} + \delta_1 \overline{P}_{\text{H},t} + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	0.08	0.01
Long run	0.11	0.02
PTM (2): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^{*}_{\text{F},t} + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$	0.09	0.01
Short run	1.01	0.93
Long run		
ERPT: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta W^{*}_t + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	0.47	0.10
Long run	1.00	1.01

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[a] See main text for a description of the different model economies and the specification of the regression models.

Table 5B. Estimates of ERPT coefficients for Import Prices in artificial data (Monetary shocks only)[a]

	Economy with $\sigma = 5, \omega = 1.5$	
Specifications	Sticky prices low LCP	Sticky prices high LCP
Structural		
Short run	0.27	0.04
Long run	0.93	0.93
Naïve: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	<0.01	<0.01
Long run	97.7	93.2
PTM (1): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^{*}_{\text{F},t} + \delta_1 \overline{P}_{\text{H},t} + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	-0.11	0.02
Long run	-0.11	0.05
PTM (2): $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta \overline{P}^{*}_{\text{F},t} + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	0.14	0.02
Long run	1.01	1.08
ERPT: $\overline{P}_{\text{F},t} = \alpha + \gamma E_t + \beta W^{*}_t + \delta_1 Y_t + \delta_2 \overline{P}_{\text{F},t-1}$		
Short run	0.48	0.12
Long run	1.00	1.00

[a] See main text for a description of the different model economies and the specification of the regression models.