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

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Abstract

Why do prices respond only partially, if at all, to changes in the nominal exchange rate? This paper develops quantitative, dynamic, open-economy models which endogenously generates high exchange rate volatility, whereas a low degree of pass-through stems from both nominal rigidities (in the form of local currency pricing) and price discrimination. Because of the presence of distribution services, the elasticity of demand is market specific, which leads firms to price-discriminate across countries. Our model accounts for a variable degree of ERPT over different horizons: as a result of price discrimination, our model predicts exchange-rate pass-through coefficients that are different than one in the long run. In the short run, we find that a very small amount of nominal rigidities — consistent with the evidence in Bils and Klenow [2004] — lowers the elasticity of import prices at border and consumer level to 27% and 13%, respectively. Remarkably, exchange rate depreciation worsens the terms of trade – in accord to the evidence stressed by Obstfeld and Rogoff [2000]. The regression models commonly used in the empirical literature on pass-trough are likely to be plagued by measurement errors and omitted variable bias. We use our model as a lab to assess the performance of the empirical literature by running two typical regression models on the time series generated by our model. While the bias in the estimated coefficient tends to be alleviated by a high exchange rate volatility, it also depends on the covariance of the exchange rate with the determinants of import prices. Our results show that, in general, a high exchange rate volatility will not be sufficient to alleviate the bias — since volatility is endogenous. Nonetheless, we provide examples of relative good performance of regression models.

1 Introduction

Large swings in exchange rates, and their slow and incomplete pass-through into import prices and domestic inflation are defining features of the international economy. By way of example, between 2002 and 2004 the dollar depreciated 15% on a trade-weighted basis, both in real and in nominal terms, and 26% against the major currencies. Yet, over the same period, the import price of non-petroleum goods has risen only by 5%; core consumer prices rose by 4.7%.

An important issue in the open macro literature is how to reconcile high exchange rate volatility with the stability of prices in local currency. One view stresses the role of nominal rigidities: indeed, if import prices are sticky, large movements in nominal exchange rates will not fully pass through to prices. Recently, however, this view has been challenged on both empirical and theoretical grounds. A large body of both micro and macro literature has convincingly argued 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. Most crucially, recent studies have estimated general equilibrium models that attribute local currency price stability exclusively to nominal rigidities. These studies yields the unrealistic result that the degree of stickiness is way larger for the price of imports than for the price of domestically produced tradables — a result suggesting mis-specification (e.g. see Lubik and Schorfheide [2005]).

However, there is also another, arguably deeper, dimension to the problem. It is often claimed that, in response to fundamental shocks, a low pass-through raises the size of exchange-rate movements necessary to bring about the required adjustments in relative prices. More generally, a conjecture voiced in the open-economy literature is that exchange rate volatility is the counterpart of the degree of insularity of national economies. This argument raises the question as of which aspects of insularity (beyond local currency pricing) can magnify the exchange-rate response to fundamental shocks hitting the economy.

In this paper, we address these issues building upon the standard international business cycle framework with traded and non traded goods (e.g. Stockman and Tesar [1995]). Since we are interested in understanding the general equilibrium link between exchange rate volatility and stability of goods prices in domestic currency, we adopt two model specifications that can endogenously generate large swings of the exchange rate in response to real and monetary shocks. Namely, we reconsider the approach suggested by Backus, Kehoe, and Kydland [1995] (henceforth BKK) and the one pursued by Chari, Kehoe and McGrattan [2003], in an incomplete market framework with 'insularity' of national economies.

In one set of experiments — according to the BKK approach — the impact of productivity and monetary shocks on international prices is magnified by a relatively low price elasticity of imports, i.e., on the low end of the range of the parameters' values adopted by the literature. While BKK adopt a complete-market specification, we show that with incomplete markets relative price movements create strong wealth effects which magnify the risk implied by asymmetric shocks across countries (see Corsetti Dedola and Leduc [2004]). Thus, while generating volatility, a low elasticity of imports also induces a low negative correlation between the real exchange rate and relative consumption, in line with the data (see Backus-Smith [1993]). A problem with this approach — highlighted by BKK — is that the response of import quantities to shocks tends to fall with their price elasticity. In our framework, however, while import volatility is low relative to the data, it is not lower than comparable international SDGE models.[1]

In another set of experiments, we follow the approach by Chari, Kehoe and McGrattan [2003] (henceforth CKM), and exploit the positive and strict link between the ratio of marginal utilities of consumption and the real exchange rate that characterizes economies with complete markets. 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 the same mechanism works in a large class of models with incomplete markets. We show that the mechanism highlighted by CKM works quite well in our model with incomplete markets, even in the absence of nominal rigidities. As is well understood, one of the main issues raised by CKM is that models of exchange rate volatility relying on the above mechanism predict a strong correlation between relative consumption and the real exchange rate, a prediction at odds with the data. The 'Backus-Smith anomaly' will obviously affect our experiments adopting

[1] Moreover, in related work we make it clear that what matters for exchange rate volatility is the price elasticity in the short-run — conforming the available evidence about a slow response of international trade to shocks (see Corsetti Dedola and Leduc []).

the CKM mechanism.

In either cases, we model relatively 'insular' economies characterized by markets segmentation and deviations from the law of one price. Following Burstein et al. [2003] and Corsetti and Dedola [2005], market segmentation in the tradable sector of our economies is an implication of the presence of distribution sector intensive in local inputs. The advantages of this specification are as follows. First, due to distribution, large exchange-rate swings do not transpire 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. 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 is not attributed exclusively to price rigidities.

Our main results are as follows. First, in all our experiments, our economies generate highly volatile international prices and can account for persistent and highly correlated movements in real and nominal exchange rates. For a degree of price stickiness consistent with the evidence in Bils and Klenow [2004], the real exchange rate is positively correlated with the terms of trade and the price of imports, while it is only very weakly with the consumer price level. Not only these results conform the strong argument by Obstfeld and Rogoff [2000], that quantitative models should be consistent the above facts about the link between exchange rates and prices. What is remarkable is that, contrary to the assumption underlying the vast literature on the PPP puzzle emphasizing nominal shocks, international price volatility and persistence are generated by real shocks.

Second, we find that a reasonably small degree of price stickiness generates a very low degree of exchange rate pass-through in the short run. So while nominal rigidities play an important role in determining a low degree of exchange-rate pass-through into consumer and producer prices in the short run, the magnitude of nominal friction need not be very high, i.e. realistically smaller and more realistic than predicted by models that ignore distribution and price discrimination.

Third, 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 isolates nominal and real determinants of pass-through in the short and the long run. Consistent with the results from the empirical literature, pass-through is initially low and rises over time (without necessarily becoming complete in the long run). In a structural sense, assuming that prices are kept unchanged on average for 4.3 months (in line with the evidence in Bils and Klenow [2004]), the short-run pass-through coefficient in our model is as low as 0.27. This coefficient falls to 0.04 when our measure of price stickiness is set equal to 3 quarters. Because of distribution, the exchange-rate pass-though 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. The importance of these results cannot be overstated: in our model a small amount of nominal rigidities generates realistically low structural pass-through coefficients, while still predicting that a depreciation worsens the terms of trade consistent with Obstfeld and Rogoff [2000]. Moreover, consistent with the evidence in Giovannini [1988], Marston [1990], and Campa and Goldberg [2002], imperfect exchange-rate pass-through lasts longer than the period in which prices are sticky. In the long run, the exchange rate pass-through coefficient on import prices is lower than one, corresponding to markup adjustments by firms that price-discriminate across national borders. This feature cannot be captured by models of incomplete pass-through relying exclusively on nominal rigidities as the determinant of deviations from the law of one price.

While our theoretical framework conforms the available empirical evidence in many dimensions, there is a potentially important contribution that our theoretical inquiry can provide to the empirical literature. As is well known, data availability constrains the specification of regression models, which are typically plagued by measurement errors and omitted variable bias. However, the implications of these deficiencies for the performance of regression models depend on the underlying economic structure generating incomplete pass-through and exchange rate movements. The importance of this issue should be appreciated by taking into account that estimates of pass-through are core inputs in the inflation projections that are used in monetary policy decision making.

In general, the estimation bias in pass-through regressions is a function of (a) the volatility of the exchange rate (negative) and (b) the covariance between the exchange rate and the determinants of import prices. We specify two regression models typically adopted in the literature

— that we dub Pricing to Market (PTM) and Exchange Rate Pass-through (ERPT) — and we run them on time series simulated using our model. Both regression specifications (PTM and ERPT) rely on proxies of the true marginal costs and ignore distribution costs — Goldberg and Verboven [2001] provide evidence that the latter are an important determinant of local currency price stability. Since our quantitative model generates endogenously high volatility of exchange rates, in some cases these regressions perform reasonably well. Yet, our results also show that, in general, a high volatility of the exchange rate is not sufficient to alleviate the bias, due to the endogeneity of the exchange rate.

In this respect, we emphasize that real exchange rate volatility is endogenous in our model specifications. Analyses attributing exchange rate volatility to exogenous noise would simply downplay the importance of regression bias. Conversely, we explore theoretical channels through which exchange rates, marginal costs and revenues may respond to the same set of shocks — and provide a quantitative assessment of them.

We conclude our introduction by reiterating that understanding the relative importance of different factors causing low pass-through and local currency price stability 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 would correspond to optimal pricing strategies by firms. In the presence of nominal rigidities, instead, they would correspond to suboptimal fluctuations of firms' profits. Hence, nominal exchange rates may not play the stabilizing role attributed to them by the received wisdom, either as a substitute for relative price adjustment in the presence of nominal rigidities, or as automatic mechanisms of risk insurance when markets are incomplete.

The paper is structured as follows. Section 2 will describe the model and the calibration will be discussed in Section 3. We discuss the predictions of our model regarding the degree of exchange-rate pass-through in Section 4. We discuss empirical models of pass-through. The last section concludes.

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.[2] They buy tradable goods and distribute them to consumers using nontraded goods as the only input in production.

In our baseline model, prices and wages will be assumed to be perfectly flexible. In alternative specifications, we will introduce nominal price and wage rigidities, by assuming that workers and firms face a quadratic cost of adjusting the nominal wage and the goods' prices, respectively.[3] 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]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.

[3]Christiano, Eichenbaum and Evans [2003] and Smets and Wouters [2001] are recent structural models providing evidence that wage stickiness is an important determinant of macroeconomic fluctuations.

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:

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

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.[4] We assume that households are monopolistically competitive and supply a differentiated labor service to firms.

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

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

[4] 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 [2001]).

2.1.2 Budget constraints and asset markets

Home and Foreign agents hold an international bond, B_{H}, which pays in units of Home currency and is zero in net supply. Only domestic residents hold the Home currency,M_t. Households derive income from working, W_tL_t, from renting capital to firms, R_tK_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 $t-1$. They pay non-distortionary (lump-sum) net taxes T, denominated in Home currency and a cost when nominal wages are changed. Households use their disposable income to consume and invest. The individual flow budget constraint for the representative agent j in the Home country is therefore:[5]

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

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 Beetsma [2005], and that the capital stock, K, can be freely reallocated between the traded (K_{H}) and nontraded (K_{N}) sectors:

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

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:

[5] $B_{\mathrm{H},t}$ denotes the Home agent's bonds accumulated during period $t-1$ and carried over into period t.

$$K_{t+1} = I_t + (1-\delta)K_t + \frac{b}{2}\left(\frac{I_t}{K_t} - \delta\right)^2, \tag{5}$$

where b is an adjustment cost parameter, as in Chari, Kehoe and Mc Grattan [2002].

The household's problem then consists of maximizing lifetime utility, defined by (1), subject to the constraints (4) and (5).

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:

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

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 Erceg and Levin [1995] and Burstein, Neves and Rebelo [2001], we thus assume that bringing one unit of traded goods to consumers requires η units of a basket of differentiated nontraded goods

$$\eta = \left[\int_0^1 \eta(n)^{\frac{\theta_{\mathrm{N}}-1}{\theta_{\mathrm{N}}}} dn\right]^{\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}}-1}}. \tag{6}$$

We note here that the Dixit-Stiglitz index above also applies 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]

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

$$\begin{aligned} \pi_t(h) &= \overline{p_t}(h) D_t(h) - W_t L_t(h) - R_t K_t(h) \\ \pi_t(n) &= p_t(n) D_t(n) - W_t L_t(n) - R_t K_t(n) \end{aligned}$$

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

$$D(n) + \eta(n) = [p_t(n)]^{-\theta_{\mathrm{N}}} P_{\mathrm{N},t}^{\theta_{\mathrm{N}}} \left[D_{\mathrm{N},t} + \eta \left(\int_0^1 D_t(h) dh + \int_0^1 D_t(f) df \right) \right], \tag{7}$$

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:

$$\begin{aligned} p_t(n) &= P_{\mathrm{N},t} = \frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}} - 1} MC_{\mathrm{N},t} \\ &= P_{\mathrm{N},t} = \frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}} - 1} \frac{W_t^{\zeta} R_t^{1-\zeta}}{Z_{\mathrm{N},t}} \end{aligned} \tag{8}$$

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

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

[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 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.

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

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

Making use of (8), the optimal wholesale prices for the consumption good $\bar{p}(h)$ and $\bar{p}^*(h)$ are:

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

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

where $\mathcal{E}_t$ is the nominal exchange rate, expressed in units of home currency units. Unlike the case of nontraded goods (8), 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. Let $mk_{\mathrm{H},t}$ and $mk_{\mathrm{H}^*,t}$ denote the state contingent component of markups:

$$mk_{\mathrm{H},t} = 1 + \frac{\eta}{\theta_{\mathrm{H}}}\frac{\theta_{\mathrm{N}}}{\theta_{\mathrm{N}} - 1}\frac{Z_{\mathrm{H},t}}{Z_{\mathrm{N},t}}\frac{W_t^{\zeta}R_t^{1-\zeta}}{W_t^{\xi}R_t^{1-\xi}}, \tag{14}$$

$$mk_{\mathrm{H}^*,t} = 1 + \frac{\eta}{\theta_{\mathrm{H}}^*}\frac{\theta_{\mathrm{N}}^*}{\theta_{\mathrm{N}}^* - 1}\frac{Z_{\mathrm{H},t}}{Z_{\mathrm{N},t}^*}\frac{\mathcal{E}_t W_t^{*\zeta}R_t^{*1-\zeta}}{W_t^{\xi}R_t^{1-\xi}}. \tag{15}$$

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:

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

and

$$AC^{p}_{t}(n) = \frac{\kappa^{p}_{\mathrm{N}}}{2}\left(\frac{p_t(n)}{p_{t-1}(n)} - \pi\right)^2 D_{\mathrm{N},t}.$$

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 $AC^{p}_{\mathrm{H},t}(h)$ and $AC^{p*}_{\mathrm{H},t}(h)$ are denominated in units of domestic traded goods.

2.2.1 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 Chari, Kehoe and McGrattan [2002]. Throughout the exercise, we will carry out 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 $\mathbf{u} \equiv (u, u^*)$ 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., Backus, Kehoe and Kydland [1994] — 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. Clearly, setting a positive correlation of shocks across countries would be useful towards the goal of replicating the pattern of international comovements. We may expect

[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.

that, as a consequence of our choice, our model may have a hard time along this dimension. 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. As argued by Backus, Kehoe and Kydland [1995], this 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 systematic policy follows a Taylor-type rule that sets the short-term nominal interest rate as a function of the output gap and expected inflation:

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

We parameterize the policy rule using the estimates in Lubik and Schorfheide [2004]: $\rho = 0.84$, $\chi = 2.19$, $\gamma = 0.3$. We assume that potential output, y_t^*, is given by the level of output in steady state. In the current version, to emphasize that our results do no depend on monetary shocks, we assume that there is no stochastic component to monetary policy, although when we add plausible monetary shocks our results are unchanged. Likewise, we obtained similar results assuming that monetary policy followed an exogenous money growth rule.

Preferences and production Consider first the preference parameters. Assuming a utility function of the 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 [2001], 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:

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

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 is selected based on the available estimates for the elasticity of substitution between traded and nontraded goods. 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 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 ($C_{\rm T}$), $a_{\rm H}$ and $a_{\rm F}$ (normalized $a_{\rm H} + a_{\rm F} = 1$) are chosen such that imports 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, $a_{\rm T}$ and $a_{\rm N}$, 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 Betsma [2005].

Due to lack of better evidence, 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 $\theta_{\rm H}$ and $\theta_{\rm N}$. In the nontraded-goods sector, the markup is the standard $\frac{\theta_{\rm N}}{\theta_{\rm N}-1}$. In the traded-good sector, the markup is:

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

where $MC_{\rm N}$ and $MC_{\rm H}$ 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 $\theta_{\rm N}$ (and $\theta^*_{\rm N}$) is equal to 7.7. We then parametrize the elasticity of substitution of traded goods varieties, $\theta_{\rm H}$ and $\theta_{\rm F}$, 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, $\phi_{\rm H}$ and $\phi_{\rm N}$, 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 discount factor (see Galí and Gertler [1999]). The quadratic adjustment-cost model gives a similar (log-linearized) difference equation for inflation, but with $\widetilde{\lambda} = \frac{\theta_{\rm J}-1}{\kappa_{\rm J}^p \pi^2}$, 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 $\kappa_{\rm H}^p$, $\kappa_{\rm H}^{*p}$, and $\kappa_{\rm N}^p$ 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 These parameters play a crucial role characterizing the two approaches to modeling real exchange rate volatility suggested by the SDGE literature. The first approach has been discussed early on by Backus, Kehoe, and Kydland [1995] 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]).[8] 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 σ is set equal to 2 and $\omega = 0.5$.[9] In ongoing work, we have found that introducing preferences and

[8] In this paper, we showed that the volatility of international prices is hump-shaped in ω, and thoroughly discussed the mechanism underlying this pattern.

[9] 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

technology in which the short run and long run elasticity of substitution across tradables is different, with the former lower than the latter, as in Cooley and Quadrini [2003], may allow us to obtain very similar results to those reported thereafter, while keeping the long run elasticity equal to the traditional value of 1.5.

The focus of the second approach, pursued by Chari, Kehoe and McGrattan [2003], 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 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 markets segmentation and deviation from the law of one price, even in the absence of nominal rigidities. Following CKM, we will study one economy in which $\sigma = 5$ and the elasticity of substitution between imported and domestic tradables in both consumption and the intermediate input to investment, ω, is set to 1.5.

4 Business cycle properties of exchange rates and prices

We report on the H-P–filtered statistics for the data, and for the two benchmark economies with different degrees of nominal rigidities, in Tables 2A-2B. The first table is referred to the specification with a relatively low elasticity, the second to the CKM parametrization. The statistics for the data are all computed with the United States as the home country and the rest of the world as the foreign country. Thus, all the numbers that refer to import and export prices, the CPI and so on are from U.S. data, while the nominal (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. 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 algorithm. 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. Each

value below 1. For instance, Anderton et al. (2004) report values between 0.5 and 0.81 for the Euro area.

panel of Table 2 reports the results from several versions of the model: a flexible-price economy, and two economies with low and high degree of local currency price stickiness (LCP), equal to 1.43 and 3 quarters, respectively.

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 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. The two economies in Table 2A and 2B, however, differ in one important respect, i.e. 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 Backus-Smith correlation between relative consumption and the real exchange rate (Table 2A).[10] Conversely, as is well understood, 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. Nonetheless, we stress our result that the mechanism proposed by CKM to generate volatility works quite well in our model with incomplete markets, independently of nominal rigidities.

The following results emerge. 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 in Table 2A the addition of price stickiness generates exchange rates and terms of trade that are too volatile, whereas in Table 2B a higher degree of LCP lowers the volatility of the nominal exchange rate and the terms of trade, bringing it more in line with the data .

Second, the real exchange rate tends to be 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 do not react to exchange rates because of nominal rigidities. In light of the debate following Obstfeld and Rogoff [2000], we obtain an important qualification of their point. In a

[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.

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 the above 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, in both Table 2A and 2B the correlation between these two variables switches from positive to negative for the higher degree of nominal rigidities.

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. By the same token, standard models with nominal rigidities and complete pass-through predict that the correlation between the exchange rate and the export price index in the domestic currency is zero, since export prices are predetermined in the short run. Because of LCP and price discrimination, our models generate a correlation that is between 0.4 and 0.8, higher than in the U.S. data (0.16) — pointing to a potentially intriguing asymmetry between U.S. import and export prices.

Fourth, a low (endogenous) import price elasticity and distributive trade imply that both consumer prices and inflation 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 level across all specifications with nominal rigidities is low but generally positive, against -0.17 in the data (excluding energy); the correlation with inflation is around 0.2 in the theoretical economies, only slightly lower than the actual value of 0.34.

Finally, while in both panels of Table 2 the relative volatility of imports is quite high (a result especially remarkable for the parameterization with a low ω) , it falls short of that in the data for all specifications. Moreover, only the economies in Table 2A are consistent with countercyclical net exports (a featured of the data emphasized in the international business cycle literature) and the fact that the cross-country correlation of output is larger than that of consumption (the so-called 'quantity puzzle').

5 Structural and empirical pass-through equations

The textbook definition of exchange pass-through (henceforth, ERPT) is 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. Textbook models of the balance of payments, as well as a host of papers in the New open-economy macroeconomics literature, assume a one-for-one response of import prices to exchange rates, namely full or complete ERPT. Notably, complete ERPT obtains if (i) markups over costs are constant, and (ii) marginal costs are also constant.[11]

Under these two conditions, the elasticity of demand for imports is a crucial determinant of the response of the trade balance to movements in the exchange rate. A classical question is whether depreciation of a nation's currency improve its trade balance — a question that is of particular interest in a world with incomplete financial markets and lies at the core of the external adjustment and the cross-border transmission of inflation.

In this section, we derive structural expressions for pass-through coefficients in the short- and the long-run. These expressions can be used in specifying empirical regression models which are consistent with alternative theoretical views of pass-through. Moreover, based on these expressions, we will be able to study the performance of empirical regression models which, because of data availability, do not exactly conform with the structural equations. We will also provide a quantitative assessment of the resulting bias.

[11] A third possibility is that changes in markups just offset changes in costs in a systematic way, leaving export prices in the exporter's currency constant.

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:

$$\widehat{\overline{P}}_{\mathrm{F},t} = \frac{1}{1+\mu\left(mk_{\mathrm{F}}-1\right)}\left(\widehat{\mathcal{E}}_t + \widehat{MC^*}_{\mathrm{F},t}\right) + \frac{\mu\left(mk_{\mathrm{F}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)}\widehat{MC}_{\mathrm{N},t} \tag{20}$$

where mk_{F} is the total markup (including both distribution and standard markup) in the home import sector and μ is the distribution margin. 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 EPRT 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:

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

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

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

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

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 monopolisitic distortions, in our model the long-run EPRT is 93 percent. Recall that 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, namely:

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

Observe that the log linear equation for the domestic prices abroad is:

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

Combining equations (assuming symmetry) we obtain a structural equation of the determinant of deviations from the law of one price at wholesale (border) level:

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

As pointed out by Corsetti and Dedola [2005], these deviations are a function of the degree of monopolistic distortions (markup), as well as the price of nontraded goods and services employed in distribution (for $\mu > 0$). Our dynamic analysis also point out a role for inflation and price adjustment costs.

5.1.3 Regression bias and endogenous exchange rate volatility

When bringing the model to the data, our analysis makes it clear that an empirically consistent specification of the regression model would call for the inclusion not only of marginal costs in the tradable sector, but also of marginal costs (or prices) in the nontradable sector to account for the effect of distribution on the price elasticity and markup, as well as for 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. We should stress here that the omission of the latter variable is bound to result into omitted-variable bias.

The log-linearized expressions derived above is already useful to shed some light into the consequences of using incomplete data set, or variables measured with large error. For simplicity, assume that the model without nominal rigidities is correct and consider a regression model in the form

$$\overline{P}_{\mathrm{F},t} = \beta_1 \mathcal{E}_t + \beta_2 X_t + \upsilon_t$$

where for notational convenience we ignore the fact that all variables should be measured in logs. Here X_t refers to a set of control variables (e.g. domestic GDP) which are imperfect proxies of the relevant variables listed above. Clearly, using our expressions, we can write the error as:

$$\upsilon_t = \frac{1}{1+\mu\left(mk_{\mathrm{F}}-1\right)} MC^*_{\mathrm{F},t} + \frac{\mu\left(mk_{\mathrm{F}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)} MC_{\mathrm{N},t} - \beta_2 X_t + \xi_t$$

whereas ξ is any uncorrelated random component (e.g., measurement error). We would get the following asymptotic estimate of β_1:

$$
\begin{aligned}
\widehat{\beta_1} &= \frac{1}{1+\mu\left(mk_{\mathrm{F}}-1\right)}+bias, \\
bias &= \left\{\frac{1}{Var\left(\mathcal{E}_t\right)-\dfrac{Cov\left(\mathcal{E}_t, X_t\right)}{Var\left(X_t\right)}}\right\}\cdot \\
&\left\{Cov\left(\mathcal{E}_t, \frac{1}{1+\mu\left(mk_{\mathrm{F}}-1\right)} MC_{\mathrm{F},t}^{*}+\frac{\mu\left(mk_{\mathrm{F}}-1\right)}{1+\mu\left(mk_{\mathrm{F}}-1\right)} MC_{\mathrm{N},t}\right)\right. \\
&\left.-Cov\left(\mathcal{E}_t, X_t\right) \frac{Cov\left(X_t, \frac{1}{1+\mu(mk_{\mathrm{F}}-1)} MC_{\mathrm{F},t}^{*}+\frac{\mu(mk_{\mathrm{F}}-1)}{1+\mu(mk_{\mathrm{F}}-1)} MC_{\mathrm{N},t}\right)}{Var\left(X_t\right)}\right\}
\end{aligned}
$$

The bias can have either sign. To see this most clearly, focus on the plausible case in which the control X_t is a very poor instrument for the omitted variable $MC_{\mathrm{N},t}$ — or, worse, X_t is missing from the regression model. Omitting X_t the bias simplifies to:

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

According to our model, this bias clearly 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. If marginal costs are basically uncorrelated across border (the case of country-idiosyncratic shocks), the sign of the bias will depend on the 'international transmission' of productivity shocks. If a positive Home shock appreciates the Home nominal exchange rate, the regression bias will be *positive*: pass-through estimates will be *higher* than the true coefficient $\frac{1}{1+\mu(mk_{\mathrm{F}}-1)}$; if a positive Home productivity shock brings about a nominal depreciation, the opposite will occur. In theory, both effects can occur.

But while the sign of the bias clearly depends on the pattern of covariances, the size of the bias will be crucially affected by the volatility of the exchange rate (relative to the covariance of the exchange rate with the control). This suggests that, *ceteris paribus*, an economy with a highly volatile exchange rate would provide a relatively better environment for empirical analysis.

5.2 Empirical models of ERPT: an assessment using simulated time series

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

$$P_t = \alpha + \gamma \mathcal{E}_t + \beta \mathcal{C}_t + \delta X_t + u_t, \tag{21}$$

where all variables are in logs: P_t is the import price denominated in local currency, $\mathcal{C}_t$ is a measure of exporter's marginal costs, X_t may include controls for shifts in import demand (like competing prices 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 X_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 only 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 (21), P_t is the export price, $\mathcal{C}_t$ is the domestic price of the same good, while X_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]).[12]

To shed light on the quantitative importance of different potential sources of biases in the empirical studies of pass-through, we run two types of regressions on the artificial data simulated

[12] 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.

using our theoretical economies. We dub the first one 'ERPT regression':

$$\overline{P}_{\mathrm{F},t} = \alpha + \gamma \mathcal{E}_t + \beta W_t^* + \delta_1 Y_t + \delta_2 \overline{P}_{\mathrm{F},t-1}, \tag{22}$$

In terms of (21), 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 second regression, which we dub the 'PTM regression', has the following specification:

$$\overline{P}_{\mathrm{F},t} = \alpha + \gamma \mathcal{E}_t + \beta \overline{P}^*_{\mathrm{F},t} + \delta_1 \overline{P}_{\mathrm{H},t} + \delta_2 \overline{P}_{\mathrm{F},t-1}, \tag{23}$$

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 constraints: $\beta = \gamma$ (e.g., see Anderton [2003]).

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, (22) 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 (23) is a potential source of bias, as this price includes a Foreign market time-varying markup.[13]

But how far are these regression models from the true values of the structural coefficients? This issue is crucial for the empirical literature, given that the problems discussed above are likely to plague virtually all applied papers trying to estimate structural ERPT empirically.

[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 X_t and Z_t in the regression, that is, the Foreign marginal cost in the tradable sector and the price of distribution in the Home country.

Moreover, it is worth keeping in mind that the accuracy of ERPT estimates has an important policy dimension: these estimates are an important input into projections of exchange rate changes onto prices and output which underlie monetary policy decision making.

Tables 3A and 3B present the results of the PTM and ERPT regressions run on our simulated time series. The estimated coefficients in the table are averages over 100 simulations of 88 quarters (a typical sample size). 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, in the benchmark model with flexible prices the short run and long run coefficients coincide, 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, in the sticky price model short run and long run coefficients differ. 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).

The tables also report a control regression in which the import price is regressed only on the exchange rate and its lag — we dub this specification "naive". This specification clearly shows that the problem of omitted variables can potentially be very serious in our setup with an endogenously volatile exchange rate. Indeed, the estimated short run ERPT is always less than 1 percent across all specifications, even with flexible prices, while the long run estimates are reasonably close to the structural coefficient only in the case of high price stickiness. This result confirms that these economies can be thought of as an interesting "worst case" scenario for assessing the performance of some popular regression models in the empirical literature on pass-through.

In light of the above results, does the inclusion of controls, albeit imperfect, improve the performance of the regression models? Interestingly, we find that in general it does so. From the tables it emerges a notable difference across the two specifications (PTM and ERPT (1)) only in the case of flexible prices. 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 (in the case of the economy with flexible prices). In contrast, the ERPT specification incorrectly estimates a different value of the short- and long-run coefficients when prices are flexible. However, both specifications perform satisfactorily with sticky prices. The PTM regression 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 very closer to the structural one than in the case of the PTM regression.

What can account for the differential performance of the two regressions? In order to answer this question we report also results for an hybrid specification (ERPT (2)), equal to the ERPT one but in which we replaced the domestic GDP with $\overline{P}_{\mathrm{H},t}$ in Table 3A and wages with $\overline{P}^{*}_{\mathrm{F},t}$ in Table 3B. This experiment shows that the overall superior performance of the PTM regression can be traced to the use of better proxies for marginal costs and demand conditions. Interestingly, these proxies also enjoy a better theoretical foundation given the general environment characterized by price discrimination, and it is thus somehow reassuring that their use leads to a better performance of the regressions.

5.2.1 ERPT coefficient and pass-through

What conclusions can be drawn from estimating ERPT coefficients? We close our analysis with an important caveat. Even if econometricians were able to recover precise estimates of structural pass-through coefficients, there will still be a question about their use in policy-oriented exercises addressing the impact of specific shocks on import prices or, more in general, on the CPI.

The main issue is that, in general, structural pass-through coefficients are not a complete description of the actual properties of the model as regards the link between import prices and exchange rates. In each particular period, this link will be determined conditional on the specific shocks causing exchange rate fluctuations. To clarify this point: in all our specifications import prices responds one-to-one to monetary shocks in the long run — and also in the short run in the benchmark economy where prices are flexible. Hence, conditional on monetary disturbances, long-run ERPT is perfect.

Even if the exchange rate coefficient in the pass-through equation is lower than one, perfect pass-through from monetary shocks will eventually results because such disturbances will bring about related movements in the other endogenous variables entering the structural equation that determines the price of imports — hence running against the 'ceteris paribus' assumption implicit in interpreting the ERPT coefficient in the structural regressions. Specifically, a monetary easing in the Home country that depreciates the Home currency will eventually cause a proportional increase in the nominal price of distribution services. Putting all elements together, it is easy to verify that import prices will eventually rise one-to-one with the exchange rate. The lesson is that using structural equations to forecast the impact of a nominal shock, but failing to control for the general equilibrium effects of such shocks, would produce an underestimation of the response of import prices to fundamental changes in exchange rates.

6 Concluding remarks

Why do prices respond only partially, if at all, to changes in the nominal exchange rate? This paper develops quantitative, dynamic, open-economy models which generates high exchange rate volatility, to analyze 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, the elasticity of demand is market specific, which leads firms to price-discriminate across countries. In our model, the combination of price discrimination and local currency pricing with nominal rigidity can account for the variable degree of ERPT over different horizons. As a result of price discrimination, our model predicts exchange-rate pass-through coefficients that are different than one in the long run. In the short run, we find that a very small amount of nominal rigidities can lower the elasticity of import prices at border and consumer level to 27% and 13%, respectively.

We stress that in our benchmark economy a limited degree of LCP makes the short-run exchange rate pass-through coefficients quite close to those found in the empirical literature; for instance Campa and Goldberg [2002] find that on average across OECD countries, exchange rate pass-through into import prices is 46% in the short run and 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]) will be enough to make our theoretical economies consistent with this dimension of the data.

Remarkably, in our model, despite the low level of pass-through, exchange rate depreciation still worsens the terms of trade – in accord to the evidence. Moreover, a high degrees of nominal rigidities are not necessary to generate volatile exchange rates.

Regression models commonly used in the empirical literature are likely to be plagued by measurement errors and omitted variable bias. We run two typical regression models on the time series generated by our model, and compare their performance with the structural features of the model. While a high volatility of exchange rates tend to alleviate the bias in the estimated coefficients, such bias also depends on the covariance of the exchange rate with the determinants of import prices. Our results show that, in general, a high exchange rate volatility will not be sufficient to alleviate the bias — due to endogeneity of such volatility. Nonetheless, we provide examples of relative good performance of regression models.

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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	$\delta = 0.025$
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	
Autocorrelation matrix	$\lambda = \begin{bmatrix} 0.95 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.95 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.95 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.95 \end{bmatrix}$
Variance-covariance matrix (in percent)	$\Omega = \begin{bmatrix} 0.7 & 0.00123 & 0.0 & 0.0 \\ 0.00123 & 0.7 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.7 & 0.00123 \\ 0.0 & 0.0 & 0.00123 & 0.7 \end{bmatrix}$

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
Export prices	0.16	0.51	0.66	0.84
CPI level	-0.17	0.42	0.40	0.30
CPI inflation	0.34	0.26	0.29	0.36
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
Export prices	0.16	0.41	0.59	0.80
CPI level	-0.17	0.15	0.15	0.19
CPI inflation	0.34	-0.33	-0.38	-0.45
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. Estimates of ERPT coefficients for Import Prices in artificial data[a]

	Economy with $\sigma = 2, \omega = 0.5$		
Specification	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
Naive Specification			
Short run	<0.01	<0.01	<0.01
Long run	1.59	1.46	1.11
PTM specification			
Short run	0.92	0.50	0.20
Long run	0.93	0.94	0.96
ERPT specification (1)			
Short run	0.17	0.13	0.10
Long run	1.00	1.00	1.00
ERPT specification (2)			
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 3B. Estimates of ERPT coefficients for Import Prices in artificial data[a]

Specification	Flexible prices	Sticky prices low LCP	Sticky prices high LCP
	Economy with $\sigma = 5, \omega = 1.5$		
Structural			
Short run	0.93	0.27	0.04
Long run	0.93	0.93	0.93
Naive Specification			
Short run	<0.01	<0.01	<0.01
Long run	0.26	0.36	1.15
PTM specification			
Short run	0.92	0.60	0.24
Long run	0.93	0.88	0.74
ERPT specification (1)			
Short run	0.08	0.06	0.06
Long run	1.00	1.00	1.00
ERPT specification (2)			
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.