Will that be Cash or Credit?
How Monetary Settlement Affects International Prices

Todd D. Mattina*

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Abstract
This paper introduces a mechanism for monetary settlement in a real exchange-rate model that distinguishes between cash and credit for domestic and international transactions. This feature of the model increases the predicted volatility of the real exchange rate, while remaining consistent with actual invoicing practices in international trade. In addition, including both monetary and productivity shocks in the model resolves the counterfactual negative correlation between the nominal exchange rate and the terms of trade implied by the pricing to market and local currency pricing models of the real exchange rate. Finally, incorporating productivity shocks in the model fosters more persistent and realistic responses in international prices.

Keywords: real exchange rate, pricing to market, international prices.

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*Department of Economics, Queen's University,Kingston Ontario Canada K7L 3N6; mattinat@qed.econ.queensu.ca. I thank Beverly Lapham, Allen C. Head, Gregor W. Smith and participants at the Queen's University macro workshop for helpful comments and suggestions. All remaining errors and omissions are my own responsibility.

1. Introduction

Explaining the behavior of the real exchange rate and international relative prices has represented an enduring challenge for open-economy macroeconomics. The pricing to market (PTM) and local currency pricing (LCP) models are the leading approaches for reconciling theoretical predictions with the empirical moments. The objective of this paper is to posit a model addressing two general criticisms of the PTM-LCP approach. First, Chari, Kehoe and McGratten (1997, 1998, 2000) demonstrated that the PTM-LCP model requires an implausible duration of price rigidity, or strong relative risk aversion, to replicate the persistence observed in the real exchange rate. However, Obstfeld and Rogoff (2000) argued that prolonged price stickiness in the local currency of buyers is incongruent with actual billing practices in trade. Furthermore, Obstfeld and Rogoff (2000) argued that the PTM-LCP approach implies an unconditional correlation between the nominal exchange rate and the terms of trade that is opposite in sign to observed values. This paper introduces a mechanism for monetary settlement that distinguishes between cash and credit for domestic and international transactions. This feature of the model increases the predicted volatility of the real exchange rate, while remaining consistent with actual invoicing practices. In addition, including both monetary and productivity shocks in the model resolves the counterfactual negative correlation between the nominal exchange rate and the terms of trade implied by PTM-LCP models. Finally, productivity shocks foster more persistent and realistic responses in international prices.

There is considerable empirical evidence documenting the strong persistence and volatility of international relative prices and exchange rates. In particular, evidence presented by Engel (1993, 1999), Engel and Rogers (1996), Parsley and Wei (1996) and others suggests that deviations of relative traded-goods prices from the law of one price account for a substantial proportion of the movements in the real exchange rate. A leading model for explaining deviations in the law of one price is the "pricing-to-market" (PTM) approach, as first advanced by Krugman (1987) and Dornbusch (1987). In these models, firms maximize profits by actively price discriminating across segmented national goods markets. Volatile fluctuations in the nominal exchange rate are absorbed in the mark-up of price over marginal cost, and exchange-rate movements are only partially passed through into goods prices. Recent dynamic general equilibrium models adopt a passive form of international price discrimination with the "local currency pricing" approach. In this model, firms establish prices in advance of monetary shocks so that the law of one price holds in expectation. As a result, subsequent movements in the nominal exchange rate lead to deviations from the law of one price.

This paper examines a dynamic general equilibrium model with PTM-LCP behavior, and a monetary technology based on the Lucas and Stokey (1987) model of cash and credit. This feature of the model is designed to address the variability of real exchange-rate movements without relying on prolonged price stickiness. In particular, the model incorporates a distinct mode of settlement for international and financial transactions. Foreign goods and state-contingent bonds require cash settlement in the model, whereas locally produced consumption and investment goods are credit items. Credit goods are defined as commodities that are available without requiring cash in advance. This dichotomy in the settlement system reflects empirical evidence from the ECU Institute (1995) indicating that most trade invoices are settled within a quarter. As a result, long periods of nominal rigidity are not highly plausible. In particular, institutional features of trade settlement often require importers to post cash balances, or the equivalent collateral, with their commercial bank. The importer's bank issues an Irrevocable Letter of Credit (ILC) to the exporting firm to insure the proper settlement of the transaction. This characteristic of the trade settlement system is captured in the model by assuming that cash is required to purchase imported goods.

As a result of introducing this monetary technology, households face an intertemporal tradeoff when selecting their cash balances. At the beginning of each period, households allocate their stock of nominal wealth between cash, which is used to acquire imported goods, and bonds that earn a state-contingent return. As Cooley and Hansen (1989, 1995) discussed, an anticipated inflation arising from a persistent monetary shock acts like a tax on nominal wealth as inflation erodes its purchasing power. However, the introduction of nominal rigidities to the environment imposes additional complexity to the household problem. Given one-period price stickiness, cash goods are temporarily inexpensive following a monetary shock. This results in a substitution into cash-acquired imported goods. Following a period of nominal adjustment, households re-optimize by substituting into domestically produced credit goods. This characteristic of the model introduces a new dynamic relationship between the real exchange rate, international consumption patterns, and monetary shocks.

Further, the benchmark model incorporates both monetary and productivity shocks. Firms observe the current productivity shock, but post prices before the realization of monetary shocks. In this manner, the firm's information set remains consistent with the local-currency pricing assumption. This modification resolves the negative unconditional correlation between the nominal exchange rate and the terms of trade implied by many PTM-LCP models. Moreover, the inclusion of productivity shocks increases the simulated autocorrelaton of the real exchange rate and other international relative prices. Finally, both productivity and monetary shocks are required in the model to generate unconditional moments for international prices that approach their empirical counterparts.

In addition to the specific puzzles discussed above, we are also interested in explaining a broad set of open-economy empirical regularities. As Rogoff (1996) summarized in his survey of the literature, the real exchange rate is both variable and persistent. For instance, researchers such as Lothian and Taylor (1996) have found that the real exchange rate is more persistent than the typical business cycle. Further, as Mussa (1986) documented, the nominal and real exchange rates are highly correlated during periods of floating exchange rates. Finally, Backus, Kehoe and Kydland (1993) found that standard models cannot readily generate sufficient volatility in the terms of trade.

The remainder of this paper is organized as follows. Section 2 provides background into recent macroeconomic research focusing on international prices. Section 3 presents a vector autoregression (VAR) analysis that establishes an empirical benchmark for the unconditional and conditional moments of international prices and exchange rates. Section 4 characterizes the model. Section 5 discusses model calibration, and presents the results of numerical simulations. Finally, concluding remarks are given in Section 6.

2. Background and Motivation

This section begins with a review of price studies identifying the prevalence of deviations from the law of one price. Dynamic general equilibrium models that study this issue are then discussed. Finally, a brief summary is presented of the literature incorporating frictions in the mode of monetary settlement.

There is considerable empirical evidence documenting both the phenomenon of pricing to market, and deviations from the law of one price. There are two categories of empirical evidence. The first class of studies involve disaggregated price index data for narrowly defined industries across countries. The second category of evidence examines the raw price data at the firm or consumer level.

First, consider the evidence based on disaggregated price index data. In an influential paper, Engel (1993) decomposed the real exchange rate into two components: the law of one price for relative traded-goods prices, and the relative price of non-traded to traded goods. Engel (1993) found that in excess of 90 percent of the volatility in the real exchange rate is the result of deviations from the law of one price for traded goods. In another influential paper, Engel and Rogers (1996) relate the importance of national borders to the relative price of traded goods. If the law of one price holds, then any deviation in relative prices should be related only to transportation costs and other factors affecting the efficacy of goods arbitrage. However, they find significant departures from the law of one price, suggesting that national borders exert a strong impact on international prices.

In addition, Goldberg and Knetter (1997) study the proportion of movements in the nominal exchange rate that is passed through into final goods prices at an annual frequency. The authors argue that approximately one half of nominal-exchange rate movements are passed through into prices, reflecting a "destination-specific mark-up". This conclusion is reinforced by previous evidence put forward by Knetter (1989, 1993) and Marston (1990), who found that exporters tend to absorb nominal exchange rate movements in the mark-up of price over marginal cost.

The second class of price studies investigating the prevalence of deviations from the law of one price are based on the raw price data of individual firms. For example, magazine prices have been studied by Ghosh and Wolf (1997), and Knetter (1997). Haskel and Wolf (1998) studied catalog prices of identical Ikea-made furniture articles that are traded across 30 countries, but manufactured within the same country of origin.

In addition, there is a long history of empirical studies investigating the behavior of international relative prices. For instance, see Isard (1977), Kravis and Lipsey (1974, 1977, 1978), Protopapadakis and Stoll (1983, 1986) and Lapham (1995). Each study found substantial deviations from the law of one price.

Following the empirical evidence, the "pricing-to-market" assumption has been incorporated into several dynamic general equilibrium models. The leading theoretical method for incorporating PTM into an economic environment has been the "local currency pricing" (LCP) model, as first described by Betts and Devereux (1996). In this class of models, firms establish prices in local currency, and in advance of monetary shocks. Firms establish prices so that expected profits are maximized each period, and the law of one price holds in expected terms. Consequently, unanticipated monetary shocks result in departures from the law of one price that are proportional to the change in the nominal exchange rate.

Early papers in this literature include Betts and Devereux (1996), Kollmann (1996) and Chari, Kehoe and McGratten (1997, 1998). The results of recent models, such as Betts and Devereux (2000), Chari *et al.* (2000), Bergin and Feenstra (1999) and Devereux and Engel (1999) indicate that the PTM-LCP framework holds potential for explaining departures of the real exchange rate from purchasing power parity (PPP).

In particular, Chari *et al.* (1997, 1998, 2000) established a strong benchmark for this literature. They examined whether monetary shocks and sticky goods prices can account for the behavior of the real exchange rate. Nominal rigidity is introduced in the model through staggered price setting, as originally proposed by Taylor (1980). The motivation for staggered price setting is to generate more persistent effects in exchange-rate responses from a given monetary shock. An interesting "persistence puzzle" arises from the results presented in Chari *et al.* (1997, 1998). Specifically, it requires up to three years of sticky prices in order to replicate the international price data. This outcome seems inconsistent with the actual duration of price stickiness, as documented by Kashyap (1995), Blinder

(1991) and Carlton (1986). Alternatively, Chari *et al.* (2000) show that only four quarters of staggered price contracts are required to replicate the empirical moments if imposed in conjunction with strong relative risk aversion by households.

This paper also extends the PTM-LCP literature by modifying the trade settlement system. Most research in this literature relies on a money-in-the-utility specification in order to motivate a demand for money. In contrast to that approach, a monetary technology involving cash and credit is introduced. In the Lucas and Stokey (1987) model, a subset of goods require cash in advance, while other goods are acquired with credit. The impact of inflation is to increase the opportunity cost of accumulating nominal wealth, which is the foregone interest from investing in the bond market. For example, Yun (1996) applied this framework in a study of the link between US inflation and the cyclical component of real GDP. The model explored in this paper adopts the cash and credit dichotomy in order to investigate if an inflation-induced distortion is capable of generating volatility and persistence in international prices.

3. Establishing an Empirical Benchmark

This section establishes a benchmark for the conditional dynamic responses of international prices following economic shocks. Specifically, a benchmark is determined for the empirical impulse response functions of international prices and exchange rates conditional on a monetary or productivity shock. This approach differs from Obstfeld and Rogoff (2000) who show that the PTM-LCP model is inconsistent with the unconditional correlation between the nominal exchange and the terms of trade. Consequently, the empirical benchmark in this paper allows for a stronger test of the PTM-LCP model than comparing only the unconditional empirical moments with the respective theoretical moments.

Following Chari *et al.* (1997, 1998, 2000), the data for this exercise correspond to the US and a "European" economy, which is constructed using trade-weighted data from nine West European economies over the 1972Q1 to 1994Q4 period. The set of countries includes Austria, Finland, France, West Germany, Italy, Norway, Spain, Switzerland and the United Kingdom. Unfortunately, the availability of several time series limits the sample size. The data include the log of US GDP in constant 1996 dollars, Y^{US}, the US inflation rate based on the Consumer Price Index for all items, ΔP^{US}, the federal funds rate, FFR, and the nominal exchange rate between the US and the European economy, $e^{US,Euro}$. The real exchange rate, $RER^{US,Euro}$, is calculated as the product of the nominal exchange rate and the ratio of the European and US consumer price indices, P^{Euro}/P^{US}. The terms of trade, $ToT^{US,Euro}$, between the US and the European economy is determined as the ratio of US import to export prices. Productivity shocks, z^{US}, are measured by calculating the Solow residual using growth accounting. Consistent with Backus *et al.* (1993), capital is excluded from the calculation because these data are not generally available for all countries in the sample. Moreover, there is little quarterly variation in the capital stock. Employment in the US is measured using aggregate weekly hours from non-farm payrolls. The CPI data are extracted from the *Main Economic Indicators*, published by the OECD. Following Obstfeld and Rogoff (2000), the export and import price data are taken from the *International Financial Statistics* database, published by the IMF. The Federal Reserve Bank of St. Louis publishes data for real US GDP and aggregate weekly hours through its *FRED* database.

The empirical approach is to estimate a vector autoregression (VAR) identifying the impulse response functions conditional on specific economic shocks. This approach follows closed-economy work by Christiano and Eichenbaum (1992) that identifies liquidity effects in the US, and an open-economy study by Eichenbaum and Evans (1995) examining responses of the exchange rate following US money shocks. The structural parameters of the VAR system are identified from the reduced-form estimates using the method of Choleski decomposition. As is well known, the estimates are sensitive to the ordering of the variables. For this model, the ordering is $\{ Y^{US}, \Delta P^{US}, FFR, RER^{US,EURO} \}$ for a model with monetary shocks, and $\{ z^{US}, Y^{US}, \Delta P^{US}, RER^{US,EURO} \}$ for a model with productivity shocks. Alternative orderings are considered, however the pattern of impulse responses remains mostly unaffected. The last variable in the ordering is the test variable whose responses are the subject of inquiry. For example, this last position may be occupied by one of the real exchange rate, $RER^{US,EURO}$, the nominal exchange rate, $NER^{US,EURO}$, or the terms of trade, $ToT^{US,EURO}$. The lag order of the VAR is determined by iterative likelihood ratio testing. Other variables could be incorporated into the ordering. However, the system is given a parsimonious specification to preserve degrees of freedom in this parameter-intensive procedure.

The federal funds rate is known to be a strong indicator of innovations to US monetary policy. Both Bernanke and Blinder (1992) and Christiano and Eichenbaum (1992) have documented its ability to identify US monetary innovations. For the ordering described above, the unanticipated US monetary innovation is the component of the movement in the FFR that is orthogonal to the innovation in real US GDP and the inflation rate. The economic interpretation for this ordering is that monetary policy decisions are formed consistently with a reaction function that depends on output and the inflation rate. For the productivity model, the Solow residual is modeled as an exogenous shock whose innovation depends only on its own variance. Consequently, the Solow residual is placed first in the VAR ordering.

The responses of the real exchange rate and real US GDP following a one-standard deviation monetary shock are depicted in Panel A of Figure 1. The exchange rate is expressed as the price of the constructed "European" currency in terms of US dollars. Thus, a decline in the exchange rate represents an appreciation of the US dollar. Note that following an expansionary monetary shock in the US, there is a persistent and variable real depreciation of the US dollar. Real GDP also expands sharply after a decline in the federal funds rate. Panel B of Figure 1 shows that the conditional correlation between the nominal exchange rate and the terms of trade is positive following a monetary shock. Specifically, the conditional correlation between the impulse response functions is .28.

Likewise, Figure 2 shows that the terms of trade and the nominal exchange rate are positively correlated following an expansionary productivity shock. Panel B of Figure 2 shows that the terms of trade and the nominal exchange rate decline following a productivity shock. The conditional correlation between these responses is .86, which is significantly stronger than the conditional correlation following a monetary shock. In response to a productivity shock, real GDP expands persistently and the real exchange rate appreciates.

As Obstfeld and Rogoff (2000) have documented, the nominal exchange rate and the terms of trade are positively correlated in the data for most country pairs. In this sample, the unconditional correlation between the logged growth rate of the terms of trade and the nominal exchange rate is .39. Consistent with the business-cycle literature, the correlation is re-calculated after the data are logged and Hodrick-Prescott (1980) filtered. However, the unconditional correlation is robust at .40.

This section has identified the conditional dynamic responses and the conditional correlations of international prices and exchange rates following monetary and productivity shocks. Replicating the conditional responses represents a challenge for theoretical models of the real exchange rate. The next section develops a theoretical model that is broadly consistent with the unconditional correlation between the nominal exchange rate and the terms of trade. The conditional dynamic relationships are then compared to the empirical benchmark established in this section.

4. The Theoretical Model

Monopolistically competitive firms produce a variety of good that is sold in both the home and foreign market. Households purchase these goods for both consumption and investment purposes. Firms employ the capital and labor services of households to produce these goods. The method of financial settlement differs by category of good. As a result, the household accumulates nominal wealth that may be converted into cash, to acquire imported goods, or used to purchase nominal bonds that earn state-contingent returns.

4.1 The Timing of Events

The timing of the model is illustrated diagrammatically in Figure 6, and proceeds as follows. Households enter a period with a physical stock of capital and nominal wealth, both of which are endogenous state variables. Firms establish prices in advance of the money shock based on expected profit maximization. However, the information set that is available to firms includes current productivity shocks and the household's endogenous state variables. Upon the realization of monetary uncertainty, firms satisfy demand for their good at the posted prices, and households receive a lump-sum monetary transfer of newly created money.

Following the monetary and productivity shocks, members of the household separate to perform their specific functions. First, the securities market opens. The household trader is constrained by the stock of nominal wealth, contingent bond receipts and lump-sum monetary transfers. From this financial base, the trader allocates household resources between current cash balances and state-contingent, one-period, nominal bonds.

Following the close of the security market, the production and goods markets open simultaneously. Firms employ the capital and labor services of households, and in turn produce output that is either consumed or invested by households. The household shopper uses cash to purchase foreign-produced goods, and credit to purchase domestically produced goods. Purchases of foreign goods are constrained by a binding cash-in-advance constraint. The model is calibrated so that the nominal interest rate is always positive. It is assumed that households are aware of this process, so that the cash-in-advance constraint is binding each period.

Following the close of all markets, household members return home. The total credit bill is re-paid by households, firms remit profits to households and factor income is paid. The physical capital stock and the level of nominal wealth to be carried forward to the next period are determined. The cycle then repeats itself.

4.2 The Household Problem

The household sector is modeled as a representative agent in each economy that solves a two-stage expected utility problem. The history of states is given by $s^t = (s_0, \ldots, s_t)$, where $\pi(s^t)$ denotes the probability of realizing a particular history, s^t. This notation is taken from Chari *et al.* (1997, 1998, 2000), and is designed to emphasize the asymmetric information that is available to different economic agents when forming their decision rules. For instance, prices are established prior to the monetary innovation. As a result, the constrained information set governing prices is denoted by s^{t-1}.

Financial markets consist of one-period nominal bonds that provide state-contingent returns. The price of a nominal bond that pays one dollar upon the realization of state s^t is given by $Q(s^t|s^{t-1})$. The state space is represented by the set, S.

Taking all prices as given, the household's first-stage dynamic problem involves selecting the consumption of home-produced goods, $C_H(s^t)$, foreign goods, $C_F(s^t)$, labor effort, $l(s^t)$, current nominal cash holdings, $m(s^t)$, investment, $x(s^t)$, the capital stock to be carried forward to the next period, $k(s^t)$, a portfolio of state-contingent bond holdings, $b_H(s^{t+1})$ and nominal wealth, $N(s^t)$. The second-stage static problem involves allocating the aggregate expenditure on home- and foreign-produced goods, denoted by $E_H(s^t)$ and $E_F(s^t)$, respectively, across a fixed unit continuum of monopolistically competitive produced varieties, each indexed by $i \in [0,1]$. In addition, the investment good is formed by combining domestically produced goods indexed over the unit continuum, $i \in [0,1]$. For simplicity, it is assumed that foreign goods are not required to form the investment good. Following empirical work by Boileau (1999), this assumption may not be innocuous, although it renders the solution tractable.

The household's second-stage static allocation problem is described formally below. Since the optimization problems are symmetric across economies, only the home-country problems are presented in what follows. The prices of a home- and foreign-produced variety of good, i, are represented by $P_H(i, s^{t-1})$ and $P_F(i, s^{t-1})$, respectively. Similarly, the consumption of a home and foreign good are denoted as $C_H(i, s^t)$ and $C_F(i, s^{t-1})$, respectively. Consider the domestic household's allocation problem for home-produced goods. The specification of the sub-utility function for home-produced consumption goods assumes an Armington (1969) functional form, which gives rise to a constant elasticity of substitution between any two varieties of goods. The household maximizes this sub-utility function with respect to the budget constraint:

$$\max_{\left\{C_H(i,s^t)\right\}} \left(\int_0^1 C_H(i, s^t)^{\rho} \, di \right)^{\frac{1}{\rho}} \tag{1}$$

subject to

$$\int_0^1 P_H(i, s^{t-1}) \, C_H(i, s^t) \, di \; = \; E_H(s^t) \; . \tag{2}$$

Total expenditure on home-produced goods is given by the right-hand side of equation (2), and is determined from the first-stage dynamic problem. An analogous problem exists for foreign goods, $C_F(i, s^t)$.

The household also allocates its aggregate expenditure on investment, $E_x(s^t)$, across a unit continuum of home-produced goods. The amount of each good, i, that is allocated towards investment is denoted by $x(i, s^t)$ for each $i \in [0, 1]$. An Armington (1969) aggregator determines the total level of investment, $x(s^t)$. As a result, the investment allocation problem resembles the sub-utility maximization problem described by equations (1) and (2):

$$\max_{\{x(i,s^t)\}} \left(\int_0^1 x(i, s^t)^\rho \, di \right)^{\frac{1}{\rho}} \tag{3}$$

subject to

$$\int_0^1 P_H(i, s^{t-1}) \, x(i, s^t) \, di \;=\; E_x(s^t) \; . \tag{4}$$

Notice that investment goods are priced equivalently to home produced consumption goods, $P_H(i, s^{t-1})$. A later section discusses this aspect of the model in greater detail.

The conditional demand functions emerging from the second-stage problems for home goods, foreign goods and the investment goods, respectively, are outlined below for a particular variety, $i \in [0, 1]$:

$$C_H(i, s^t) \;=\; \left(\frac{P_H(s^{t-1})}{P_H(i, s^{t-1})} \right)^{\frac{1}{1-\rho}} C_H(s^t) \; , \tag{5}$$

$$C_F(i, s^t) \;=\; \left(\frac{P_F(s^{t-1})}{P_F(i, s^{t-1})} \right)^{\frac{1}{1-\rho}} C_F(s^t) \; , \tag{6}$$

$$x(i, s^t) \;=\; \left(\frac{P_H(s^{t-1})}{P_H(i, s^{t-1})} \right)^{\frac{1}{1-\rho}} x(s^t) \; . \tag{7}$$

In these expressions, the aggregate price level for home and foreign goods is given by $P_H(s^{t-1})$ and $P_F(s^{t-1})$, respectively, and the elasticity of substitution between any two varieties is given by $(1-\rho)^{-1}$. The aggregate price indices are determined as the deflators that satisfy the expenditure expressions, which can be expressed as $E_H(s^t) = P_H(s^{t-1})C_H(s^t)$ and $E_F(s^t) = P_F(s^{t-1})C_F(s^t)$ as a result of homotheticity. The resulting deflators are given by the following equations:

$$P_H(s^{t-1}) \;=\; \left(\int_0^1 P_H(i, s^{t-1})^{\frac{\rho}{\rho-1}} \, di \right)^{\frac{\rho-1}{\rho}} \; , \tag{8}$$

$$P_F(s^{t-1}) \ = \ \left(\int_0^1 \ P_F(i, s^{t-1})^{\frac{\rho}{\rho-1}} \ di \right)^{\frac{\rho-1}{\rho}} . \tag{9}$$

Prior to the static allocation problem, the household solves the first-stage dynamic optimization problem. The period utility function is separable in consumption and leisure. This specification is consistent with the utility function from Chari *et al.* (1998), which they show generates results that are more consistent with the empirical moments. In the problem described below, the lump-sum monetary transfer is represented by $T(s^t)$. Profits, $PR(s^t)$, are remitted by lump-sum at the end of each period. The nominal wage and rental rate on capital are denoted by $w(s^t)$ and $r(s^t)$, respectively, and are taken as given by the household. The household maximizes intertemporal expected utility by choosing $C_H(s^t)$, $C_F(s^t)$, $l(s^t)$, $b_H(s^{t+1})$, $m(s^t)$, $k(s^t)$ and $N(s^t)$ as follows:

$$\max \sum_{t=0}^{\infty} \ E_0 \ \beta^t \left\{ \left(\frac{1}{1-\sigma} \right) \left(C_H(s^t)^\theta \ C_F(s^t)^{1-\theta} \right)^{1-\sigma} + \eta \ log \left(\ 1 - l(s^t) \ \right) \right\} \tag{10}$$

subject to

$$N(s^{t-1}) + b_H(s^t) + T(s^t) \geq m(s^t) + \int_S Q(s^{t+1}|s^t) b_H(s^{t+1}) dS \ , \tag{11}$$

$$m(s^t) \geq \ E_F(s^t) \ , \tag{12}$$

$$\begin{aligned} & PR(s^t) \ + \ w(s^t) l(s^t) \ + \ r(s^t) k(s^{t-1}) \ + \ T(s^t) \ + \ b_H(s^t) \ + \ m(s^t) \ + \\ N(s^{t-1}) \ = \ & E_H(s^t) \ + \ E_F(s^t) \ + E_x(s^t) \ + \ \int_S \ Q(s^{t+1}|s^t) \ b_H(s^{t+1}) \ dS \ + \ N(s^t) \ , \end{aligned} \tag{13}$$

$$k(s^t) = (1-\delta) \ k(s^{t-1}) + \left(\frac{x(s^t)}{k(s^{t-1})} \right)^{\frac{1}{\psi}} k(s^{t-1}) \ , \tag{14}$$

$$E_H(s^t) \ = \ P_H(s^{t-1}) \ C_H(s^t) \ , \tag{15}$$

$$E_F(s^t) \; = \; P_F(s^{t-1}) \; C_F(s^t) \; , \tag{16}$$

$$E_x(s^t) \; = \; P_H(s^{t-1}) \; x(s^t) \; . \tag{17}$$

Equation (11) represents the securities-market constraint, equation (12) reflects the cash-in-advance constraint for foreign goods, equation (13) is the budget constraint and equation (14) is the law of motion for physical capital. Expenditure on home and foreign produced goods is given by equations (15) and (16), respectively. Expenditure on the investment good is given by equation (17).

The parameters of the model are as follows. The share of home-produced goods in the utility function is given by θ. The parameter η is related to the elasticity of labor supply. The coefficient of relative risk aversion is given by σ. The introduction of convex adjustment costs into the accumulation of capital constrains excessive volatility in investment responses following shocks. This convention is standard in the business-cycle literature, and follows work by Backus *et al.* (1993). The magnitude of adjustment costs is determined by the parameter ψ, where $\psi \in (0, 1)$. The inequality constraints are binding so long as the nominal interest rate is positive each period, which is assured with a money-supply growth process that is always positive. The Euler equations arising from this problem are summarized in appendix B.

4.3 The Producers' Problems

There is a fixed unit continuum of imperfectly competitive firms in both the home and foreign economies. The market structure is based on the Dixit and Stiglitz (1977) model of monopolistically-competitive firms. The information available to firms at the beginning of a period includes the stocks of capital and nominal wealth owned by households, and the state of productivity. However, firms do not observe the monetary shock before setting prices. Despite the absence of complete information, prices are determined so that expected profits are maximized and the law of one price holds in expectation.

Since firms are imperfectly competitive, they maximize profits with respect to prices taking account of the conditional demand for their variety of output. Firms cannot distinguish between households' demand for consumption versus investment goods. As a result, the home firm charges only one price to local households, $P_H(i, s^{t-1})$. Foreign households demand the home firm's output strictly for consumption purposes, and are charged a local-currency price of $P^*_H(i, s^{t-1})$. The unit cost in nominal terms for producing variety i is given by $v(i, s^t)$. The firm discounts the set of possible profit outcomes by the value of a dollar in each state, $Q(s^t|s^{t-1})$. The firm maximizes the following expected profit function with respect to $P_H(i, s^{t-1})$ and $P^*_H(i, s^{t-1})$, where the nominal exchange rate is given as $e(s^t)$:

$$\int Q(s^t|s^{t-1}) \left\{ \left[P_H(i, s^{t-1}) - v(i, s^t) \right] \left(C_H(i, s^t) + x(i, s^t) \right) + \left[e(s^t) \, P^*_H(i, s^{t-1}) - v(i, s^t) \right] \left(C^*_H(i, s^t) \right) \right\} ds^t$$

subject to

$$C_H(i, s^t) + x(i, s^t) = \left[\frac{P_H(s^{t-1})}{P_H(i, s^{t-1})} \right]^{\frac{1}{1-\rho}} \left(C_H(s^t) + x(s^t) \right)$$

$$C^*_H(i, s^t) = \left[\frac{P^*_H(s^{t-1})}{P^*_H(i, s^{t-1})} \right]^{\frac{1}{1-\rho}} C^*_H(s^t) \, , \qquad (18)$$

where the aggregate prices, $P_H(s^{t-1})$ and $P^*_H(s^{t-1})$, are taken as given by firms.

The optimality conditions that emerge from the expected profit problem yield constant mark-up pricing rules for home-produced goods destined for the domestic and foreign markets, respectively:

$$P_H(i, s^{t-1}) = E_{t-1} \, \frac{v(i, s^t)}{\rho} \, , \qquad P^*_H(i, s^{t-1}) = E_{t-1} \left(\frac{v(i, s^t)}{e(s^t) \, \rho} \right) . \qquad (19)$$

The elasticity-of-substitution parameter, ρ, determines the constant mark-up of prices over marginal cost. A key characteristic of the local currency pricing model is that without monetary "surprises", the firms would price consistently with the law of one price. Therefore, after a single period of price adjustment the firm will fully incorporate the effects of monetary shocks into prices. As a result, nominal rigidity in this model exerts only short-lived propagation of monetary shocks.

The production technology exhibits constant returns to scale. As a result, the unit cost variable, $v(i, s^t)$, is equivalent to marginal cost. The firm identifies its marginal cost from minimizing the cost function with respect to $l(i, s^t)$ and $k(i, s^{t-1})$:

$$v(i, s^t) \;=\; \min \;\left[\; w(s^t)\; l(i, s^t) \;+\; r(s^t)\; k(i, s^{t-1}) \;\right]$$

subject to

$$1 \;\geq\; z(s^t)\; k(i, s^{t-1})^{\alpha}\; l(i, s^t)^{1-\alpha}. \tag{20}$$

The productivity shock, $z(s^t)$, is embodied in total factor productivity. The cost minimization problem gives rise to the following expression for marginal cost:

$$v(i, s^t) \;=\; \frac{1}{(1-\alpha)\; z(s^t)}\; w(s^t) \left(\frac{l(i, s^t)}{k(i, s^{t-1})} \right)^{\alpha}. \tag{21}$$

4.4 Market Clearing and Forcing Processes

The goods, bond, money and factor markets clear each period. In addition, the aggregate consistency conditions hold, so that individual household decisions are consistent with aggregate outcomes. These conditions are described formally in Appendix B.

The exogenous state variables in this economy include the productivity and money-supply shocks in each economy. The productivity shocks also allow cross-economy spillover effects and correlated disturbances. The joint Markov process describing the evolution of productivity shocks in terms of deviations from the steady state is described below:

$$\begin{bmatrix} \hat{z}(s^t) \\ \hat{z}^*(s^t) \end{bmatrix} \;=\; \begin{bmatrix} \rho_z & \rho_{z,z^*} \\ \rho_{z,z^*} & \rho_z \end{bmatrix} \begin{bmatrix} \hat{z}(s^{t-1}) \\ \hat{z}^*(s^{t-1}) \end{bmatrix} \;+\; \begin{bmatrix} \epsilon(s^t) \\ \epsilon^*(s^t) \end{bmatrix} \;, \tag{22}$$

where the productivity disturbances are assumed to be joint normally distributed. The variance-covariance matrix of the disturbances is given by, $\epsilon(s^t)\epsilon(s^t)^T \;=\; \Omega$. This structure also allows the productivity innovations to be correlated across economies.

The growth rate of the money supply in each economy evolves as a univariate Markov process. This approach is consistent with Chari *et al.* (1997, 1998). The money supply expands according to the following rule: $M(s^t) = \mu(s^t)\ M(s^{t-1})$. The stochastic growth rate of money, expressed in terms of deviations from the steady state, is as follows:

$$exp(\ \hat{\mu}(s^t)\ ) = \rho_\mu\ exp(\ \hat{\mu}(s^{t-1})\ ) + \chi(s^t) \tag{23}$$

Maintaining the assumption adopted by Chari *et al.* (1997, 1998), the disturbances are normally distributed with a zero mean, and a variance given by σ_μ^2.

4.5 Symmetric Equilibrium

A symmetric equilibrium for this economy is defined as follows. Prices are equal for each variety of good so that given a unit continuum of varieties, the price of each good is equal to the price index given by equations (8) and (9).

$$P_H(i, s^{t-1}) = P_H(s^{t-1}), \quad P_F(i, s^{t-1}) = P_F(s^{t-1}), \quad \forall i \in [0,1]\ , \tag{24}$$

$$P_F^*(i, s^{t-1}) = P_F^*(s^{t-1}), \quad P_H^*(i, s^{t-1}) = P_H^*(s^{t-1}),\ \forall i \in [0,1]\ . \tag{25}$$

Further, the consumption and investment quantities are also symmetric.

The equilibrium for this economy is a sequence of domestic choice variables, $C_H(s^t)$, $C_F(s^t)$, $x(s^t)$, $l(s^t)$, $b_H(s^{t+1})$, $k(s^{t-1})$, $m(s^t)$, $N(s^t)$, a corresponding set of foreign choice variables, a set of goods prices, $P_H(s^{t-1})$, $P_F(s^{t-1})$, $P_F^*(s^{t-1})$, $P_H^*(s^{t-1})$, $P(s^t)$, $P^*(s^t)$, a set of factor prices, $w(s^t)$, $r(s^t)$, $w^*(s^t)$, $r^*(s^t)$, nominal interest rates in both economies, $R(s^t)$, $R^*(s^t)$ and a nominal exchange rate, $e(s^t)$, that satisfy the following conditions. First, households are maximizing expected intertemporal utility and allocating across varieties of goods efficiently while observing all relevant constraints. Second, firms set prices so that expected profits are maximized, taking into account the conditional demand for their output. Firms take factor prices as given. Third, all resource and market-clearing conditions are satisfied each period.

4.6 Nominal and Real Exchange Rates in Equilibrium

Households diversify risk through a set of nominal one-period bonds that provide state-contingent returns. These state-contingent claims are denominated in the currency units of the home economy. The availability of these assets implies an invariant distribution of wealth across countries, so that the simulated dynamic path is stationary over time. Comparing the home and foreign Euler equations for a state-contingent bond produces a marginal-utility condition that determines the equilibrium nominal exchange rate, $e(s^t)$. For instance, consider the Euler equations from the home and foreign households, respectively, for a state-contingent bond:

$$Q(s^{t+1}|s^t) \;=\; \beta\, \pi(s^{t+1}|s^t) \left(\frac{C(s^{t+1})}{C(s^t)} \right)^{1-\sigma} \left(\frac{P_F(s^{t-1})\; C_F(s^t)}{P_F(s^t)\; C_F(s^{t+1})} \right) , \tag{26}$$

$$\frac{Q(s^{t+1}|s^t)}{e(s^t)} \;=\; \beta\, \pi(s^{t+1}|s^t) \left(\frac{C^*(s^{t+1})}{C^*(s^t)} \right)^{1-\sigma} \left(\frac{P_H^*(s^{t-1})\; C_H^*(s^t)}{P_H^*(s^t)\; C_H^*(s^{t+1})} \right) \left(\frac{1}{e(s^{t+1})} \right) . \tag{27}$$

These equations are combined and solved by backward iteration to obtain the following expression for the nominal exchange rate:

$$e(s^t) \;=\; \left(\frac{C^*(s^t)}{C(s^t)} \right)^{1-\sigma} \left(\frac{P_F(s^{t-1})C_F(s^t)}{P_H^*(s^{t-1})C_H^*(s^t)} \right) , \tag{28}$$

which is obtained after imposing the initial condition,

$$1 \;=\; e_0\, \frac{C_0}{C_0^*}\, \frac{P_{H0}^* C_{H0}^*}{P_{F0} C_{F0}} , \tag{29}$$

where the subscript 0 denotes the initial time period. The equilibrium expression given by equation (28) holds each period, and for each contingent state. By imposing the cash-in-advance constraints, and transforming equation (28) accordingly, the nominal exchange rate is expressed as follows:

$$e(s^t) \;=\; \left(\frac{C^*(s^t)}{C(s^t)} \right)^{1-\sigma} \left(\frac{M(s^t)}{M^*(s^t)} \right) , \tag{30}$$

which is consistent with the nominal exchange-rate condition considered by Helpman and Razin (1982). In particular, Lucas (1982) assumed that goods prices are denominated in the currency of sellers in his two-country cash-in-advance model. In contrast, Helpman and Razin (1982) examined the effect of setting prices in the currency of buyers. This latter assumption is consistent with the PTM-LCP approach of explaining international prices and exchange rates.

Equation (30) shows that the nominal exchange rate is a function of the marginal utilities and money stocks in each country. In contrast, other models in this literature express the nominal exchange rate as a function of the ratio in the marginal utilities and the price levels in each country. Intuitively, the representation given by equations (28) and (30) should amplify the variability of exchange-rate responses following shocks because both trade and monetary variables are more volatile than aggregate consumption.

The real exchange rate is defined as the product of the nominal exchange rate, and the ratio of the foreign-to-home aggregate price levels, $P^*(s^t)/P(s^t)$:

$$RER(s^t) \ = \ \frac{e(s^t) \ P^*(s^t)}{P(s^t)} \ . \tag{31}$$

Substituting for the nominal exchange rate in equation (31) gives the following expression for the real exchange rate:

$$RER(s^t) \ = \ \left(\frac{C^*(s^t)}{C(s^t)} \right)^{1-\sigma} \left(\frac{M(s^t)/P(s^t)}{M^*(s^t)/P^*(s^t)} \right) . \tag{32}$$

The real exchange rate depends on the ratio of real money balances in the home and foreign economies. In this environment, the real exchange rate varies over time as monetary shocks affect the intertemporal choice between investing in bonds and holding cash balances. In addition, real money balances vary as a result of sticky prices and local currency pricing.

The above conditions govern the dynamic behavior of the nominal and real exchange rates. Specifically, equations (28) and (30) show that the opportunity cost of investing in state-contingent bonds is balanced with the marginal-utility benefit from consuming cash-acquired imports. If prices are sticky, so that the prices in equation (28) are fixed, the home monetary shock results in a substitution into cash-acquired import goods before prices adjust.

4.7 Defining the Price Level and Constant-Dollar Quantities

To compare the simulated and empirical moments properly, it is first necessary to calculate real variables consistently with the System of National Accounts. Data that are expressed in "real" terms are evaluated in constant-currency units relative to a base year. In practice, statistical agencies collect the current (or nominal) value of each category of good. Appendix A describes the formal method used by statistical agencies to construct Paasche variable-weight price indices and Laspeyres fixed-weight quantity indices from currently observed values. From these indices, the constant-dollar series may be obtained.

The simulated price indices and the "real" quantity variables are generated consistently with the method detailed in Appendix A. In this manner, the simulated moments are consistent with the empirical moments. A natural selection for the base year in the theoretical economy is the steady state. These values are denoted with a bar above the relevant variable. For instance, consumption is evaluated in constant-dollar terms as follows:

$$C(s^t) \;=\; \bar{P_H}\; C_H(s^t) \;+\; \bar{P_F}\; C_F(s^t)\;, \tag{33}$$

which contrasts with the utility-based measure of real consumption, $C_H(s^t)^{\theta}\; C_F(s^t)^{1-\theta}$. Similarly, real constant-dollar GDP ($RGDP$) is evaluated as

$$RGDP(s^t) \;=\; \bar{P_H}\;\big(\; C_H(s^t) \;+\; x(s^t)\;\big) \;+\; \bar{e}\;\bar{P_F}\; C_H^{*}(s^t)\;. \tag{34}$$

There are two methods for expressing the aggregate price level. The most common measure is the fixed-weight Laspeyres price index, usually described as the Consumer Price Index (CPI). An alternative measure is the Paasche Price Index (PI). The aggregate price level, denoted $P(s^t)$ in the model, may be measured by either the CPI or Paasche specification. The two price variables are illustrated below,

$$CPI \;=\; \omega_H \left(\frac{P_H}{\bar{P_H}}\right) \;+\; \omega_F \left(\frac{P_F}{\bar{P_F}}\right)\,, \tag{35}$$

$$PI \;=\; \tilde{\omega_H}\left(\frac{P_H}{\bar{P_H}}\right) \;+\; \tilde{\omega_F} \left(\frac{P_F}{\bar{P_F}}\right)\,, \tag{36}$$

where ω_H and ω_F are the steady-state expenditure weights, and $\tilde{\omega_H}$ and $\tilde{\omega_F}$ reflect the current-value expenditure weights of the home and foreign good in consumption, respectively. The simulated results use both methods for expressing prices, however the choice of index method does not affect the theoretical simulated moments.

4.8 Monetary Non-neutrality in the Steady State

An interesting property of the steady state is that the consumption of home goods relative to foreign goods is increasing in the nominal interest rate. In the steady state, the nominal interest rate is expressed as,

$$\bar{R} = \frac{exp(\bar{\mu})}{\beta} , \tag{37}$$

where the steady-state growth rate in the money supply is given by $\bar{\mu}$. The steady-state relationship between home- and foreign-produced goods may be expressed as,

$$\left(\frac{\theta}{1-\theta} \right) \bar{R} = \frac{\bar{C_H}}{\bar{C_F}} , \tag{38}$$

so that the share of home goods relative to foreign goods increases with the steady-state growth rate of the money supply. This property of the international macroeconomy demonstrates the long-run monetary non-neutrality that affects the ratio of domestically-produced consumption goods to imports.

5. Calibration and Numerical Simulation

5.1 Calibration

To foster greater comparability with existing studies, the parameters of the model are calibrated based largely on values taken from Chari *et al.* (1997, 1998, 2000). This approach is consistent with the objective of comparing the simulated moments with the data as constructed by Chari *et al.* (1997, 1998, 2000). The sample spans the 1972Q1 to 1994Q4 period.

The household parameters are generally consistent with the business-cycle literature. The value for β is set at .99. The coefficient of relative risk aversion, σ, is calibrated at 2.0.

The labor supply parameter, η, is given a value of 2.0. The quarterly rate of depreciation is given by .026. The share of home-to-foreign goods in aggregate US consumption is 15.58. As a result, the value for θ, or the share of home goods in the utility function, is calculated to be .93827. This value satisfies the steady-state condition given by (38) linking the nominal interest rate, foreign consumption and home goods consumption.

Investment is highly volatile in many business-cycle models. As a result, the law of motion for physical capital is constrained by a convex adjustment cost. The parameter, ψ, determines the magnitude of these costs. The parameter is calibrated to match the observed relative volatility of investment to real GDP at 3.28. In the benchmark model including both monetary and productivity shocks, the value of ψ that achieves this criterion is .872.

The production parameters are given as follows. The share of capital in the production function, α, is calibrated to .33. The mark-up parameter is calibrated from empirical studies of the average mark-up in the US economy. The value for ρ employed by both Chari *et al.* (1998) and this paper is .90. This calibration leads to an average mark-up of 11 percent. However, the empirical range of estimates for the mark-up is wide. A sensitivity analysis of the value for this parameter is undertaken, but the simulation results are not dramatically affected by reasonable changes in the parameter values.

The forcing processes for the productivity shocks are calibrated to be consistent with Backus *et al.* (1993) and Chari *et al.* (1997, 1998, 2000). The persistence of shocks, ρ_μ, is .57. The productivity process exhibits an autocorrelation, ρ_z, of .906, and the cross-correlation with the foreign economy, ρ_{z,z^*}, is .088. The variance-covariance matrix of shocks is calibrated so that the standard deviation of monetary shocks, σ_μ, is .0035, while the standard deviation of productivity shocks, ρ_z, is set to, .00852. The cross-correlation of monetary shocks, σ_{μ,μ^*}, is zero, but the cross-correlation of productivity shocks, σ_{z,z^*}, is .258. The growth rate of the money supply is calibrated at 1.5 percent per quarter. This follows Cooley and Hansen (1995) and Chari *et al.* (1997, 1998, 2000).

5.2 Computational Experiments

The asymmetric information underlying the decision rules of different economic agents presents a challenge for numerical simulation. The method of undetermined coefficients, developed by Christiano (1998), represents an ideal method for simulating this type of environment. The method allows for the derivation of policy functions that explicitly account for asymmetric information. Appendix B provides greater detail regarding the method of simulation, and the system of equilibrium equations that characterize the simulation path. Results are based on 1,000 replications of logged and Hodrick-Prescott (1980) filtered data, so that each draw simulates 92 quarters to match the empirical sample.

The results of numerical simulations are presented relative to a benchmark economy. The benchmark case involves one-period sticky prices, and includes both monetary and productivity shocks. The first experiment removes monetary shocks and examines the specific impact of productivity shocks. In this case, prices respond flexibly to all shocks. The second experiment isolates the impact of monetary shocks by removing the effects of productivity shocks. The simulated moments are presented in Tables 1 through 3.

The computational exercise produces the following set of major findings. First, consider the unconditional moments. The benchmark model generates a positive unconditional correlation between the terms of trade and the nominal exchange rate at .21. This addresses the Obstfeld and Rogoff (2000) critique of PTM-LCP models. In addition, the monetary model increases the predicted volatility of the real exchange rate and international prices compared to similar findings in the literature. This result stems from the mechanism for cash and credit settlement, which amplifies consumption responses following monetary shocks. In addition, the productivity model generates similar autocorrelation in the real exchange rate as found by Chari *et al.* (1997, 1998, 2000), without imposing strong relative risk aversion or an implausible duration of price rigidity.

In contrast to the unconditional moments, the model encounters difficulty at explaining the conditional dynamic responses. For instance, the predicted conditional correlation between the nominal exchange rate and the terms of trade is negative following a monetary shock. This finding conflicts with the data. The predicted conditional correlation following a productivity shock is positive. However, the conditional dynamic responses behave inconsistently with the empirical impulse response functions. These findings are likely to be robust to others in the literature. As a result, replicating the conditional dynamic responses and correlations represents a new puzzle for the PTM-LCP model.

5.2.1 Unconditional Moments

Consider the unconditional moments generated by the benchmark economy for international prices and exchange rates. As described above, the model successfully replicates the positive correlation between the terms of trade and the nominal exchange rate. In addition, Table 2 shows that the correlation between the nominal and real exchange rate is .51, which is superior to a similar model simulated by Chari *et al.* (1997). However, this moment remains well below its empirical level of .99, which Mussa (1986) has demonstrated to be a persuasive empirical regularity in the open-economy data. The predicted volatility of the terms of trade is relatively strong. This feature broadly addresses the "price puzzle" discussed by Backus *et al.* (1993). Deviations from the law of one price are negatively autocorrelated in the benchmark model. This finding reflects the rapid response of prices following persistent monetary shocks, and only a single period of nominal price rigidity.

The unconditional moments for the business-cycle variables are reported in Table 3. The benchmark is calibrated to replicate the relative volatility of investment to real GDP at 3.28. The model understates the volatility and persistence of consumption relative to the data. However, employment responses tend to be more volatile than output, but less persistent than the empirical moment. Consistent with Backus *et al.* (1993), international consumption is more strongly correlated across countries than output. This finding is consistent with the well-documented "quantity puzzle" in the open-economy literature. However, the magnitude of the correlation is relatively low compared to other papers in this literature at .26. Devereux, Gregory and Smith (1992) demonstrated that international models with complete markets and separable utility imply strong cross-country consumption correlations. This model generates a relatively low consumption correlation partially as a result of the cash and credit mechanism. A monetary expansion causes a substitution into foreign produced goods, which leads to international consumption diverging until prices adjust. Moreover, only home-produced goods are required to generate the aggregate investment good. This aspect of the model also contributes to the relatively low correlation of international consumption.

The results of two computational experiments are also reported in Tables 1 through 3. The first experiment removes productivity shocks from the environment, isolating the impact of monetary innovations. Removing productivity shocks increases the simulated volatility of most variables, but only at the cost of generating diminished persistence. Specifically, the real exchange rate and deviations from the law of one price become negatively autocorrelated in this case, reflecting rapid nominal adjustment after a period of price rigidity. However, the simulated volatility of the real and nominal exchange rates increase significantly to 1.31 and 1.77, respectively. This result reflects the effect of the cash and credit mechanism for monetary settlement, which enhances the volatility of responses after monetary shocks.

Removing monetary shocks from the environment improves the predicted persistence of the real and nominal exchange rates significantly. For instance, the predicted autocorrelation increases to .65 for the theoretical real and nominal exchange rates, and the terms of trade. This result is consistent with the findings from Chari *et al.* (2000) who require a coefficient of relative risk aversion of six, combined with four quarters of staggered price setting. One implication of removing monetary shocks in this model is that there are no deviations from the law of one price. This occurs because firms observe current productivity shocks, and incorporate this information into their pricing decisions. This feature of the environment suggests that although productivity shocks are successful at addressing the counterfactual correlation between the nominal exchange rate and the terms of trade, and improving the autocorrelation of the simulated responses, they cannot account for all of the stylized open-economy facts.

5.2.2 Conditional Moments and Dynamics

Consider next the conditional dynamic responses of international prices and exchange rates following specific shocks. Figure 3 depicts the predicted impulse responses of the nominal and real exchange rates, the terms of trade and real GDP following a monetary shock. The simulated dynamic responses are analogous to the empirical impulse response functions illustrated in Figure 1. The negative conditional correlation between the theoretical impulse response functions for the nominal exchange rate and the terms of trade, $ToT(s^t)$, can be understood from the following expression:

$$ToT \;=\; \left(\frac{P_F(s^{t-1})}{P_H^*(s^{t-1})}\right)\left(\frac{1}{e(s^t)}\right) . \tag{39}$$

If prices are sticky during the period, so that P_F/P_H^* is fixed, then nominal exchange-rate movements will generate a negative correlation with the terms of trade. The theoretical impulse response functions confirm this result. A monetary shock causes the simulated terms of trade to decline, while the nominal exchange rate depreciates. In contrast, the empirical responses show that the terms of trade increase following a monetary shock. The empirical response is consistent with expenditure switching by households from relatively expensive imports to home-produced goods following a nominal exchange-rate depreciation. These results suggest that a stronger form of the Obstfeld and Rogoff (2000) critique of PTM-LCP models is framed in terms of the conditional response to monetary shocks.

The conditional dynamic responses are broadly replicated for real GDP and the exchange rates following a monetary shock. However, the theoretical impulse response functions of the nominal and real exchange rate illustrate the weak propagation of monetary shocks in the model with only one period of sticky prices. In contrast, the empirical impulse response functions demonstrate substantial persistence and variability.

In response to a home monetary shock, the real and nominal exchange rates depreciate in tandem. It can be seen from equations (28) and (40) that the contemporaneous responses are perfectly correlated given sticky prices.

$$RER(s^t) \;=\; \left(\frac{C(s^t)}{C^*(s^t)}\right)^{\sigma-1}\left(\frac{C_F(s^t)}{C_H^*(s^t)}\right)\left(\frac{P_F(s^{t-1})/P(s^t)}{P_H^*(s^{t-1})/P^*(s^t)}\right) . \tag{40}$$

After a single period of nominal adjustment to the monetary shock, the real exchange rate quickly reverts to its steady-state level. This pattern of impulse responses demonstrates the rapid assimilation of inflationary effects into prices, which results in diminished persistence. Longer periods of staggered price setting, as considered by Chari *et al.* (1997, 1998, 2000), would improve persistence following money shocks. However, this feature of the model requires an unrealistic degree of nominal rigidity.

Figure 4 illustrates the dynamic responses of international prices, exchange rates and real GDP following a productivity shock. These conditional dynamic responses are anologous to the empirical impulse response functions depicted in Figure 2. A favorable productivity shock results in a persistent depreciation of the nominal exchange rate, and a steady increase in the terms of trade. The productivity shock causes the price of domestically produced items to decrease over time, reflecting the reduced marginal cost of production. As a result, the productivity shock causes a larger proportional increase in the relative price P_F/P_H^* in equation (39), compared to the downward effect of $1/e(s^t)$. As a result, the conditional correlation is positive. Although productivity shocks generate a favorable conditional correlation between the nominal exchange rate and the terms of trade, the dynamic responses diverge from the empirical responses. In particular, the empirical exchange rates appreciate persistently following a productivity shock. In contrast, the predicted dynamic responses depreciate persistently. These empirical responses are inconsistent with the theoretical dynamic responses depicted in Figure 4.

Figure 5 depicts the conditional responses of business-cycle aggregates following a monetary and productivity shock. Following a monetary shock, the responses are consistent with other dynamic general equilibrium models incorporating money, such as Cooley and Hansen (1995). In addition, the conditional responses following a productivity shock are consistent with Backus *et al.* (1993).

6. Summary and Conclusions

The hypothesis investigated in this paper is that the distortionary impact of monetary policy, acting through the mode of international settlement, impacts the determination of international prices. The mechanism underlying this hypothesis is the inflation tax on the stock of nominal wealth. Households accumulate nominal wealth each period in order to purchase interest-bearing bonds and cash balances. Expansionary monetary policy results in a substitution into credit-financed consumption and investment goods. However, short-run nominal rigidity allows households to exploit temporarily inexpensive imports before prices adjust to shocks. This mechanism fosters greater variability. Productivity shocks are introduced to the environment to foster greater autocorrelation in the dynamic responses. In addition, the impact of PTM-LCP is fully incorporated into the model, and contributes to explaining movements in the real exchange rate, the terms of trade and departures from the law of one price.

This paper has also established an empirical benchmark for the conditional impulse responses and correlations following shocks. Replicating these moments and dynamic relationships represents a stronger test than comparing unconditional moments. Although the model posited in this paper encounters difficulty satisfying these stronger tests, it is likely that standard open-economy models would experience similar difficulty. As a result, addressing these conditional relationships is left as a puzzle to be resolved in future research.

This line of research can be extended in several directions. First, firms have access to derivative instruments that enable the hedging of exchange rate risk. For example, Engel (1996) has explored this issue. Hedging may explain the lack of pass through in exchange rate movements into final goods prices. In addition, a more complex market structure that allows for strategic forms of competition could lead to interesting dynamic responses in international prices and exchange rates. For instance, Lapham (1995) has explored international relative prices in environments with strategic forms of imperfect competition.

Appendix A: Measuring Constant-Dollar Quantities

A constant-dollar series is constructed using variable-weight Paasche price indices, and fixed-weight Laspeyres quantity indices. These indices are derived from a discrete number of goods, indexed by $j = 1, \ldots N$, using the current values of each good, j, and relating them to base-year values. For example, consider the following expression for an arbitrary constant-dollar series, $W(s^t) = \sum_{j=1}^{N} P_0(i)\ Q(j, s^t)$. Let $P_0(j)$ represent the base-year price for good j, and $Q(j, s^t)$ represent the current quantity produced of good j. The Paasche price index is determined as follows,

$$P_p = \frac{\sum_{j=1}^{N} P(j)\ Q(j)}{\sum_{j=1}^{N}\ P(j)\ Q(j)\left(\frac{P_0(j)}{P(j)}\right)}, \tag{A1}$$

where the numerator represents the nominal (current) value of the variable, and the denominator is the constant-dollar value for the series. From the consumer price survey, both $P_0(j)$ and $P(j)$ are known each period. The Laspeyres quantity index is determined by the following expression,

$$L_q = \frac{\sum_{j=1}^{N} P_0(j)\ Q(j)}{\sum_{j=1}^{N} P_0(j)\ Q_0(j)}, \tag{A2}$$

where the numerator represents the constant-dollar value of the variable, and the denominator reflects the base-year values. In practice, the constant-dollar series is recovered using the following procedure,

$$W(s^t) = L_q \times \left[\ \sum_{j=1}^{N} P_0(j)\ Q_0(j)\ \right], \tag{A3}$$

while the Laspeyres quantity index is itself derived using the observable Paasche price index, P_p, with the following transformation,

$$L_q = \frac{\sum_{j=1}^{N} P_0(j)\ Q(j)}{\sum_{j=1}^{N} P_0(j)\ Q_0(j)} \times \left(\frac{1}{P_p}\right). \tag{A4}$$

The Paasche price index, and the other series involved in equation ($A4$), are available to statistical agencies each period.

Appendix B: The Simulation Method, and System of Equilibrium Equations

The system of equilibrium equations that characterize the simulation path is linearized about the steady state using a Taylor series expansion. Following Christiano (1998), the system of N variables is expressed in terms of the following N expectational difference equations,

$$E_t \left[\sum_{i=0}^{r} \alpha_i \; Z_{t+r-1-i} \; + \; \sum_{i=0}^{r-1} \; S_{t+r-1-i} \right] \; = \; 0 \; , \qquad (B1)$$

where r is sufficiently large to account for the number of lags in the system that captures all dynamic relationships. The vector Z_t represents the variables included in the equilibrium equation system, and S_t is the vector of exogenous state variables. The expectation operator allows for different information sets underlying each decision variable composing Z_t. The following conjecture of the decision rules is then postulated,

$$Z_t \; = \; A \; Z_{t-1} \; + \; B \; S_t \; , \qquad (B2)$$

where the matrix A reflects the "feedback" effects linking current decisions to the endogenous state variables. The matrix B contains the feedforward responses, linking current decision rules to the exogenous state variables, S_t. The simulation method operates to solve the undetermined coefficients comprising the feedforward and feedback matrices. Incomplete information is accommodated with an appropriate transformation of the A and B matrices. For example, the elements of matrix B linking the pricing rules to the money supply shocks will enter as zero. This reflects the one-period nominal rigidity of prices following monetary shocks. In contrast, the elements of the B matrix relating prices to productivity shocks are non-zero, reflecting the fact that such shocks are included in the firms' information set.

The Euler equations from the household problem are described below. Several additional variables are required for these expressions. For instance, aggregate consumption, $C(s^t)$, is defined by $C_H(s^t)^\theta \; C_F(s^t)^{1-\theta}$. The state-contingent nominal interest rate is given by $R(s^{t+1}|s^t)$, and is simply the inverse of the contingent bond price, $Q(s^{t+1}|s^t)$, for each possible realization of s^{t+1}. The optimality equation for labor effort is:

$$\eta \;=\; \theta \left(\frac{w(s^t)}{P_H(s^{t-1})} \right) \left(\frac{C(s^t)^{1-\sigma}}{C_H(s^t)} \right) . \qquad (B3)$$

The asset-pricing Euler equation for each contingent claim is given by:

$$1 \;=\; \beta \; E_t \left(\frac{C(s^{t+1})}{C(s^t)} \right)^{1-\sigma} \left(\frac{P_F(s^{t-1}) \; C_F(s^t)}{P_F(s^t) \; C_F(s^{t+1})} \right) R(s^{t+1}|s^t) \; . \qquad (B4)$$

The intertemporal Euler equation governing the evolution of nominal wealth is given by:

$$1 \;=\; \beta \; E_t \left(\frac{C(s^{t+1})}{C(s^t)} \right)^{1-\sigma} \left(\frac{1-\theta}{\theta} \right) \left(\frac{P_H(s^{t-1}) \; C_H(s^t)}{P_F(s^t) \; C_F(s^{t+1})} \right) . \qquad (B5)$$

Finally, the optimality condition for the intertemporal allocation of capital is given by:

$$\frac{1}{\psi} \left(\frac{k(s^t)}{k(s^{t-1})} \;-\; (1-\delta) \right)^{\frac{1}{\psi}-1} \;=\; \beta \; E_t \left(\frac{C(s^{t+1})}{C(s^t)} \right)^{1-\sigma} \left(\frac{C_H(s^t)}{C_H(s^{t+1})} \right) \Bigg[\frac{r(s^{t+1})}{P_H(s^t)} - \left(\frac{k(s^{t+1})}{k(s^t)} \;-\; (1-\delta) \right)^{\frac{1}{\psi}} \;+\; \frac{1}{\psi} \left(\frac{k(s^{t+1})}{k(s^t)} \;-\; (1-\delta) \right)^{\frac{1}{\psi}-1} \left(\frac{k(s^{t+1})}{k(s^t)} \right) \Bigg] . \qquad (B6)$$

The goods market clearing condition, derived by aggregating over all firms, $i \in [0,1]$, is given by equation $(B7)$,

$$C_H(s^t) \;+\; C_H^*(s^t) \;+\; x(s^t) \;=\; z(s^t) \; K(s^{t-1})^{\alpha} \; L(s^t)^{1-\alpha} \; , \qquad (B7)$$

where $L(s^t)$ and $K(s^{t-1})$ are total employment and capital aggregated over all identical households. The bond-market clearing condition is given by,

$$b_H(s^t) \;+\; b_F(s^t) \;= 0 \; , \; \forall s^t \; , \qquad (B8)$$

where all state-contingent bonds are denominated in units of home currency. Thus, there is a zero net supply of each contingent bond. The money-market clearing condition requires that money demanded by households exhausts total supply,

$$m(s^t) \;=\; M(s^t) \; , \qquad (B9)$$

where $m(s^t)$ is the money demanded by the representative household.

Factor markets must clear each period, and the aggregate consistency conditions must be satisfied. These conditions are summarized below,

$$L(s^t) = \int_{j=0}^{1} l(j, s^t)\, dj \ , \qquad K(s^{t-1}) = \int_{j=0}^{1} k(j, s^{t-1})\, dj \ . \tag{B10}$$

The total capital and labor supplied by the many identical households, indexed over a unit continuum $j \in [0, 1]$, aggregate so that total factor quantities satisfy the demand of firms.

The system of equilibrium equations that characterize the simulation path are detailed as follows. The 15 variables comprising the system include, $l(s^t)$, $l^*(s^t)$, $w(s^t)$, $w^*(s^t)$, $K(s^t)$, $K^*(s^t)$, $P_H(s^{t-1})$, $P_H^*(s^{t-1})$, $P_F^*(s^{t-1})$, $P_F(s^{t-1})$, $C_H(s^t)$, $C_H^*(s^t)$, $C_F^*(s^t)$, $C_F(s^t)$ and $e(s^t)$. The equilibrium equations are given by the home and foreign counterparts of equations, ($B3$), ($B5$), ($B6$), ($B7$), (12), (19) and (28). There are four pricing rules, and equation (35) outlines the two respective pricing rules of home-economy firms. An analogous condition exists for the foreign pricing rules. The nominal variables are deflated by the pre-shock money supply, so that the simulation system is stationary.

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Table 1
International Prices and Exchange Rates: Volatility and Persistence

	Data	Benchmark	Money Only	Productivity Only	CKM Results
Std. Deviation Relative to GDP					
Real Exchange Rate	4.44	.97	1.31	.80	.41
		(.08)	(.10)	(.08)	(.11)
Nominal Exchange Rate	4.74	.86	1.77	.38	.71
		(.15)	(.31)	(.04)	(.22)
Terms of Trade	1.77	1.07	1.28	.91	—
		(.12)	(.10)	(.09)	
Deviations from LOP	1.99	.56	1.28	0.0	—
		(.06)	(.10)	(0.0)	
P^*/P	.74	.91	1.90	.42	.33
		(.15)	(.32)	(.04)	(.14)
Autocorrelation					
Real Exchange Rate	.85	.35	-.18	.65	.20
		(.12)	(.09)	(.08)	(.19)
Nominal Exchange Rate	.83	.69	.71	.65	.82
		(.08)	(.09)	(.08)	(.06)
Terms of Trade	.83	.46	.05	.65	—
		(.10)	(.11)	(.08)	
Deviations from LOP	.49	-.08	-.09	0.0	—
		(.10)	(.11)	(0.0)	
P^*/P	.90	.72	.75	.65	.49
		(.07)	(.07)	(.08)	(.10)

NOTES:

Simulation results are average moments of the artificial data over 1,000 replications, each simulating the model over the 92-quarter sample period. Moments are calculated from logged and Hodrick-Prescott (1980) filtered data. The mean standard deviation for each moment over the 1,000 replications are placed in parentheses. Results from Chari *et al.* (1997) are based on one-period price stickiness, with both productivity and monetary shocks.

Table 2
Key Correlations

Correlation	Data	Benchmark	Money Only	Productivity Only	CKM Results
NER, ToT	.40	.21	-.35	1.0	—
		(.15)	(.08)	(0.0)	
RER, NER	.99	.51	.28	1.0	.27
		(.13)	(.07)	(0.0)	(.12)
$RGDP, RGDP^*$	.52	-.13	.07	-.41	.41
		(.13)	(.11)	(.16)	(.10)
C, C^*	.27	.26	-.01	.41	.30
		(.15)	(.11)	(.16)	(.11)

NOTES:
Simulation results are average moments of the artificial data over 1,000 repetitions, each replicating the model over the 92-quarter sample period. Moments are calculated from Hodrick-Prescott (1980) filtered data. The mean standard deviation for each moment over the 1,000 replications are placed in parentheses. Results from Chari *et al.* (1997) are based on one-period price stickiness, and including both types of shocks.

Table 3
Business-Cycle Variables: Volatility and Persistence

	Data	Benchmark	Money Only	Productivity Only	CKM Results
Std. Deviation Relative to GDP					
Consumption	.79	.36	.40	.34	.44
		(.03)	(0.0)	(.04)	(0.0)
Investment	3.28	3.28	3.28	3.28	3.28
		(.10)	(.01)	(.11)	(.08)
Employment	.72	1.07	1.51	.54	1.52
		(.09)	(0.0)	(.06)	(0.0)
Autocorrelation					
Consumption	.85	.50	-.08	.68	-.09
		(.11)	(.10)	(.08)	(.11)
Investment	.95	.21	-.08	.61	-.09
		(.11)	(.10)	(.09)	(.11)
Employment	.91	-.04	-.09	.61	-.09
		(.10)	(.10)	(.08)	(.11)
Real GDP	.87	.30	-.09	.62	-.09
		(.11)	(.10)	(.09)	(.11)

NOTES:

Simulation results are average moments of the artificial data over 1,000 replications, each simulating the model over the 92-quarter sample period. Moments are calculated from logged and Hodrick-Prescott (1980) filtered data. The mean standard deviation for each moment over the 1,000 replications are placed in parentheses. Results from Chari *et al.* (1998) are based on one-period price stickiness, with only monetary shocks. Results presented in Chari *et al.* (1997) are not available for business-cycle variables that include both types of shocks.