Openness and the Persistence of Real Exchange Rates:
Calvo versus Taylor Price Settings

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We analyze the interactions between openness and two well-known nominal price settings—the Calvo and the Taylor price settings. We show that the two price settings produce different mechanisms for the propagation of monetary shocks in open macro economies, regardless of parameterizations of the frequency of price adjustment. In particular, we find that the Taylor staggered price setting does not generate endogenous persistence of real exchange rates in the standard DGE model, while the Calvo price setting results in strong internal propagation mechanisms. Further, we find that under the assumption of complete openness, various nominal and real frictions that dampen the response of marginal cost do not generate endogenous persistence in real exchange rates.

Keywords: Calvo price setting, Taylor price setting, openness, endogenous persistence.

JEL Classification: E30, E32, F41, F44.

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I. Introduction

Two well-known nominal price settings, the Taylor staggered price setting [Taylor (1980)] and the Calvo price setting [Calvo (1983)], induce price and wage stickiness and have been widely used to study persistent real effects of monetary shocks in a class of dynamic general equilibrium (DGE) models. The prevalent presumption in the literature was that both price settings in those models would generate similar dynamics of aggregate activity such as output and real exchange rates. However, Kiley (2002) and Moon (2010) show that the Calvo price setting generates more persistent output movements than the Taylor staggered price setting in the typical DGE model, when the frequency of price adjustment is assumed to be the same in the two price settings. On the other hand, Dixon and Kara (2006) consider various criteria for comparing Taylor and Calvo price settings and argue that both price settings generate similar autocorrelation of output if one chooses the right parameterization for comparison.

The present paper deviates from this line of research and shows that the two price settings produce different propagation mechanisms of monetary shocks in open macro economies, regardless of parameterizations about frequency of price adjustment. In particular, we focus on the role of openness in the propagation of monetary shocks and investigate both analytically and quantitatively interactions between openness and these two nominal price settings.

Both Calvo and Taylor nominal price settings can be characterized by two equations: One is the individual price equation at the firm level. The other is the aggregate price index. Under the Taylor staggered price setting, a fraction

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(say, $1/N$) of firms set their prices in each period and fix them for $N$ periods before reoptimizing them. On the other hand, a firm can renew its price with a constant probability (say, $1/N$) in each period and thus faces uncertainty regarding the timing of reoptimizing its price under the Calvo price setting. This uncertainty is reflected in the construction of the aggregate price index and places in a fundamental difference between the two price settings. For example, the Taylor aggregate price index is just a simple average of prices renewed over the past $N$ periods since all individual price settings have the same length of the duration of the contract. On the other hand, the Calvo aggregate price index is a distribution of current and all the past individual prices that had never been renewed. Here weights in the distribution reflect uncertainty of timing of reoptimizing price. Consequently, the Calvo aggregate price index includes prices renewed even in the far past, while the Taylor price setting does not include prices beyond the duration of the contract. This different way of aggregating individual prices due to the uncertainty about the timing of reoptimizing price produces the aggregate index inertia in the Calvo price setting and affects real exchange rate dynamics different from the Taylor price setting.

We find that the Taylor staggered price setting does not generate endogenous persistence of real exchange rates in the standard DGE model with completeness openness, while the Calvo price setting produces strong internal propagation mechanisms. When the economy is completely open, this result holds true even if we add various real and nominal frictions such as input-output production structure and sticky wages known to improve endogenous persistence of output movements in closed economies through mechanisms which dampen the response of marginal cost to monetary shocks [See for example, Anderson (1998), Christiano et al. (2005), Huang and Liu (2002), and Huang and Liu (2003)]. The main reason is that openness shuts down those propagation mechanisms in models with the Taylor price setting, regardless of the length of contract periods. Finally, our result suggests that the behavior of real exchange rate persistence would be very sensitive with the
degree of openness in models with the Taylor staggered price settings and sheds new light on the literature with the estimation of parameters in a typical DGE open economy model where price rigidity is induced by either one of the two price settings.

II. A Model of Nominal Price Settings

We present a standard two-country monetary general equilibrium model that features monopolistic competition in the goods market to study the roles of nominal price rigidity specifications in the determination of real exchange rates. In order to obtain fluctuations in the real exchange rate, we further assume that international goods markets are segmented between two countries as do Chari et al. (2002). We introduce either the Calvo or Taylor nominal price settings in the goods market in which the elasticity of relative price is endogenously determined and compare roles of the Taylor price setting to those of the Calvo price setting for the real exchange rate dynamics, focusing on the interaction between these price settings and openness. In what follows, we mainly describe the economy of the home country. Foreign quantities and prices are attached an asterisk superscript.

1. Households

There are two countries in the world, home \((H)\) and foreign \((F)\), and a continuum of households indexed by \(n \in [0, 1]\) live in each country. The home household \(n\) has preference given by the expected infinite life-time utility function

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) U(C(n, s^t), M(n, s^t)/P(s^t), L(n, s^t))
\]
where $C(n)$ denotes a composite consumption index, $M(n)/P$ real money balances, and $L(n)$ labor supply for home household $n$, and $0 < \beta < 1$ denotes the discount factor. Here, $s^t = (s^{t-1}, s_t)$ is the history of past states up to time $t$. $\pi(s^t)$ is a probability of occurring $s^t$ as of time 0.

Both home and foreign households can trade state contingent nominal discount bonds denominated in the home currency. Let $Q(s^{t+1} \mid s^t)$ denote the nominal price (in home currency units) of one home state contingent bond paying one unit of home currency at $s^{t+1}$ and 0 otherwise. $B(n, s^{t+1} \mid s^t)$ denotes the number of home state contingent bonds held by the home household $n$ between $s^t$ and $s^{t+1}$. The home household $n$’s budget constraint (in home currency units) is:

$$\forall s_t, s_t^{t+1}$$

$$P(s^t) Y(n, s^t) + M(n, s^t) + \hat{\delta} Q(s^{t+1} \mid s^t) B(n, s^{t+1} \mid s^t)$$

$$\hat{\delta} W(s^t) L(n, s^t) R^k(s^t) K(n, s^{t-1}) + M(n, s^{t-1}) + B(n, s^t) + P(n, s^t) + T(n, s^t)$$

where $M(n, s^t)$ represents nominal money balances held by $n$ at $s^t$; $W(s^t)$ is the nominal wage; $\Pi(n, s^t)$ represents profits of home intermediate producers; $T(n, s^t)$ denotes nominal transfers paid from the home government, $R^k(s^t)$ is the nominal rental rate on capital service, and $K(n, s^{t-1})$ is the amount of capital stock held by $n$ at the beginning of $s^t$. The final good $Y(n, s^t)$ can be either consumed or invested according to the following technology:

$$Y(n, s^t) = C(n, s^t) + K(n, s^t) - (1 - \delta) K(n, s^{t-1}) + \chi \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right) K(n, s^{t-1})$$

where $\delta$ is the capital depreciation rate, $I(n, s^t) = K(n, s^t) - (1 - \delta) K(n, s^{t-1})$ and $\chi \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right)$ is a convex function of the capital
adjustment cost.

Households are assumed to take prices of goods and labor as given. Then, the household $n$'s first order conditions can be derived by maximizing its expected utility subject to the budget constraint (1)

$$Q(s^{t+1} | s^t) = \beta \frac{\pi(s^{t+1})}{\pi(s^t)} \frac{U_c(n, s^{t+1})}{P(s^{t+1})} / \frac{U_c(n, s^t)}{P(s^t)}$$

(3)

$$\frac{U_in(n, s^t)}{P(s^t)} = \frac{U_c(n, s^t)}{P(s^t)} - \beta \sum_{s'} \pi(s^{t+1} | s^t) \left[ \frac{U_c(n, s^{t+1})}{P(s^{t+1})} \right]$$

(4)

$$U_c(n, s^t) \left[ 1 + \chi \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right) K(n, s^{t-1}) \right]$$

(5)

$$= \beta \sum_{s'} \pi(s^{t+1} | s^t) \left\{ U_c(n, s^{t+1}) \left[ \frac{R^k(s^{t+1})}{P(s^{t+1})} + (1 - \delta) + \chi \left( \frac{I(n, s^{t+1})}{K(n, s^t)} \right) \right] \right\}$$

$$U_i(n, s^t) = \frac{U_i(n, s^t)}{P(s^t)} W(s^t)$$

(6)

where $\pi(s^{t+1} | s^t) = \pi(s^{t+1})/\pi(s^t)$ is the probability of state $s^{t+1}$ given state $s^t$ and $\chi' \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right) = \partial \chi' \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right) / \partial K(n, s^{t-1})$. Equation (3) represents home nominal intertemporal Euler equation expressed in the home currency for each state. The price $Q(s^{t+1} | s^t)$ of state contingent home nominal bond should be equal to the marginal rate of substitution in home consumption between $s^t$ and $s^{t+1}$ weighted by the change in purchasing power of the home currency. Or, it should be equal to the marginal rate of substitution in foreign consumption weighted by the change in purchasing power of the foreign currency once converted into the home
currency. Equation (4) represents home money market clearing condition: the marginal rate of substitution between consumption and real money balances should be equal to the user costs of holding an extra unit of real balances for one period. Equation (5) represents household’s optimal investment decision and (6) represents labor leisure trade-off condition.

2. Firms and Nominal Price Settings

A competitive representative firm produces a final composite good \( X(s^t) \) using a continuum of home and foreign intermediate inputs \( X_H(i, s^t) \) and \( X_F(i, s^t) \) indexed by \( i \in [0, 1] \) according to the following CES technology:

\[
X(s^t) = \left[ \frac{1}{h^\theta} X_H(s^t) \left( \frac{\theta - 1}{\theta} \right) + (1 - h)^\theta X_F(s^t) \left( \frac{\theta - 1}{\theta} \right) \right]^{\frac{\theta}{\theta - 1}} \tag{7}
\]

where \( X_H(s^t) = \left[ \int_0^1 (X_H(i, s^t))^\nu di \right]^{\frac{1}{\nu - 1}} \) denotes a composite home intermediate good and \( X_F(s^t) = \left[ \int_0^1 (X_F(i, s^t))^\nu di \right]^{\frac{1}{\nu - 1}} \) denotes a composite foreign intermediate good. \( \theta \) denotes the elasticity of substitution between the home and foreign composite goods, \( \nu \) denotes the elasticity of substitution among differentiated goods, and \( h \) denotes an expenditure share for the home composite good and represents the degree of home bias in preferences. The final good producer takes as given the price \( P(s^t) \) of the final good, and prices \( P_H(i, s^t) \) and \( P_F(i, s^t) \) of intermediate differentiated goods produced in both countries. The final good can be consumed or invested by households according to a linear technology: \( X(s^t) = Y(s^t) \). Finally, the demand for home and foreign intermediate good \( i \) can be derived from the profit maximization problem of the final good producer subject to:
where $P_H(s^t) = \left[ \int_0^1 (P_H(i, s^t))^{1-\nu} di \right]^{\frac{1}{1-\nu}}$ denotes the price of the home composite good and $P_F(s^t) = \left[ \int_0^1 (P_F(i, s^t))^{1-\nu} di \right]^{\frac{1}{1-\nu}}$ denotes the price of the foreign composite good. The price of the final good is, then, defined by

$$P(s^t) = \left[ hP_H(s^t)^{1-\theta} + (1 - h)P_F(s^t)^{1-\theta} \right]^{\frac{1}{1-\theta}}$$

(9)

A firm that produces an intermediate good $i$ uses labor and capital services using the following technology:

$$X(i, s^t) = F(L(i, s^t), K(i, s^t)) = K(i, s^t)^{(1-\alpha)} L(i, s^t)^{\alpha}$$

(10)

where $L(i, s^t)$ denotes labor services, $K(i, s^t)$ denotes capital services, and $\alpha$ is the cost share for the labor input. By assuming that firms producing intermediate goods take prices of inputs as given, we can derive marginal cost from the cost minimization problem

$$MC(s^t) = (\alpha)^{-\alpha} ((1 - \alpha))^{-(1-\alpha)} R^{(1-\alpha)} (s^t) W^{\alpha} (s^t)$$

(11)

Here, all firms face the same marginal cost because of assumptions of symmetry and competitive factor markets, that is $MC(i, s^t) = MC(s^t)$ for all $i \in [0, 1]$. We further assume that markets for intermediate goods are segmented across countries so that consumers cannot engage in arbitrage.
activities. Under this assumption, firms can price discriminate across countries. We finally assume that firms set their prices in the consumer's currency (local currency pricing).

We now introduce each of the two price settings: the Taylor and Calvo price settings. Under the Taylor staggered price setting, in each period a fraction $\frac{1}{N}$ of firms set new prices before monetary shocks are realized and fix them for $N$ periods. In particular, firms with type $i \in [0, 1/N]$ set new prices in $t$, $t + N$, $t + 2N$, $\cdots$ while firms with type $i \in [1/N, 2/N]$ set new prices in $t + 1$, $t + 1$, $t + 2N + 1$, $\cdots$ and so on. Then, in period $t$ a firm $i$ maximizes its expected profit by choosing home price $P_H^T(i, s^t)$ in home currency for sales to home market and foreign price $P_H^{sT}(i, s^t)$ in foreign currency for sales to foreign market subject to

$$X(i, s^t) = X_H^d(i, s^t) + X_H^{sd}(i, s^t):$$

$$\max_{P_H^T(i, s^t), P_H^{sT}(i, s^t)} \sum_{t=1}^{t+N-1} \sum_{s'} Q(s^\tau \mid s^{t-1}) [P_H^T(i, s^t) X_H^d(i, s^\tau) + e(s^\tau) P_H^{sT}(i, s^t) X_H^{sd}(i, s^\tau) - MC(s^\tau)(X_H^d(i, s^\tau) + X_H^{sd}(i, s^\tau))]$$

where superscript $T$ denotes prices under the Taylor staggered price setting. The optimal conditions for the prices of the intermediate good $i$ at $t$ are derived from the above problem

$$P_H^T(i, s^t) = \frac{\nu}{\nu - 1} \frac{\sum_{\tau=t}^{t+N-1} \sum_{s'} Q(s^\tau \mid s^{t-1}) [MC(s^\tau)(X_H^d(i, s^\tau))]}{\sum_{\tau=1}^{t+N-1} \sum_{s'} Q(s^\tau \mid s^{t-1}) [X_H^d(i, s^\tau)]}$$

$$P_H^{sT}(i, s^t) = \frac{\nu}{\nu - 1} \frac{\sum_{\tau=t}^{t+N-1} \sum_{s'} Q(s^\tau \mid s^{t-1}) [MC(s^\tau)(X_H^{sd}(i, s^\tau))]}{\sum_{\tau=1}^{t+N-1} \sum_{s'} Q(s^\tau \mid s^{t-1}) [X_H^{sd}(i, s^\tau)]}$$
By assuming that firms set the same prices within the cohort, the composite prices $P^T_H(s^t), P^s_T(s^t)$ can be simplified to

$$P^T_H(s^t) = \left[ \frac{\sum_{I(i) = 1}^{N} (P^T_H(I(i), s^t + I(i) - 1))^{1-\nu}}{N} \right]^{\frac{1}{1-\nu}},$$

$$P^s_T(s^t) = \left[ \frac{\sum_{I(i) = 1}^{N} (P^s_T(I(i), s^t + I(i) - 1))^{1-\nu}}{N} \right]^{\frac{1}{1-\nu}}$$  \hspace{1cm} (14)$$

where $I(i)$ is an integer indicator. $I(i) = 1$ when $i \in [0, 1/N]$, $I(i) = 2$ when $i \in [1/N, 2/N]$, and so on.

Under the Calvo price setting, in each period $t$ a monopolistic firm can choose its prices with a constant probability of $1 - \phi_p$. The ability of being able to renew its prices is independent across households and over time. Then, the home firm $i$ that can reoptimize its prices at time $t$ maximizes its expected profit by choosing $P^C_H(i, s^t)$ in the home currency for sales to the home market and $P^s_C(i, s^t)$ in the foreign currency for sales to the foreign market subject to $X(i, s^t)$:

$$\max_{\{P_H^C(i, s^t), P^s_H(i, s^t)\}} \sum_{t=1}^{\infty} (\phi_p)^{t-1} \sum_{s^t} Q(s^t | s^{t-1})$$

$$\left\{ P_H^C(i, s^t) X_H^d(i, s^t) + e(s^t) P_H^s(i, s^t) X_H^{ds}(i, s^t) - MC(S^*) (X_H^d(i, s^t) + X_H^{ds}(i, s^t)) \right\}$$  \hspace{1cm} (15)$$

where $(\phi_p)^{t-1}$ is a probability of not being able to reoptimize its prices at time $\tau - t$ as of time $t$ and superscript $C$ denotes prices under the Calvo price setting. Now, the optimal conditions for the prices of the intermediate good $i$ at $t$ can be derived.
We assume that producers that are able to reoptimize their prices at $t$ set the same prices $\bar{P}_H^C(s^t) = P_H^C(i, s^t)$ and $\bar{P}_H^{s,C}(s^t) = P_H^{s,C}(i, s^t)$. The composite prices at $s^t$ under the Calvo nominal price setting read

$$P_H^C(s^t) = \frac{\nu}{\nu - 1} \sum_{\tau=t}^{\infty} (\varphi_p)^{t-\tau} \sum_{s^{\tau}} Q(s^{\tau} | s^{t-1}) [MC(s^{\tau}) X^d(i, s^{\tau})]$$

$$P_H^{s,C}(s^t) = \frac{\nu}{\nu - 1} \sum_{\tau=t}^{\infty} (\varphi_p)^{t-\tau} \sum_{s^{\tau}} Q(s^{\tau} | s^{t-1}) [e(s^{\tau}) X^d(i, s^{\tau})]$$

where $(1 - \varphi_p)$ represents the fraction of firms in the economy that reoptimize their prices at time $t$.

3. Monetary Policy

The home government issues home currencies and runs a balanced budget in each period. The home money stock evolves according to

$$\frac{M(s^t)}{M(s^{t-1})} = G(s^t)$$

where $G(s^t)$ is the growth rate at $s^t$ and evolves by
\[ g(s^t) = (1 - \rho)\bar{g} + \rho_m g(s^{t-1}) + u(s^t) \]  
(19)

where \( g(s^t) = \log G(s^t) \). Nominal transfers are given by \( T(s^t) = M(s^t) - M(s^{t-1}) \).

4. Equilibrium

An equilibrium for this economy is a collection of quantities for the home and foreign governments \( M(s^t), T(s^t), M^*(s^t), T^*(s^t) \), quantities for home and foreign households \( C(n, s^t), L(n, s^t), K(n, s^t), M(n, s^t), T(n, s^t), B(n, s^t), C^*(n, s^t), L^*(n, s^t), K^*(n, s^t), M^*(n, s^t), T^*(n, s^t), B^*(n, s^t) \), indexed by \( n \in [0, 1] \); quantities for the home and foreign final good producers \( X(s^t), X^*(s^t) \); quantities for intermediate goods producers \( L(i, s^t), K(i, s^t), X(i, s^t), L^*(i, s^t), K^*(i, s^t), X^*(i, s^t) \) indexed by \( i \in [0, 1] \); together with prices \( P(s^t), W(s^t), R(s^t), P^*(s^t), W^*(s^t), R^*(s^t), Q(s^{t+1} | s^t) \) and \( P_H(i, s^t), P^*_H(i, s^t), P_F(i, s^t), P^*_F(i, s^t) \) for \( i \in [0, 1] \); nominal exchange rate \( e(s^t) \) that satisfy the following conditions: for each \( s^t \),

- Optimality of households' behavior: taking prices as given, household \( n \)'s quantities solve its problem for each \( n \in [0, 1] \);
- Optimality of intermediate firms' behavior: taking all prices except its own as given, firm \( i \)'s quantities and prices solve its problem for each \( i \in [0, 1] \);
- Optimality of Final firms' behavior: taking the prices as given, the final firm's quantities solve its problem;
- Government's budget balance: the government runs a balanced budget;
- All markets clear including goods markets, labor markets, capital markets, and bonds markets.
5. Determination of Real Exchange Rates

From equation (3) and the foreign analogous, one can derive the following optimal risk sharing condition:

$$\frac{P^*(s^{t+1})(s^{t+1})}{P(s^{t+1})} \frac{Uc(s^{t+1})}{Uc^*(s^{t+1})} = \frac{P^*(s^t)(s^t)}{P(s^t)} \frac{Uc(s^t)}{Uc^*(s^t)}$$

This condition holds regardless of price flexibility and assumptions of money demand. It can be further simplified so that the real exchange rate is equal to the marginal rate of substitution between home and foreign consumption:

$$\frac{P^*(s^t)\psi(s^t)}{P(s^t)} = k \frac{Uc^*(s^t)}{Uc(s^t)}$$

(21)

where \(k = \frac{P^*(s^0)\psi(s^0)}{P(s^0)} \frac{Uc(s^0)}{Uc^*(s^0)}\). When PPP holds the consumption is equalized across countries. In this model the real exchange rate fluctuates because the law of one price does not hold for each intermediate good \(i\) due to the assumption of the international goods market segmentation.

6. A Comparison: Calvo versus Taylor Price Settings

Let us compare characteristics of the Taylor price setting to the Calvo price setting. If the probability \(1 - \varphi_p\) of being able to reoptimize price in each period under the Calvo price setting is equal to \(1/N\) under the \(N\)-period Taylor staggered settings then the same fraction \(1 - \varphi_p = 1/N\) of firms can change their prices in each period in both price settings. For example, if prices are preset only one period in advance in a synchronized way \((N = 1\) or \(\varphi_p = 0\)) then there is no difference between the two price settings because
equations (13)-(14) and (16)-(17) become identical. That is, prices respond identically to current monetary shocks in both settings. However, when prices are fixed for more than one period, the apparent difference between equations (13) and (16) can be placed on whether or not the timing of reoptimizing price is known. For example, suppose $N = 4$. Then, a firm that optimizes its prices at $t$ would hold it until $t + 3$ and renew it at $t + 4$ under the Taylor staggered price setting. Hence, the probability of not being able to reoptimize it is equal to one at $t + 1$, $t + 2$, and $t + 3$, but it is zero after $t + 3$. On the other hand, each firm faces a constant probability $\varphi_p$ of not being able to reoptimize its price in each period under the Calvo price setting. The probability of not being able to reoptimize it for two consecutive periods is $\varphi_p^2$, the probability for three consecutive periods is $\varphi_p^3$, and so on. As shown in (13) and (16), firms take into account of these probabilities when they set their prices: Firms discount all future expected marginal costs by $\varphi_p^{t-t}$ over time as of $t$ under the Calvo price setting, while the probability $\varphi_p^{t-t}$ is either one or zero in the Taylor price setting. This implies that firms put less weights on changes in future expected marginal costs within the $N$ period and more on them beyond that period in determining their optimal prices under the Calvo setting than under the Taylor setting. We call this front-loading incentives.

The uncertainty on the timing of reoptimizing price is also reflected in the construction of the aggregate index. As shown in (14), the composite prices under the Taylor staggered price setting are a simple average of individual prices multiplied by probability 1 during the duration of the contract and 0 beyond it. That is, the effects of prices renewed in each period on the composite price indexes are the same over the duration of the contract and immediately disappear after the contract expires. Therefore, the aggregate index itself does not have a mechanism for endogenous persistence beyond exogenously given contract period, $N$. On the other hand, the composite prices at time $t$ under the Calvo price setting are a weighted average of all
individual prices that have never had a chance of reoptimizing price. As shown in (17), weight \( \varphi^\tau \) implies that price is set in period \( t - \tau \) but never reoptimized since then. Therefore, the effects of prices on the composite price indexes are asymmetric under the Calvo price setting and geometrically die out over time. This partial adjustment creates a large amount of extra nominal rigidities that affect real exchange rate dynamics in qualitatively and quantitatively different ways between the two types of price settings. We call this index inertia.

III. Real Exchange Rate Persistence and Openness

In this Section, we analytically investigate the effects of nominal price rigidities for the real exchange rate dynamics. In particular, we focus on interactions between openness and the price settings for the propagation of monetary shocks. From now on, we suppress notation for state.

1. Taylor Staggered Price Setting

We first consider the Taylor staggered price setting. Let \( P^T_H(1, t) \) and \( P^*_T_H(1, t) \) denote home and foreign prices set by type 1 home firms right after time \( t \) monetary shocks are realized. Analogously, type 1 foreign firms set their home and foreign prices denoted by \( P^T_H(1, t) \) and \( P^*_T_H(1, t) \). Under this price setting, a fraction \( 1/N \) of home firms set \( P^T_H(1, t) \) and \( P^*_T_H(1, t) \) at \( t \); another fraction \( 1/N \) set \( P^T_H(2, t - 1) \) and \( P^*_T_H(2, t - 1) \) at \( t - 1 \), and so on. Then, the log-linearized versions of prices in equation (13) and foreign counterparts are
From now on, small letters represent log deviations of the corresponding capital letters. For deriving these prices, we assume that steady state money growth rates are zero. For example, \( mc \) represents the log deviation of marginal cost. Since there are \( N \) types of home and foreign firms, the corresponding composite prices are

\[
\begin{align*}
P^T_H(1, t) &= \frac{1}{\sum_{\tau=t}^{t+N-1} \beta^{\tau-t}} \sum_{\tau=t}^{t+N-1} \beta^{\tau-t} E_t[mc]_\tau, \\
P^*_H(1, t) &= \frac{1}{\sum_{\tau=t}^{t+N-1} \beta^{\tau-t}} \sum_{\tau=t}^{t+N-1} \beta^{\tau-t} E_t[mc^*_\tau], \\
P^*_H(1, t) &= \frac{1}{\sum_{\tau=t}^{t+N-1} \beta^{\tau-t}} \sum_{\tau=t}^{t+N-1} \beta^{\tau-t} E_t[mc^*_\tau], \\
P^T_H(1, t) &= \frac{1}{\sum_{\tau=t}^{t+N-1} \beta^{\tau-t}} \sum_{\tau=t}^{t+N-1} \beta^{\tau-t} E_t[mc^*_\tau - e_\tau] \quad \text{(22)}
\end{align*}
\]

Using the definition of the aggregate price index in equation (9), we can derive the log-linearized real exchange rate

\[
\begin{align*}
P^T_{H,t} &= \frac{1}{N} \sum_{\tau=1}^{N} P^T_H(\tau, t + \tau - 1), \quad P^*_H(1, t) = \frac{1}{N} \sum_{\tau=1}^{N} P^*_H(\tau, t + \tau - 1), \\
P^T_{F,t} &= \frac{1}{N} \sum_{\tau=1}^{N} P^T_F(\tau, t + \tau - 1), \quad P^*_F(1, t) = \frac{1}{N} \sum_{\tau=1}^{N} P^*_F(\tau, t + \tau - 1) \quad \text{(23)}
\end{align*}
\]

Using the definition of the aggregate price index in equation (9), we can derive the log-linearized real exchange rate

\[
rq_t = e_t + p^*_t - p_t = h (e_t + p^*_F - p^*_H) + (1-h) (e_t + p^*_H - p^*_F) \quad \text{(24)}
\]

The real exchange rate can be rewritten using (22) and (23)
Equation (25) says that if the economy is completely open \( (h = 0.5) \) then the Taylor staggered price setting itself does not generate endogenous persistence in the real exchange rate regardless of the length of the contract periods. That is, endogenous persistence in the real exchange rate depends critically on the degree of openness under the Taylor staggered price setting. This result suggests that any nominal and real frictions which aim at dampening the response of marginal cost to monetary shocks would not generate endogenous persistence in real exchange.

2 Calvo Price Setting

We now consider the Calvo price setting. Analogous to (22), we derive log-linearized home and foreign individual prices from (16) and foreign analogous

\[
\overline{p}_H(t) = (1 - \beta \varphi_p) mc_t + \beta \varphi_p E_t \left[ \overline{p}_H(t+1) \right],
\]

\[
\overline{p}^*_H(t) = (1 - \beta \varphi_p) (mc_t - e_t) \beta \varphi_p E_t \left[ \overline{p}^*_H(t+1) \right]
\]

\[
\overline{p}_F(t) = (1 - \beta \varphi_p) (mc_t + e_t) + \beta \varphi_p E_t \left[ \overline{p}_F(t+1) \right],
\]

\[
\overline{p}^*_F(t) = (1 - \beta \varphi_p) mc_t + \beta \varphi_p E_t \left[ \overline{p}^*_F(t+1) \right]
\]

Equation (26) says that \( \overline{p}^*_H(t) \) is the expected present value current and future marginal cost. That is, the Calvo price setting extends the effects of front-loading incentives to the entire future periods because there always exists
a possibility that firms may not have an opportunity to renew their prices in the future.

Analogous to (23), we now derive the log-linearized composite prices,

\[ p^C_{Ht} = (1 - \varphi_p) p^C_H(t) \quad \text{and} \quad p^{*C}_{Ht} = (1 - \varphi_p) p^{*C}_H(t) \]

\[ p^C_{Ft} = (1 - \varphi_p) p^C_F(t) \quad \text{and} \quad p^{*C}_{Ft} = (1 - \varphi_p) p^{*C}_F(t) \]

In contrast to the Taylor aggregate price indexes in (23), the Calvo aggregate price indexes extend the effects of index inertia to the entire past periods because some firms would not have opportunities to reoptimize their prices over the entire past periods. Note that the extension of the contract periods to the entire periods due to the uncertainty about the timing of reoptimizing price generates a large amount of price stickiness and thus the responses of real variables to a monetary shock become more rigid. This channel is a key mechanism that makes differences between the two price settings in qualitative and quantitative manners.

Now combining (26)-(27) with definitions of home and foreign aggregate price indexes, the log-linearized real exchange rate is defined by

\[ r_q(t) = (2h - 1) \frac{1}{1 + \beta \varphi_p^2} \left[ (1 - \varphi_p) (1 - \beta \varphi_p) E_t[m e^*_t + e_t - m e^*_t] \right] \]

\[ + \frac{1}{1 + \beta \varphi_p^2} (\beta \varphi_p E_t [r_{q_{t-1}}] + \varphi_p r_{q_{t-1}}) + \frac{1}{1 + \beta \varphi_p^2} [\beta \varphi_p (e_t - E_t[e_{t+1}]) + \varphi_p (e_t - e_{t-1})] \]

In contrast to equation (25), the real exchange rate now contains an additional term, \( \frac{1}{1 + \beta \varphi_p^2} (\beta \varphi_p E_t [r_{q_{t-1}}] + \varphi_p r_{q_{t-1}}) \), which is independent of the degree of openness. This term is a source of endogenous persistence in real exchange rate movements even if the world economy is completely open. For example, by assuming that \( \beta = 1 \) and \( h = 0.5 \), one can easily show that
the first order autocorrelation coefficient in the real exchange rate is $\varphi_p$. As
the constant probability $1 - \varphi_p$ of being able to reoptimize prices in each
period becomes smaller the real exchange rate becomes more persistent.
Interestingly, equation (28) also suggests that the nominal and real frictions
which are known to improve endogenous persistence in output through
mechanisms of dampening the response of marginal cost are sensitive to the
degree of openness, similar to the case of the Taylor price setting.

3. Index Inertia versus Front-Loading Incentives

We show that the main difference between the two price settings is due to
the uncertainty about the timing of reoptimizing price which affects both the
determination of individual prices and aggregate indexes. In this subsection we
decompose the effects of this uncertainty on the real exchange rate dynamics
into two: front-loading incentives and index inertia. For this purpose, we
consider two hybrid models. One is the model with a combination of the
individual price settings in equation under the Taylor contract and the Calvo
aggregate price indexes. The other is the model with a combination of the
individual price settings under the Calvo contract and the Taylor price indexes.
The first model can be used to investigate the effect of index inertia on the
real exchange rate dynamics, while the second model can be used to
investigate the effect of front-loading incentives.

We obtain the first hybrid model by combining (22) and (27)

$$
\begin{align*}
\bar{r}_t &= \varphi_p \bar{r}_{t-1} + (2h-1)(1-\varphi_p) \frac{1}{N} \sum_{t=1}^{N} \beta^{t-1} E_t \left[ mc_{t+\tau-1} - mc_{t+\tau-1} + e_{t+\tau-1} \right] \\
&\quad + \varphi_p (\epsilon_t - \epsilon_{t-1}) + (1-\varphi_p) \frac{1}{N} \sum_{t=1}^{N} \beta^{t-1} (\epsilon_t - E_t [\epsilon_{t+\tau-1}])
\end{align*}
$$

(29)
Equation (29) shows that the real exchange rate follows an AR(1) process with the first order coefficient of $\varphi_p$, regardless of the degree of openness. Therefore, this hybrid model generates similar real exchange rate dynamics to the model with the Calvo price setting.

Now consider the second hybrid model by combining (23) and (26):

$$r_q = (2h-1) \frac{1 - \beta \varphi_p}{N} \sum_{\tau=1}^{N} \sum_{\eta=1}^{\infty} \beta^{\tau-1} E_{t+1-\tau}[mc^*_{t+\tau} - mc_{t+\tau} + e_{t+\tau}]$$

$$+ \frac{1 - \beta \varphi_p}{N} \sum_{\tau=1}^{N} \sum_{\eta=1}^{\infty} \beta^{\tau-1} (e_{t} - E_{t+1-\tau}[e_{t+\tau}])$$

In contrast to equation (29), the real exchange rate does not exhibit any persistence when $h = 0.5$. That is, the second hybrid model is similar to the model with the Taylor price setting. The results from the two hybrid models imply that the main difference between the Calvo and Taylor price settings in terms of generating endogenous persistence in real exchange rate movements comes from the index inertia: The Calvo aggregate price index contains a significant fraction of individual prices set in far past periods, which produces a significant amount of extra price stickiness and thus increases persistence in the real exchange rate.

**IV. Robustness: Real and Nominal Frictions**

As a robustness check, we consider two popular frictions which contribute to improving endogenous business cycle persistence in closed economies. Those include input-output production structure and sticky nominal wages. As well known, these frictions generate a mechanism that dampens the response of marginal cost to monetary shocks and thus increase persistence in output. Our objective is to understand the role of these frictions in generating endogenous persistence in real exchange rates. In particular, we investigate
how these model features affect the interaction between openness and the two price settings. For this purpose, we add one feature at a time to the benchmark model in Section 2.

1. Input-Output Production Structure

We first introduce an input-output production structure into our benchmark model. Under this modification, a firm that produces an intermediate good \( i \) uses labor and capital services as well as the final good, using the following technology:

\[
X(i, s^l) = F(i, s^l), \quad K(i, s^l), \quad Z(i, s^l) = K(i, s^l)^{1-\alpha_z}L(i, s^l)^{\alpha_z}Z(i, s^l)^{1-\alpha_z}. \quad (31)
\]

where \( Z(i, s^l) \) denotes the composite final good used to produce the intermediate good \( i \) and \( 1-\alpha_z \) is the cost share for the final good. Analogously, the log linearized marginal cost can be derived

\[
m_{c_t} = \alpha_z \alpha w_t + \alpha_z (1-\alpha) r^k_t + (1-\alpha_z)p_t \quad (32)
\]

where \( r^k_t \) is the log of the rental price of capital. The marginal cost tends to less respond to the monetary shocks in this model when price is sticky. Further, this channel leads to some endogenous price stickiness since individual prices move one-for-one with respect to marginal cost. As a result, the response of the real exchange rate may die out more slowly in the model with input-output structure.

To see this in detail, consider difference in the marginal cost in the two countries adjusted by the nominal exchange rate

\[
m_{c_t}^* - m_{c_t} + e_t = \alpha_z \alpha (w^*_t - w_t + \varepsilon_t) + \alpha_z (1-\alpha) (r^*_t r^k_t - r^k_t + \varepsilon_t) + (1-\alpha_z)(p^*_t - p_t + \varepsilon_t) \quad (33)
\]
Combining equation (28) under the Calvo price setting with (33) and assuming \( \beta - 1 \), we obtain

\[
E_t[q_{t+1}] - \frac{1+Y}{1-Y} q_t + q_{t-1} = (2h-1)(1-\varphi_p)(1-\varphi_p) \left[ \alpha z \alpha (w_t^* - w_t + e_t) \right.
\]

\[
+ \alpha z (1-\alpha) (r_t^k - r_t^k + e_t)] - [\varphi_p (e_t - E_t[e_{t+1}]) + \varphi_p (e_t - e_{t-1})]
\]

where \( Y = \frac{\Phi - 1}{\Phi + 1} \) and \( \Phi = \frac{1+\varphi_p^2}{2\varphi_p} - \frac{(2h-1)(1-\varphi_p)(1-\varphi_p)(1-\alpha)}{2\varphi_p} \). Then, using standard methods we obtain the first order coefficient \( \frac{1-\sqrt{Y}}{1+\sqrt{Y}} \) in the real exchange rate holding other things constant. Here, we do not obtain the exact first order coefficient in the real exchange rate because both \( (w_t^* - W_t + e_t) \) and \( (r_t^k - r_t^k + e_t) \) are simultaneously determined. Instead, we investigate how the friction considered affects persistence in the real exchange rate, holding these terms constant, while relegating the complete analysis to the quantitative experiments. Note that the first order coefficient increases as \( \Phi \) decreases. That is, the model with the input-output production structure generates more persistent real exchange rate movements because it mutes the response of the marginal cost to the monetary shocks and thus reduces magnitude of \( \Phi \). Note that this mechanism also relies critically on the degree of openness. Suppose \( h = 0.5 \). Then, input-output structure does not contribute to improving endogenous persistence of real exchange rate dynamics in both price settings (the result from the Taylor price setting is obvious in this case as seen in (25)). Therefore our result implies that openness can significantly attenuate the effects of the friction on the real exchange rate persistence. In the next section, we also conduct our quantitative analysis by varying the value of \( h \).
2. Nominal Wage Rigidities

We now add sticky wages into the previous model: As well known, the marginal cost less responds to monetary shocks in the presence of sticky wages than flexible wages holding other things constant (See also equation (32)). Consequently, sticky wages can lead to endogenous price stickiness and thus increase endogenous persistence in the real exchange. To investigate this, we extend the previous model by assuming that each household $n$ is a monopoly supplier of a differentiated labor input $L(i, n, s^t)$. Household $n$’s labor service is assumed to be transformed into an aggregate labor $L(s^t)$ using the following technology:

$$L(s^t) = \left( \int_0^1 L(n, s^t) \frac{\eta - 1}{\eta} dn \right)^{\eta - 1}$$ (35)

Then, the intermediate goods firm $i$’s demand for labor type $n$ can be derived by minimizing labor cost subject to the production function in (31):

$$L^d(i, n, s^t) = \left[ \frac{W(n, s^t)}{W(s^t)} \right]^{-\eta} L(i, s^t)$$ (36)

where all firms are assumed to face the same unit nominal wage, that is $W(s^t) = W(i, s^t)$ for all $i \in [0, 1]$. Now, the total demand for labor type $n$ can be obtained by aggregating the demand of the intermediate goods producers:

$$L^d(n, s^t) = \left[ \frac{W(n, s^t)}{W(s^t)} \right]^{-\eta} \int_0^1 L(i, s^t) di$$ (37)

where $L(s^t) = \int_0^1 L(i, s^t)$. We now contrast two types of nominal wage contracts: the Taylor versus Calvo nominal wage contract. Under the Taylor
staggered wage contract, a monopolistic household is assumed to set his wage for \( N_w \) periods in a staggered way. In particular, in period \( t \) households with labor type \( n \in [0, 1 / N_w] \) set new wages in \( t, t + N_w, t + 2N_w \), while households with labor type \( n \in [1 / N_w, 2 / N_w] \) set new wages in \( t + 1, t + N_w + 1, t + 2N_w + 1 \), and so on. Then, the household \( n \) for \( n = [0, 1 / N_w] \) maximizes

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) \left[ U(C(n, s^t), \frac{M(n, s^t)}{P(s^t)}, L^d(n, s^t)) \right] \tag{38}
\]

subject to his budget constraint \( \forall s^t, s^{t+1} \)

\[
P(s^t) Y(n, s^t) + M(n, s^t) + \sum_{s^t+1} Q(s^{t+1} \mid s^t) B(n, s^{t+1} \mid s^t) \leq \int_{0}^{t} W(n, s^t) L^d(n, s^t) + R(s^t) K(n, s^{t-1}) + M(n, s^{t-1}) + B(n, s^t) + \Pi(n, s^t) + T(n, s^t)
\]

and the total demand in equation (4-6). The optimality condition for nominal wage for the labor type \( n \) at \( t \) is

\[
W^T(n, s^t) = \frac{1}{\eta-1} \sum_{t=0}^{t+N_w-1} \sum_{s^t} Q(s^t \mid s^{t-1}) \left[ U_1(s^t) L^d(n, s^t) \right]
\]

where \( W^T(n, s^t) = W^T(n, s^{t+1}) = W^T(n, s^{t+N_w-1}) \) and \( U_1(s^t) = (1 - L^d)^{-\mu} \). Equation generates relative wage effects through \( U_1(s^t) \). Note that \( U_1(s^t) = (1 - L^d)^{-\mu} \) when wages are flexible because \( W^T(n, s^t) = W^T(s^t) \). By assuming that households within each cohort are identical the
aggregate nominal wage index can be defined by

\[ W^t(s^t) = \left( \sum_{I(n) = 1}^{N_w} \frac{(W^T(I(n), s^{t+1(n)-1}))^{1-\eta}}{N_w} \right)^{1/(1-\eta)} \] (41)

where \( I(n) \) is an integer indicator. \( I(n) = 1 \) when \( n \in [0, 1/N_w] \), \( I(n) = 2 \) when \( n \in [1/N_w, 2/N_w] \), \ldots, and so on.

Under the Calvo nominal wage setting, in each period \( t \) a monopolistic household can choose a wage with a constant probability of \( 1 - \varphi_w \). The ability of being able to reoptimize its wage is independent across households and over time. Then, the optimal wage at \( s^t \) for households who can renew their wages is

\[ \overline{W}^C(s^t) = \frac{\eta}{\eta-1} \sum_{\tau=t}^{\infty} (\varphi)^{\tau-t} \sum_{s^\tau} Q(s^\tau | s^{t-1}) \left[ \frac{U_i(s^\tau)}{L^d(n, s^\tau)} \right] \] (42)

where \( \overline{W}^C(s^t) \) denotes nominal wages set by households who renewed their nominal wages. Here, \( \overline{W}^C(s^t) \) is determined by discounting the expected future marginal disutilities of working and the marginal utilities of consumption by a factor of \( \varphi_w^{\tau-t} \) (i.e., the probability of not being able to reoptimize at \( \tau \) as of time \( t \)). The aggregate nominal wage index at \( s^t \) under the Calvo nominal wage contract is then defined by

\[ W^C(s^t) = \left[ (1 - \varphi_w) \sum_{\tau=0}^{\infty} \varphi_w^\tau \left( \overline{W}^C(s^{t-\tau}) \right)^{1-\eta} \right]^{1/(1-\eta)} \] (44)

As in the case of the price settings, the apparent difference between (40)-(41) and (42)-(43) is placed on whether or not the timing of reoptimizing
wage is known. Consequently, the Calvo aggregate wage index generates extra amounts of wage stickiness which will contribute to improving endogenous persistence in real exchange rates by dampening the response of marginal cost. Nevertheless, the factor price stickiness itself cannot have persistent real effects on the real exchange rate when the economy is completely open in both price settings.

V. Quantitative Analysis

In this section, we conduct the quantitative analysis.

1. Calibration

Consider a utility function of the form

\[ U(C, L, M/P) = \frac{1}{1-\sigma} \left[ \omega C^{-\phi} + (1-\omega) (M/P)^{-\phi} \right]^{1-\sigma} + \frac{\kappa}{1-\mu} (1-L)^{1-\mu} \]

(44)

where \( \sigma \) denotes the coefficient of relative risk aversion, \( \phi \) denotes the elasticity of substitution between consumption and money, and \( \mu \) denotes weight on leisure. First, we set \( \sigma = \mu \) to be consistent with balanced growth path. Next, we choose \( \kappa \) so that households devote one quarter of their time to market activities. The discount factor \( \beta \) is set to be 0.99 so that an annualized steady state interest rate is to be 4 percent. The degree of the relative risk aversion \( \sigma \) is set at 4 so is the parameter \( \mu \). We follow Chari et al. (2002) for the parameterization of \( \omega \) and \( \phi \), and set \( \omega = 0.94 \) and \( \phi = 0.39 \). We choose the capital adjustment function of the form

\[ \chi \left( \frac{I(n, s^t)}{K(n, s^{t-1})} \right) = \xi \left( \frac{I(n, s^t)}{K(n, s^t)} \right)^2 \]

We calibrate \( \xi \) so that the relative standard deviation of consumption to output is the same as is in the data. The depreciation rate \( \delta \) is set at 0.021.
Consider a production function of the form

\[ X(L, K, Z) = K^{(1-\alpha)\alpha_z} L^{\alpha z} Z^{(1-\alpha_z)} \]  \hspace{1cm} (45)

The labor share parameter \( \alpha \) in the production function is set at 2/3 and the share of aggregate intermediate goods is set at 0.6 following Huang et al. (2004). We derive the steady state shares of intermediate goods and investment goods in output by combining goods market clearing conditions with expenditure share equations and with pricing equations. We set \( \nu = 10 \) so that a steady state markup is 0.11. Further, the elasticity of substitution across countries is set at \( \theta = 1.5 \). We relate \( h \) in the final good production function to the share of imports and use a US import share of 0.15 to obtain a value for \( h \). We also vary the value of \( h \) to investigate the effects of openness on the real exchange rate persistence.

We set \( N = 4 \) for the Taylor staggered price setting so that prices are fixed for one year. Accordingly, we set \( \varphi_p = 0.75 \) for the Calvo price setting so that one fourth of firms can renew their prices in each quarter. For the sticky wage models, we set \( \eta = 4, \ N_w = 4 \) in the Taylor contract, and \( \varphi_w = 0.75 \) in the Calvo contract. Finally, we estimate and choose the serial correlation parameter \( \rho_m = 0.68 \) in the stochastic process for money growth rates using quarterly US data for M1 between 1973 and 2001, obtained from the Board of Governors of the Federal Reserve System Database. We use this sample period for our calibration to compare the results from Chari et al. (2002). For each economy, the standard deviation of the monetary shocks is chosen so that the standard deviation of GDP is the same as in the data.

2. Results

We now investigate the quantitative effects of the Calvo and Taylor price settings on the persistence of the real exchange rate by calculating impulse responses of the real exchange rate to one-time one percent increase in the US
money supply. Overall, we find that impulse responses of the real exchange rate to a monetary shock die out more slowly in the Calvo setting than in the Taylor setting.

We begin with the benchmark models in Section 2 to abstract any interaction between the two price settings and real and nominal frictions. As shown in Figure 1, the Taylor staggered price setting does not generate endogenous persistence beyond the duration of the contract in the sense that the real exchange rate initially rises and then returns to the steady state very quickly as the initial contract becomes expired. In contrast, the response of the real exchange rate gradually dies out under the Calvo price setting. We measure the magnitude of persistence by the ratio of the response of the real exchange rate at the beginning of the next contract duration to that in the impact period so that all firms have had a chance to renew their prices after realization of the monetary shock. We call this ratio a contract multiplier. The ratio under the Calvo price setting is 27 percent while it is -4 percent under the Taylor staggered price setting.

To understand this result more clearly, we plot impulse responses in the two hybrid models. ‘Hybrid-Index’ represents a hybrid model in which combines the individual price settings under the Taylor contract and the Calvo aggregate price indexes. The model generates almost identical dynamics for the real exchange rate to the model with the Calvo contract. On the other hand, ‘Hybrid-Front’ represents a hybrid model in which combines the individual price settings under the Calvo contract and the Taylor aggregate price indexes. This model now generates almost identical dynamics to the model with the Taylor contract. These results imply that the effect of index inertia on real exchange rate persistence dominates that of front-loading incentives in the individual price settings, consistent with the qualitative result in Section 3.

We now investigate how persistence in the real exchange rate changes with respect to the degree of openness between the two contracts, while incorporating both real and nominal frictions in the benchmark model. Figure 2 plots impulse response functions of the real exchange rate with respect to
the degree of openness in the two contracts. First, as the degree of openness increases the real exchange rate more quickly dies out in both contracts: The contract multipliers are 67, 51, and 31 percent as $h$ is 1, 0.85, and 0.5 in the Calvo price setting while they are 36, 18, and 0 percent in the Taylor staggered price setting. Second, the Calvo price setting generates more persistent real exchange rate movements than the Taylor contract for a given degree of openness. In particular, when the world economy is completely open, the real exchange rate quickly returns to the steady state level beyond the duration of the contract, that is, one year after monetary shocks are realized in the Taylor staggered price setting regardless of presence of various frictions that we have considered, consistent with our analysis in Sections 3 and 4. In contrast, the contract multiplier is about 31 percent under the Calvo price setting even when $h = 0.5$ because the dynamics of the real exchange rate is mainly governed by the probability $\varphi_p$, regardless of the degree of openness. By setting $1 - \varphi_p = 1 / N$, in each period the same fraction of new prices are included in the composite price indexes under the Calvo price setting. However, since there is always a positive probability that some prices have never had a chance to be reoptimized, composite price indexes include those past prices no matter when they were set. As a result, the Calvo price setting generates more persistence in the real exchange rate regardless of the presence of various real frictions and the degree of openness.

We also study the quantitative effects of the frictions on the persistence in the real exchange rate and how these frictions interact with the two price settings. We find that the results are consistent with the qualitative analysis in Section 4. For saving the space, we do not provide those impulse responses but they are available upon request. The responses of the real exchange rate are slower than those in the model without those frictions in both price settings as long as there is a significant degree of home bias.

6. Concluding Remarks
In this paper, we find that the standard DGE model with the Taylor price setting does not generate endogenous persistence in real exchange rates when the economy is completely open. This result holds true even if the model include both input-output production structure and sticky wages. On the other hand, the standard DGE model with the Calvo price setting produces sizable endogenous persistence even when the economy is completely open. This is mainly because the Calvo price setting generates additional price rigidities induced by aggregate index inertia. Our qualitative and quantitative results also show that the index inertia in the Calvo contract mainly produces different results in the real exchange rate persistence between the two price settings.
References


Real Wages Change over Time,” *The American Economic Review*.


Figure 1: Impulse responses of the real exchange rate in the model with capital.

Figure 2: Impulse responses of the real exchange rate in the model with capital, input-output structure, and sticky wages.