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Monetary Policy in a Low Pass-Through Environment

In a dynamic New Keynesian optimizing model, we introduce incomplete exchange rate pass-through on import prices. Three results stand out. First, unlike canonical models with perfect pass-through which emphasize a type of isomorphism, incomplete pass-through renders the analysis of monetary policy of an open economy fundamentally different from the one of a closed economy. Second, productivity-driven deviations from the law of one price assume the interpretation of endogenous cost-push shocks. Third, the optimal commitment policy, relative to discretion, entails a smoothing of the deviations from the law of one price and requires more stable nominal and real exchange rates.

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RECENTLY WE HAVE witnessed a growing interest in macroeconomics for small-scale models applied to the analysis of monetary policy. The so-called New Keynesian synthesis, exemplified by the work of Clarida, Galí, and Gertler (1999) and Woodford (2003), has the attractive feature of preserving tractability within the rigor of a dynamic optimizing general equilibrium setup. Surprisingly, much less attention has been devoted to the open economy counterpart of such a paradigm. Several recent contributions within the so-called New Open Economy Macroeconomics (NOEM henceforth) literature have taken the form of elegant but highly stylized models in which the analysis of monetary policy is often still confined to inspecting the effects of money supply shocks.[1] The goal of a realistic representation of the practice of monetary policy in open economies has motivated the work of Benigno and Benigno (2003), Galí and Monacelli (2005), McCallum and Nelson

1. As of now this literature is extremely rich. See Lane (2001) for a survey.

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(2000), Clarida, Galí, and Gertler (2001), and Ghironi (2000). Yet an important limitation shared by all these models is the assumption that the pass-through of exchange rates to (import) prices is complete (and therefore the law of one price holds continually). This lies in stark contrast with two well-established empirical facts. First, there is overwhelming failure of the law of one price for tradables.[2] Second, exchange rate pass-through on wholesale import prices is more rapid than on retail consumer prices.[3]

In this paper we argue that allowing for incomplete pass-through yields important implications for the design of monetary policy. First, it alters the form of the canonical small-scale model of the New Keynesian synthesis. That framework typically reduces to a tractable two-equation dynamical system for inflation and output gap, consisting of a Phillips curve and of a dynamic IS-type equation. Unlike Clarida, Galí, and Gertler (2001), who argue that the closed and the open economy version of this "canonical model" are isomorphic to one another, we show that the introduction of incomplete pass-through renders the analysis of monetary policy of an open economy fundamentally different from the one of a closed economy.

Second, under incomplete pass-through, productivity-driven deviations from the law of one price assume the interpretation of endogenous cost-push shocks. This marks a distinction from some of the recent literature (based on the prototype Calvo sticky-price model with perfect pass-through) that, in order to generate a meaningful policy trade-off, has typically resorted to *ad-hoc* cost-push shocks as exogenous shifters of the Phillips curve (Clarida, Galí, and Gertler, 1999, 2001).

Third, by generating a real policy trade-off (as already emphasized in Corsetti and Pesenti 2005), incomplete pass-through allows to contrast the features of the optimal policy program under commitment to the one under discretion. The study of this dimension of monetary policy is unfeasible within a large class of NOEM models that assumes one-period predetermined prices (or wages).[4] For such an assumption typically gives rise to a Lucas-type aggregate supply curve in which the forward-looking nature of inflation is neglected, and along with it the channel through which the anticipation of future policy conduct comes to play a role. In our setting, a critical element of the optimal commitment policy (relative to discretion) is the possibility, through the exchange rate (which is a forward-looking variable), to affect the expected future path of the deviations from the law of one price, and in turn the equilibrium path of inflation and output gap. A key contribution is to show that the optimal program, relative to the case with discretion, entails a partial, though not a complete, stabilization of the deviations from the law of one price. This is suggestive of a puzzle in the light of the established empirical evidence that such deviations are rather large and persistent.

2. See Rogoff (1996) and Goldberg and Knetter (1997) for extensive theoretical and empirical surveys. The work by Engel (1993, 1999, 2002) and Rogers and Jenkins (1996) strongly documents deviations from the law of one price for consumer prices also at a high level of disaggregation.

3. See Obstfeld and Rogoff (2000) and Campa and Goldberg (2002).

4. See, e.g., Obstfeld and Rogoff (1995), Corsetti and Pesenti (2005), and Sutherland (2005).

Turning to the recent literature, Corsetti and Pesenti (2005), Devereux and Engel (2002), and Sutherland (2005) also study the impact of incomplete pass-through on the optimal conduct of monetary policy. Their framework differs from the one of the present paper for it features one-period predetermined prices and hence does not lend itself to the analysis of the dynamic gains from commitment undertaken here.[5] Adolfson (2002) and Smets and Wouters (2002) are contributions more in line with the present paper. They differ in two dimensions. First, their setting cannot be reduced to a tractable compact form easily comparable to the canonical New Keynesian model previously adopted by the literature. Second, they focus only on the optimal policy under discretion, and hence neglect the crucial role played under commitment by the expectational channel of the exchange rate to inflation.

The rest of the paper is organized as follows. Section 1 presents the model. Section 2 analyzes the basic trade-offs implied by the introduction of incomplete pass-through and the details of the optimal monetary policy program. Section 3 gives the conclusions.

1. THE MODEL

1.1 Domestic Households

The domestic economy is populated by infinitely-lived households, consuming Dixit–Stiglitz aggregates of domestic (C_{H}) and imported (C_{F}) goods, by domestic firms producing a differentiated good, and by a continuum of importing firms that operate as price setters in the local market. All goods are tradeable. In the following, lower case letters indicate log-deviations from respective steady-state values, while capital letters indicate levels. Let us define C as a composite consumption index $C_t \equiv [(1-\gamma)^{1/\eta}\, C_{\mathrm{H},t}{}^{(\eta-1)/\eta} + \gamma^{1/\eta}\, C_{\mathrm{F},t}{}^{(\eta-1)/\eta}]^{\eta/(\eta-1)}$, with C_{H} and C_{F} being indexes of consumption of domestic and foreign goods, respectively.[6] Notice that, under this specification, η measures the elasticity of substitution between domestic and foreign goods. The optimal allocation of expenditures across types of goods implies standard demand functions: $C_{\mathrm{H},t} = (1-\gamma)(P_{\mathrm{H},t}/P_t)^{-\eta}\, C_t$, and $C_{\mathrm{F},t} = \gamma(P_{\mathrm{F},t}/P_t)^{-\eta}\, C_t$, where $P_t \equiv [(1-\gamma)P_{\mathrm{H},t}^{1-\eta} + \gamma P_{\mathrm{F},t}^{1-\eta}]^{1/(1-\eta)}$ is the consumer price index (CPI).

We assume the existence of complete markets for state-contingent money claims expressed in units of domestic currency. Under this assumption, the first order

5. Furthermore, Burstein, Eichenbaum, and Rebelo (2002) obtain incomplete pass-through as a consequence of the presence of distribution costs. Betts and Devereux (2000b) analyze optimal policy under discretion in a pricing-to-market framework.

6. Such indexes are in turn given by CES aggregators of the quantities consumed of each type of good. The optimal allocation of any given expenditure within each category of goods yields the demand functions:

$$C_{\mathrm{H},t}(i) = \left(\frac{P_{\mathrm{H},t}(i)}{P_{\mathrm{H},t}}\right)^{-\varepsilon} C_{\mathrm{H},t};\mathrm{C}_{\mathrm{F},t}(i) = \left(\frac{P_{\mathrm{F},t}(i)}{P_{\mathrm{F},t}}\right)^{-\varepsilon} C_{\mathrm{F},t},$$

for all $i \in [0, 1]$, where $P_{\mathrm{H},t} \equiv \left(\int_0^1 P_{\mathrm{H},t}(i)^{1-\varepsilon}\, di\right)^{1/(1-\varepsilon)}$ and $P_{\mathrm{F},t} \equiv \left(\int_0^1 P_{\mathrm{F},t}(i)^{1-\varepsilon}\, di\right)^{1/(1-\varepsilon)}$ are the price indexes for domestic and imported goods, respectively, both expressed in home currency. The elasticity of substitution between goods within each category is given by $\varepsilon > 1$.

conditions of the consumer's problem are standard and can be written in a convenient log-linearized form as:

$$w_t - p_t = \sigma c_t + \varphi n_t \,, \tag{1}$$

$$c_t = E_t\{c_{t+1}\} - \frac{1}{\sigma}(r_t - E_t\{\pi_{t+1}\}) \,, \tag{2}$$

where w_t is the nominal wage, n_t is labor hours, r_t is the log nominal interest rate, and π_t is the *CPI inflation rate*.[7]

In the rest of the world, a representative household faces a problem identical to the one outlined above. Hence, a set of analogous optimality conditions characterize the solution to the consumer's problem in the world economy. As in Galí and Monacelli (2005), however, the size of the small open economy is negligible relative to the rest of the world, an assumption that allows the treatment of the latter as if it was a closed economy.[8]

Pass-through, the real exchange rate, and deviations from PPP. Log-linearization of the CPI expression around a steady-state yields $p_t = (1 - \gamma)\, p_{H,t} + \gamma p_{F,t}$. Domestic producer inflation $\pi_{H,t}$ (defined as the rate of change in the index of domestic goods prices), and CPI-inflation are linked according to

$$\pi_t = \pi_{H,t} + \gamma \Delta s_t \,, \tag{3}$$

where $s_t \equiv p_{F,t} - p_{H,t}$ denotes the (log) terms of trade, i.e., the *domestic currency relative price of imports*. Notice that the above equation holds independently of the degree of pass-through.

The treatment of the rest of the world as an (approximately) closed economy (with goods produced in the small economy representing a negligible fraction of the world consumption basket) implies that $p_t^* = p_{F,t}^*$, and $\pi_t^* = \pi_{F,t}^*$, for all t. Hence, an equivalence between domestic and CPI inflation holds in the world economy.

Under incomplete pass-through the *law of one price* does *not* hold. Let us define ε_t as the nominal exchange rate (i.e., the domestic currency price of one unit of foreign currency). In particular, the real exchange rate can be written:

$$q_t = e_t + p_t^* - p_t = \psi_{F,t} + (1 - \gamma) s_t \,, \tag{4}$$

where $e_t \equiv \log \varepsilon_t$ and

$$\psi_{F,t} \equiv (e_t + p_t^*) - p_{F,t} \,, \tag{5}$$

7. This follows from maximizing a separable utility function of the form $(1/(1 - \sigma))C_t^{1-\sigma} - (1/(1 + \varphi))N_t^{1+\varphi}$ under a standard sequence of budget constraints. Hence, σ denotes the inverse of the intertermporal elasticity of consumption and φ the inverse of the elasticty of labor supply.

8. Notice that, more precisely, this is a world of two asymmetric countries in which one is small relative to the other (whose equilibrium is in the limit taken as exogenous). This kind of setup allows the explicit modeling of the role of financial markets and risk sharing and to overcome a typical problem of unit-root in consumption that characterizes traditional small open economy models with incomplete markets. See Schmitt-Grohe and Uribe (2002) for a discussion on how to "close small open economy models."

denotes the deviation of the *world* price from the *domestic* currency price of imports, a measure of the deviations from the law of one price. In what follows we will define this measure as the *law of one price gap* (l.o.p gap henceforth).

Equation (4) deserves some comments. Clearly, two are the sources of deviation from aggregate PPP in this framework. The first lies in the heterogeneity of consumption baskets between the small economy and the rest of the world, an effect captured by the term $(1 - \gamma)s_t$, as long as $\gamma < 1$. For $\gamma \rightarrow 1$, in fact, the two aggregate consumption baskets coincide and relative price variations are not required in equilibrium. The second source of deviation from PPP is due to the deviation from the law of one price, captured by movements in $\psi_{F,t}$. Hence, with incomplete pass-through, the l.o.p gap contributes to the volatility of the real exchange rate.

1.2 Domestic Producers

In the domestic goods market, there is a continuum of monopolistic competitive firms (owned by consumers), indexed by $i \in [0, 1]$. They operate a production technology (expressed in logs): $y_t(i) = z_t + n_t(i)$, where z_t is (log) labor productivity. Cost minimization typically leads to the following efficiency condition for the choice of labor input:

$$\mathrm{mc}_t = (w_t - p_{H,t}) - z_t\,, \tag{6}$$

where mc indicates the real marginal cost, which is common across producers. In the following, (log) productivity is assumed to follow a simple stochastic autoregressive process $z_t = \rho z_{t-1} + \xi_{z,t}$, where $0 \leq \rho \leq 1$ is a persistence parameter and $\xi_{z,t}$ is an i.i.d shock.

For simplicity we assume that the *export* price of the domestic good, $P^*_H(i)$, is flexible and determined by the law of one price. Under a standard Calvo–Yun pricing rule, which implies receiving a price signal at a constant random rate θ_H, domestic producer inflation evolves according to a typical forward-looking Phillips curve (see Galí and Monacelli 2005):

$$\pi_{H,t} = \beta E_t\,\{\pi_{H,t+1}\} + \lambda_H\,\mathrm{mc}_t\,, \tag{7}$$

where $\lambda_H \equiv ((1 - \theta_H)(1 - \beta\theta_H))/\theta_H$. An aggregate supply relation of this form has become a basic ingredient of recent optimizing models of the so-called New Keynesian Synthesis.[9]

1.3 Incomplete Pass-Through and Imports Pricing

We now discuss the dynamics of import pricing. In recent work, Campa and Goldberg (2002) estimate import pass-through elasticities for a range of OECD countries. They find that: (i) the degree of pass-through is partial in the short-run and becomes gradually complete only in the long-run; (ii) the sensitivity of prices to exchange rate movements is much larger at the *wholesale* import stage than at the

9. See Woodford (2003) and Clarida, Galí, and Gertler (1999).

consumer stage. Their results imply a rejection of both the extreme assumptions on import pricing that characterize a wide array of papers in the NOEM literature: *local* vs. *producer* currency pricing.[10] According to the first view, domestic currency prices of imports are totally unresponsive to exchange rate movements in the short run, while the opposite is true in the latter case.

In this section, we develop the model in order to account for these facts. We assume that the domestic market is populated by local retailers who import differentiated goods for which the law of one price holds "at the dock." In setting the *domestic currency* price of these goods, the importers solve an optimal (dynamic) markup problem. This generates deviations from the law of one price in the short run, while complete pass-through is reached only asymptotically, implying a long-run holding of the law of one price. This feature is more in line with the empirical patterns described above and critically distinguishes our modeling of incomplete pass-through from the one of other recent papers (see, e.g., Corsetti and Pesenti 2005).

Consider a local retailer importing good j at a cost (i.e., price paid in the world market) $\varepsilon_t P^*_{F,t}(j)$. Like local producers, the same retailer faces a downward sloping demand for such goods and therefore chooses a price $P^{new}_{F,t}(j)$, expressed in units of domestic currency, to maximize:

$$E_t\left\{\sum_{k=0}^{\infty}\beta^k \Lambda_{t,t+k}\,\theta_F^k\,(P^{new}_{F,t}(j) - \varepsilon_{t+k}P^*_{F,t+k}(j))\,C_{F,t+k}(j)\right\},$$

$$\text{s.t. } C_{F,t+k}(j) = \left(\frac{P^{new}_{F,t}(j)}{P_{F,t+k}}\right)^{-\varepsilon} C_{F,t+k},$$

where $P^*_{F,t}(j)$ is the foreign-currency price of the imported good, θ_F^k is the probability that the price $P^{new}_{F,t}(j)$ set for good j at time t still holds k periods ahead, and $\beta^k\Lambda_{t,t+k}$ is a relevant stochastic discount factor. Notice that, in general, $\theta_H \neq \theta_F$. The FOC of this problem yields:

$$P^{new}_{F,t}(j) = \left(\frac{\varepsilon}{\varepsilon-1}\right)\frac{E_t\left\{\sum_{k=0}^{\infty}\beta^k\Lambda_{t,t+k}\,\theta_F^k\,(\varepsilon_{t+k}P^*_{F,t+k}\,C_{F,t+k}(j))\right\}}{E_t\left\{\sum_{k=0}^{\infty}\beta^k\Lambda_{t,t+k}\,\theta_F^k\,C_{F,t+k}(j)\right\}}. \tag{8}$$

The log-linear aggregate import price evolves according to:

$$p_{F,t} = \theta_F\,p_{F,t-1} + (1-\theta_F)\,p^{new}_{F,t}. \tag{9}$$

10. The original Obstfeld and Rogoff (1995) paper assumes producer currency pricing, while in the local currency pricing category fall, among many others, papers by Betts and Devereux (2000a,b), Chari, Kehoe, and Mc Grattan (2002), Devereux and Engel (2002).

The log-linear version of Equation (8) yields:

$$p_{F,t}^{new} = (1 - \beta\theta_F)\, E_t \left\{ \sum_{k=0}^{\infty} (\beta\theta_F)^k \,(\psi_{F,t+k} + p_{F,t+k}) \right\}. \tag{10}$$

By combining Equations (9) and (10), one can obtain an aggregate supply curve for import prices:

$$\pi_{F,t} = \beta E_t\{\pi_{F,t+1}\} + \lambda_F\, \psi_{F,t}, \tag{11}$$

where $\lambda_F \equiv ((1 - \theta_F)(1 - \beta\theta_F))/\theta_F$. Therefore import price inflation rises as the world price of imports exceeds the local currency price of the same good. In other words, a nominal depreciation determines a wedge between the price paid by the importers in the world market and the local currency price applied in the domestic market. This wedge acts as an increase in her real marginal cost and therefore boosts foreign goods inflation. The parameter θ_F governs the degree of pass-through.[11] Notice that, in the case $\theta_F = 0$, Equation (8) reduces (in log-linearized form) to a simple law of one price equation $p_{F,t} = e_t + p_t^*$.

Risk sharing, uncovered interest parity, and real marginal cost. Under complete markets for nominal state-contingent securities, movements in the ratio of the marginal utilities of consumption must imply, in equilibrium and up to a constant, movements in the real exchange rate.[12] This typically implies a log-linearized condition $c_t = c_t^* + (1/\sigma)q_t$, which in our case can be rewritten as

$$c_t = c_t^* + \frac{1}{\sigma}((1 - \gamma)s_t + \psi_{F,t}). \tag{12}$$

Hence, deviations from the law of one price, by affecting the movements of the real exchange rate, affect also the relative consumption baskets. Under complete international asset markets it is also possible to derive a standard log-linear version of an uncovered interest parity condition

$$r_t - r_t^* = E_t\{\Delta e_{t+1}\}. \tag{13}$$

It is easy to show that this equation obtains from combining efficiency conditions for an optimal portfolio of bonds held by both domestic and foreign residents.

By combining Equations (2), (6), and (12), imposing market clearing $c_t^* = y_t^*$ in the world economy (where y_t^* is world output), and substituting the production function, one obtains, after aggregation, an equilibrium equation for the domestic real

11. In fact, the textbook definition of exchange rate pass-through is the percentage change in the local currency import price resulting from a 1% change in the exchange rate betwen importing and exporting countries (see Goldberg and Knetter 1997).

12. See Chari, Kehoe, and Mc Grattan (2002) and Galí and Monacelli (2005) for a formal derivation of this condition. Notice, also, that this obtains under the assumption that the initial distribution of wealth is taken as given. See Devereux and Engel (2003) for a discussion.

marginal cost (or inverse of the domestic markup), which also expresses the equilibrium in the labor market:

$$\mathrm{mc}_t = (w_t - p_t) + \gamma s_t - z_t = \varphi y_t - (1 + \varphi) z_t + \sigma y_t^* + s_t + \psi_{F,t}\,. \tag{14}$$

Notice the open economy factors that affect the real marginal cost: world output y_t^* (through its effect on labor supply via risk sharing) and a "relative price effect" captured by s_t and $\psi_{F,t}$.

1.4 Goods Market Equilibrium

Local and foreign demand for domestic goods can be written, respectively, as $c_{H,t} = \eta\gamma s_t + c_t$ and $c_{H,t}^* = \eta(s_t + \psi_{F,t}) + c_t^*$. Hence, export demand *rises* both when the terms of trade depreciate (i.e., the price p_H falls relative to p_F) and when the domestic currency price of foreign goods p_F falls relative to the world price (i.e., ψ_F rises). Furthermore, the demand for imports will read $c_{F,t} = -\eta(1 - \gamma)s_t + c_t$.

Goods market clearing implies $y_t(i) = (1 - \gamma)\, c_{H,t}(i) + \gamma c_{H,t}^*(i)$ for all goods i. After aggregating, substituting the above demand functions and rearranging by using Equation (12), one obtains a simple proportionality relation between domestic and foreign output which is affected by the existence of incomplete pass-through:

$$y_t - y_t^* = \frac{1}{\sigma}\left[\omega_s\, s_t + \omega_\psi\, \psi_{F,t}\right], \tag{15}$$

where $\omega_s \equiv 1 + \gamma(2 - \gamma)(\sigma\eta - 1) > 0$ and $\omega_\psi \equiv 1 + \gamma(\sigma\eta - 1) > 0$ are, respectively, the elasticities of relative output to the terms of trade and the l.o.p gap, with $\omega_s \geq \omega_\psi$.

1.5 Policy Target in the Rest of the World

The equilibrium world real marginal cost is given by $\mathrm{mc}_t^* = (\sigma + \varphi)y_t^* - (1 + \varphi)z_t^*$, which is simply the closed economy (i.e., obtained for $\gamma = 0$) version of Equation (14). Therefore the natural (flexible-price) level of output in the world economy easily obtains, after imposing $\mathrm{mc}_t^* = 0$ (which implies $\pi_t^* = 0$), as $\bar{y}_t^* = ((1 + \varphi)/(\sigma + \varphi))z_t^*$. As in a canonical sticky-price model with Calvo price staggering, the output gap will be completely stabilized under fully flexible prices, i.e., $\tilde{y}_t^* \equiv y_t^* - \bar{y}_t^* = 0$. Throughout, it is assumed that the monetary authority in the rest of the world aims at replicating the flexible price allocation by simultaneously stabilizing inflation and the output gap.

1.6 Flexible Domestic Prices

In this section we describe the equilibrium dynamics in the small economy under the assumption that *domestic producer* prices are flexible. This is useful to formally derive two results. First, that nominal exchange rate volatility is linked to the degree of pass-through. Second, that, for a sufficiently low degree of pass-through, the l.o.p gap must respond positively to a (relative) productivity shock.

By imposing a constant markup in Equation (14) and substituting Equation (15) an expression for the domestic flexible price level of output reads:

$$\bar{y}_t = \bar{y}_t^n - \left(\frac{\omega_s - \omega_\psi}{\sigma + \varphi\omega_s}\right)\bar{\psi}_{F,t}\,, \tag{16}$$

where $\bar{y}_t^n \equiv ((\omega_s\,(1 + \varphi))/(\sigma + \varphi\omega_s))\,z_t + ((\sigma(1 - \omega_s))/(\sigma + \varphi\omega_s))y_t^*$ denotes the *natural* level of output, i.e., the one that would obtain in the case of both flexible domestic prices *and* complete pass-through. Below we show how to obtain a reduced form expression for $\bar{\psi}_{F,t}$. Notice also that $\bar{y}_t = \bar{y}_t^n$ in the special case $\omega_s = \omega_\psi$.

The l.o.p gap can then be written as $\bar{\psi}_{F,t} = \bar{e}_t - \bar{p}_{F,t}$ and the terms of trade as $\bar{s}_t = \bar{e}_t - \bar{\psi}_{F,t}$. By using Equation (15) and noticing that $\bar{s}_t = (\sigma/\omega_s)(\bar{y}_t - y_t^*) - (\omega_\psi/\omega_s)\bar{\psi}_{F,t}$, the nominal exchange rate can be written as $\bar{e}_t = (\sigma/\omega_s)(\bar{y}_t - y_t^*) + (1 - (\omega_\psi/\omega_s))\bar{\psi}_{F,t}$, which can be rearranged, using Equation (16), to obtain

$$\bar{e}_t = \bar{e}_t^n + \left(\frac{\varphi(\omega_s - \omega_\psi)}{\sigma + \varphi\omega_s}\right)\bar{\psi}_{F,t}\,, \tag{17}$$

where $\bar{e}_t^n \equiv ((\sigma(1 + \varphi))/(\sigma + \varphi\omega_s))(z_t - z_t^*)$ is the natural nominal exchange rate. Hence, as long as $\omega_s \neq \omega_\psi$, deviations from the law of one price contribute to the volatility of the nominal exchange rate beyond the one implied by its natural level. This implies that the model is consistent with the view that low pass-through is associated to higher exchange rate volatility.[13] Intuitively, the lower the pass-through the larger the nominal exchange rate variation required to achieve a given adjustment in real relative prices along the transition to the equilibrium.

Next, it is instructive to derive a reduced-form expression for the l.o.p gap as a function of relative productivity. In Appendix A we show that such an expression reads:

$$\bar{\psi}_{F,t} = \Gamma(z_t - z_t^*) - \frac{\mu_1(\sigma + \varphi\omega_s)}{\sigma + \varphi\omega_\psi}\bar{p}_{F,t-1}\,, \tag{18}$$

where $\mu_1 < 1$ and $\Gamma \equiv ((\sigma(1 + \varphi))/(\sigma + \varphi\omega_\psi))(1 - ((\sigma + \varphi\omega_s)\beta\mu_1\lambda_F)/((\sigma + \varphi\omega_\psi)(1 - \rho\beta\mu_1)))$. One can easily show that $\Gamma > 0$ for a sufficiently low degree of pass-through, which in turn implies that the l.o.p gap *must rise* in response to a relative rise in domestic productivity.[14] This result, which indeed depends on importers only gradually feeding nominal exchange rate movements through domestic currency import prices, will be useful below in our analysis of inflation dynamics in response to productivity shocks.

13. See e.g., Betts and Devereux (2000a).

14. In particular $\Gamma > 0$ is satisfied for $\lambda_F < ((\sigma + \varphi\omega_\psi)(1 - \rho\beta\mu_1))/((\sigma + \varphi\omega_s)\beta\mu_1)$, which in turn requires a sufficiently low degree of pass-through, i.e., a sufficiently high θ_F.

1.7 The Supply Block

Let us define the *output gap* as the percentage deviation of current output from its natural level, i.e., $\tilde{y}_t \equiv y_t - \bar{y}_t^n$. Equation (15), in turn, implies:

$$\tilde{y}_t = \frac{\omega_s}{\sigma}\tilde{s}_t + \frac{\omega_\psi}{\sigma}\psi_{F,t}\,. \tag{19}$$

Therefore the equilibrium real marginal cost (Equation 14) can be written, after combining with Equation (19), as

$$\mathrm{mc}_t = \left(\varphi + \frac{\sigma}{\omega_s}\right)\tilde{y}_t + \left(1 - \frac{\omega_\psi}{\omega_s}\right)\psi_{F,t}\,. \tag{20}$$

Hence, the presence of incomplete pass-through breaks down the proportionality relationship between the real marginal cost and the output gap which typically characterizes the canonical sticky-price model with imperfect competition. In response to productivity shocks, the potentially contrasting equilibrium behavior of the output gap and of the l.o.p gap will be the key to understanding the policy trade-off faced by the monetary authority.[15]

Equation (20) allows an interesting interpretation of the deviations from the law of one price as *endogenous supply shocks*. In fact, by replacing Equation (20) in Equation (7) one obtains

$$\pi_{H,t} = \beta\{E_t\pi_{H,t+1}\} + \kappa_y\tilde{y}_t + \kappa_\psi\psi_{F,t}\,, \tag{21}$$

where $\kappa_y \equiv \lambda_H(\varphi + \sigma / \omega_s)$ and $\kappa_\psi \equiv \lambda_H(1 - \omega_\psi / \omega_s)$. The result in Equation (18) establishes that the term $\psi_{F,t}$ will rise in response to a rise in domestic productivity (for a sufficiently low degree of pass-through). Hence (for any given output gap) positive movements in inflation can result from endogenous movements in the l.o.p gap which can in turn be induced by positive variations in productivity. This contrasts with a practice that has become common in models of the New Keynesian Phillips curve of "appending" cost-push terms to the right hand side of Equation (21) and labeling them supply shocks.

The above interpretation of the deviations from the law of one price continues to hold also when the broader CPI measure of inflation is considered. By combining Equations (14), (7), (11), and (19) with the definition of CPI inflation one obtains the following expression for a CPI-based aggregate supply curve:

$$\pi_t = \beta E_t\{\pi_{t+1}\} + \kappa_y^c\,\tilde{y}_t + \kappa_\psi^c\psi_{F,t}\,, \tag{22}$$

where $\kappa_y^c \equiv (1 - \gamma)\kappa_y$ and $\kappa_\psi^c \equiv (1 - \gamma)\kappa_\psi + \gamma\lambda_F$.

15. One can also notice that the theory-based measure of the output gap implied by this setup is one in which the same output gap is proportional not only to the labor share (via the real marginal cost) but also to the l.o.p gap, which is another observable variable. The same would not hold in the case of complete pass-through, where one would recover the proportionality between labor share and real marginal cost that characterizes prototypical closed economy models.

Therefore, like domestic producer inflation, CPI inflation also features a Phillips curve with forward-looking representation. A rise in the l.o.p gap, for a given output gap, causes a rise in CPI inflation. A full stabilization of inflation, then, would require a fall in the output gap. Furthermore, notice that $\sigma = \eta = 1$ implies $\kappa_\psi^c = \gamma\lambda_F > 0$. Hence, deviations from the law of one price continue to affect CPI inflation (unlike producer inflation) even in the special case of $\sigma = \eta = 1$.

1.8 The Demand Block

By using Equation (12), one can rewrite the market clearing condition as $y_t = (\omega_s/(1-\gamma))c_t + (1-(\omega_s/(1-\gamma)))c_t^* - (\gamma\eta/(1-\gamma))\psi_{F,t}$. By substituting this equation into Equation (2) and making use of the definition of the output gap and of Equation (3) one can write the following aggregate demand equation:

$$\tilde{y}_t = E_t\{\tilde{y}_{t+1}\} - \frac{\omega_s}{\sigma}(r_t - E_t\{\pi_{H,t+1}\} - \overline{rr}_t) + \Gamma_y E_t\{\Delta\psi_{F,t+1}\}, \tag{23}$$

where $\Gamma_y \equiv (\gamma(1-\gamma)(\sigma\eta - 1))/\sigma$, and $\overline{rr}_t \equiv \sigma((\varphi(\omega_s - 1))/(\sigma + \varphi\omega_s))E_t\{\Delta y_{t+1}^*\} - ((\sigma(1-\rho)(1+\varphi))/(\sigma + \varphi\omega_s))z_t$ is the *natural real interest rate*. Notice that the natural real rate depends not only on domestic productivity, but also on the expected growth in world output. Equation (23) shows that, to the extent that $\sigma\eta > 1$, expected changes in the output gap are negatively related to expected future changes in the l.o.p gap.

1.9 Breaking the Canonical Representation

One result of the recent open economy New Keynesian optimizing framework is that the model's equilibrium dynamics can be represented in an output gap-(domestic producer) inflation space (a so-called *canonical representation*) which is isomorphic to its closed economy counterpart. The effect of adding openness results only in a modification of the *slope* coefficients of the standard optimizing aggregate demand and supply relationships. By inspecting the system composed by the supply equation (Equation 21) and the demand equation (Equation 23), it is clear that the introduction of incomplete pass-through has the effect of breaking the isomorphism between the closed and the open economy version of the canonical sticky-price model. In the case of full pass-through, which implies $\psi_{F,t} = 0$ for all t, the same system reduces to the case analyzed in Clarida, Galí, and Gertler (2001). However, notice that, even with incomplete pass-through, the open–closed economy isomorphism continues to hold in the particular cases of $\gamma = 0$ (closed economy), $\gamma = 1$ (consumption basket of the small economy coinciding with the one of the foreign economy), and $\sigma = \eta = 1$. In this last case, in fact, we have $\kappa_\psi = \Gamma_y = 0$.

2. POLICY TRADE-OFFS AND MONETARY POLICY DESIGN

The introduction of incomplete pass-through crucially shapes the range of trade-offs faced by the monetary authority. We first have the following result:

- *Under incomplete pass-through, and under the assumption that* $\sigma\eta > 1$, *the domestic producer flexible price allocation is no longer feasible. Therefore the monetary authority faces a trade-off between stabilizing producer inflation variability and stabilizing either the output gap or the l.o.p gap.*

This in fact translates into our dynamic context the results of Corsetti and Pesenti (2005) and Devereux and Engel (2002). The intuition follows directly from the real marginal cost equation (Equation 20). Consider a relative rise in productivity of the domestic economy. This, *ceteris paribus*, tends to lower the output gap and to exert a downward pressure on the real marginal cost. However, it also implies a nominal depreciation and, considering the result in Equation (18), also a rise in the l.o.p gap. Any attempt to stabilize the output gap by lowering interest rates would then boost the nominal depreciation and therefore imply a further rise in the l.o.p gap. Therefore the monetary authority *cannot simultaneously stabilize the domestic markup and target the law of one price*. Notice that, unlike the framework with complete pass-through, this trade-off arises endogenously in response to productivity shocks.

Next we characterize the monetary policy design problem. The focus of attention, similar to Woodford (2003) for the case of a closed economy, is on the nature of the optimal dynamic program for the monetary authority in the presence of households and firms adopting forward-looking decisions. The possibility of affecting future private sector's expectations gives rise to gains from commitment relative to a regime in which only discretionary optimization is feasible. This is a central insight of the recent analysis of optimal monetary policy in sticky-price models.[16] The open economy dimension, along with the presence of incomplete pass-through, adds further wrinkles to the analysis. The presence of a l.o.p channel to inflation, as it is clear from inspecting Equation (22), calls for an optimal management of the deviations from the law of one price and therefore of both the nominal and the real exchange rates along the optimal path. Furthermore, and in order to affect future inflation expectations, such deviations must be optimally managed against the output gap path, with these two variables further interacting through the aggregate demand relationship summarized by Equation (23).

We assume that the domestic authority sets policy in order to minimize a quadratic loss function which penalizes the variability of CPI inflation and output gap around some target values. These targets are zero for both variables.[17] The choice of including CPI inflation in the loss function appears the most natural. As pointed

16. See Woodford (2003) and Clarida, Galí, and Gertler (1999).

17. This implies that there is no bias in the *average* inflation rate resulting from discretionary optimization.

out in Svensson (2000), all small economies that have adopted regimes of inflation targeting have chosen to target a CPI measure of inflation, rather than a producer price or GDP measure, which would correspond to the index π_H in this analysis.[18]

Let us define by $b_w > 0$ the relative weight attached to output gap variability in the loss criterion. Under *discretion*, the problem becomes the one of minimizing the objective $\frac{1}{2}[\pi_t^2 + b_w \tilde{y}_t^2]$ in each given date t, subject to the constraints given by Equations (3), (5), (11), (13), and (21)–(23). In Appendix B we show that this problem leads to the following simple optimality condition linking inflation and the output gap in every period t:

$$\tilde{y}_t = -\Theta_c \pi_t, \text{ all } t \tag{24}$$

where $\Theta_c \equiv (\kappa_y^c + (\kappa_\psi^c / a)) / b_w > 0$ and $a \equiv (1 + \gamma(\sigma\eta - 1)) / \sigma > 0$. Condition (24) suggests that the monetary authority contracts real activity in response to a rise of CPI inflation above the target. As in Clarida, Galí, and Gertler (1999), the parameter Θ_c measures the magnitude of the required optimal adjustment of the output gap. In our context, Θ_c is affected by the degree of pass-through, namely it is decreasing in θ_F. In fact, the lower the pass-through (the higher θ_F) the smaller the slope λ_F of the import price equation (Equation 11).

When *commitment* is feasible, the policy authority is assumed to choose a state-contingent plan $\{\pi_t, \pi_{H,t}, \tilde{y}_t, \pi_{F,t}, \psi_{F,t}, e_t, r_t\}_{t=0}^{\infty}$ to minimize the discounted sum of losses $\frac{1}{2}E_0\{\sum_{t=0}^{\infty}\beta^t(\pi_t^2 + b_w \tilde{y}_t^2)\}$ subject to the Constraints (3), (5), (11), (13), (21)–(23). For the sake of exposition the details of such problem are deferred to Appendix B.

2.1 Dynamics

In this section we compute numerically the equilibrium dynamics of the model conditional on the optimal policy program and in response to an unexpected *rise in domestic productivity* (relative to the rest of the world).[19] Figure 1 compares the response of selected variables under the optimal commitment policy (*solid* line) to the one under discretionary optimization (*dashed* line). Several aspects are worth emphasizing. First, under discretion and in response to the rise in relative productivity, CPI inflation and the l.o.p gap both tend to *rise* on impact, while the output gap falls below the target value. The rise in the l.o.p gap, in particular, is

18. The obvious alternative would be to assume that the monetary authority tries to maximize the welfare of domestic households. Woodford (2003) shows how to obtain, within a closed economy model, a second order *accurate* approximation of households' utility and use it to solve a tractable linear quadratic control problem. In open economy forward-looking models with Calvo pricing, this has been shown to be a more complicated task, as argued in Benigno and Benigno (2003). In particular, in such models, an accurate quadratic approximation of households' welfare can be obtained only under specific assumptions on preferences and on the value of the international elasticity of substitution.

19. The benchmark calibration employed is as follows. We assume $\beta = 0.99$, $\sigma = 1$, $\eta = 1.5$, $\varphi = 3$. Parameters θ_H and θ_F are both set equal to 0.75, although θ_F will vary depending on the sensitivity analysis conducted. The persistence of the productivity process is set $\rho = 0.9$ and its standard deviation is calibrated to take a unitary value. The relative weight attached to output gap volatility b_w in the monetary authority's loss function is set equal to a baseline value of 0.2 (although it will be varied in the analysis below). All parameters describing the equilibrium in the foreign economy are assumed to take values identical to the ones in the small open economy. In addition, the small economy is characterized by an openness index $\gamma = 0.4$.

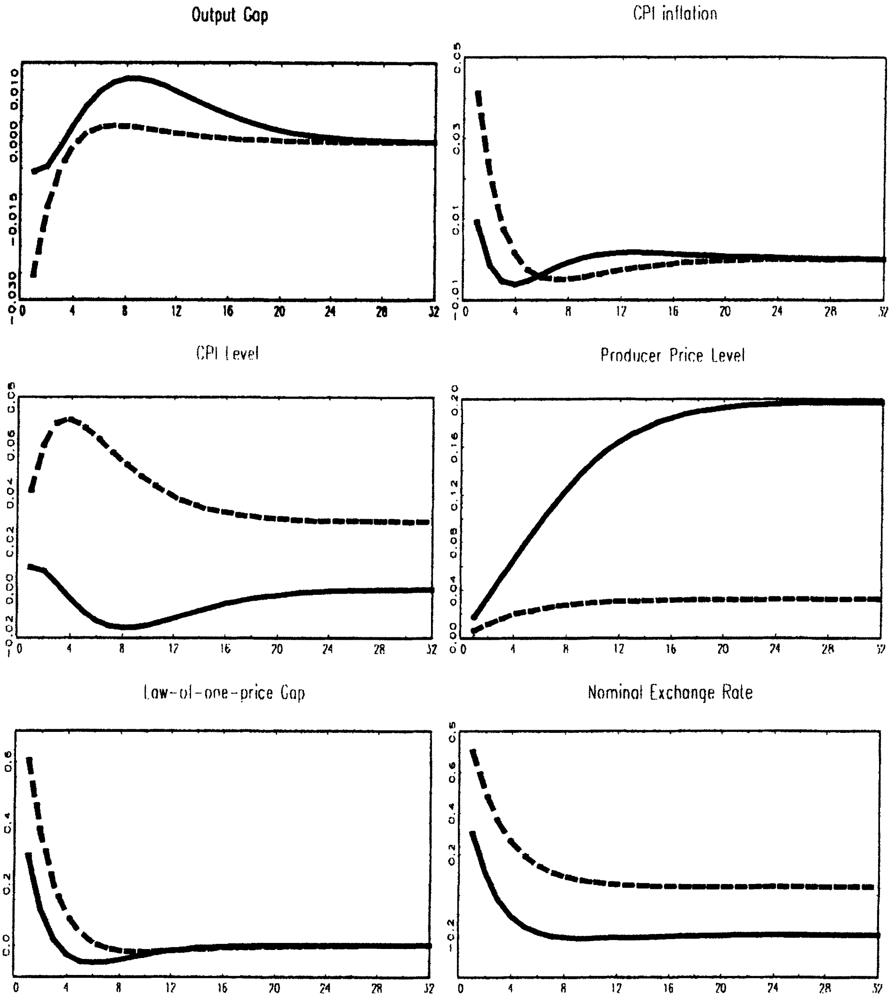

FIG. 1. Impulse Responses to a Domestic Productivity Shock: Commitment (*solid line*) vs. Discretion (*dashed line*)

the result of a nominal depreciation combined with a sluggish movement in the domestic currency price of imports. The important point to notice is that the impact effect of the positive productivity shock on inflation and output gap resembles the one in response to a cost-push shock.

Second, under commitment the Central Bank trades off some volatility in the output gap in order to achieve, relative to discretion, a stronger stabilization of the l.o.p gap and in turn a stronger stabilization of the variables of interest for her loss criterion. The key is that under commitment the Central Bank can manipulate the expectations about the future behavior of the exchange rate and therefore indirectly

TABLE 1
VOLATILITY AND CENTRAL BANK LOSS UNDER ALTERNATIVE MONETARY POLICY ARRANGEMENTS

	Low Weight on Output Gap $b_w = 0.2$		High Weight on Output Gap $b_w = 0.5$	
	Commitment	Discretion	Commitment	Discretion
CPI inflation	0.0002	0.0022	0.0004	0.0023
Output gap	0.0012	0.0008	0.0005	0.0001
Law of one price gap	0.1101	0.5164	0.1452	0.5340
Producer inflation	0.0024	0.0001	0.0015	0.0001
Nominal exchange rate	0.1472	0.5442	0.1865	0.5638
Real exchange rate	0.1396	0.4995	0.1748	0.5153
CB loss	0.0004	0.0024	0.0006	0.0024

NOTE: Standard deviation of domestic and foreign productivity shocks is one. The cross-country correlation of the shocks is 0.7.

of the l.o.p gap. In this case, the initial nominal exchange rate depreciation is strongly dampened. Expectations of a persistent nominal appreciation are then generated to smooth the current rise in the l.o.p gap and in turn induce a fall in the expected future l.o.p gap. This produces an overshooting in inflation which is observed to fall persistently below steady state after a few periods. Correspondingly, and given the trade-off between the stabilization of the output gap and of the l.o.p gap, the output gap rises above its long run value for several periods. It is important to notice that this entails a possibly larger volatility of the output gap under commitment relative to discretion (see the quantitative results below). Yet the larger instability in the output gap is traded off against a smoother path of the l.o.p gap, a strategy which yields a more stable path of inflation.

The results above already illustrate the gains from commitment that characterize the optimal policy design problem. The statistics reported in Table 1 confirm this intuition. Second moments of selected variables under commitment are compared to the ones under discretion. Two scenarios are reported. The first is labelled "low weight on the output gap" and corresponds to a value of $b_w = 0.2$, while the second scenario features $b_w = 0.5$, which is typically considered a high value in the literature. Two observations are in order. First, policy under commitment, relative to discretion, trades off a larger output gap volatility for smoother deviations from the law of one price. This is particularly evident when the weight on output gap volatility is high. Second, implementing the optimal commitment policy entails much less volatile nominal and real exchange rates relative to discretion.[20] Hence, the presence of incomplete pass-through builds a case for restricting exchange rate volatility but not for fixing exchange rates which would correspond to a suboptimal policy in our case.

3. CONCLUSIONS

We have analyzed the impact of incomplete exchange-rate pass-through in a dynamic forward-looking model of monetary policy. Our framework aims at accounting for

20. Notice that Table 1 reports second moments for nominal and real depreciation *rates*, as the corresponding levels are non-stationary in this context.

the widespread evidence that deviations from the law of one price are not only large but also gradual and persistent, as well as for the fact that the pass-through on import prices is more rapid than on retail consumer prices. We have shown that incomplete pass-through alters the form of the canonical New Keynesian optimizing model in a fundamental way. In fact, and unlike the case with full pass-through, it precludes from reducing it to a structure isomorphic to its closed economy counterpart already popularized by Woodford (2003) and Clarida, Galí, and Gertler (1999). Furthermore, with incomplete pass-through, productivity-driven deviations from the law of one price produce equilibrium effects similar to those of cost-push shocks.

The framework developed in this paper, due to its tractability, lends itself to several possible extensions. For example, and given the particular form of the New Keynesian Phillips curve derived here, one could explore empirically the role of the l.o.p gap in the determination of the real marginal cost and therefore of the inflation dynamics. Furthermore, one may wish to extend this setup, along the lines of McCallum and Nelson (2000), to include a role for imported inputs of production along with imported consumer goods, and allow for possibly different degrees of pass-through on different types of goods' prices. Finally, it would be particularly interesting to analyze, in our framework, the interaction between monetary policy regimes and degree of pass-through in a setup where the latter is determined endogenously. Important steps in this direction have been recently taken by Devereux, Engel, and Storgaard (2004).

APPENDIX A: DERIVATION OF EQUATION (18)

In this Appendix we show how to obtain Equation (18). By substituting in the expression for $\bar{\psi}_{F,t}$ one can write an expression for the domestic currency price of imports as a function of relative productivity and the l.o.p gap:

$$\bar{p}_{F,t} = \frac{\sigma(1+\varphi)}{\sigma+\varphi\omega_s}(z_t - z_t^*) - \left(\frac{\sigma+\varphi\omega_s}{\sigma+\varphi\omega_\psi}\right)\bar{\psi}_{F,t}\,. \tag{A1}$$

Notice, in particular, that under PPT the above expression reduces to:

$$\bar{p}^n_{F,t} = \bar{e}^n_t = s^n_t = \frac{\sigma(1+\varphi)}{\sigma+\varphi\omega_s}(z_t - z_t^*)\,, \tag{A2}$$

i.e., the domestic currency price of imports moves exactly in line with the nominal exchange rate and the terms of trade. By combining Equations (A1) and (11) one can express the dynamics of the imports price $\bar{p}_{F,t}$ in terms of a second order stochastic difference equation:

$$\delta_F\,\bar{p}_{F,t} = \bar{p}_{F,t-1} + \beta E_t\{\bar{p}_{F,t+1}\} + \frac{\lambda_F\sigma(1+\varphi)}{\sigma+\varphi\omega_\psi}(z_t - z_t^*)\,, \tag{A3}$$

where $\delta_F \equiv 1 + \beta + (\lambda_F(\sigma + \varphi\omega_\psi))/(\sigma + \varphi\omega_s) > 1$. Under the assumption, for the sake of simplicity, that $\rho = \rho^*$, the above equation has a unique stationary solution of the form

$$\bar{p}_{F,t} = \mu_1 \bar{p}_{F,t-1} + \Omega(z_t - z_t^*), \tag{A4}$$

where $\mu_1 \equiv (\delta_F/2)(1 - (1 - (4\beta/\delta_F^2))^{1/2}) < 1$ and $\Omega \equiv (\lambda_F\beta\mu_1\sigma(1 + \varphi))/((\sigma + \varphi\omega_\psi)(1 - \rho\beta\mu_1)) > 0$. Hence, the domestic currency price of imports must rise in response to a rise in relative productivity. Among other things, the elasticity of $\bar{p}_{F,t}$ to relative productivity depends positively on λ_F (the slope of the imports price inflation equation (Equation 11)) and therefore on the degree of pass-through (with a low degree of pass-through implying a high θ_F and in turn a low λ_F). Finally, by substituting Equations (17) and (11) into $\psi_{F,t}$ one can derive an expression for the l.o.p gap which corresponds to Equation (18) in the text.

APPENDIX B: DERIVING THE OPTIMAL PLAN

When commitment for the monetary authority is feasible the quadratic control problem consists in choosing a state-contingent plan $\{\pi_t, \pi_{H,t}, \tilde{y}_t, \pi_{F,t}, \psi_{F,t}, e_t, r_t\}_{t=0}^{\infty}$ to minimize $\frac{1}{2}E_0\{\sum_{t=0}^{\infty}\beta^t(\pi_t^2 + b_w\tilde{y}_t^2)\}$ subject to the sequence of Constraints (3), (5), (11), (13), and (21)–(23) holding in all periods $t + j$, $j \geq 0$. After taking first differences of Equation (5) and combining with Equation (13) one can setup the Lagrangian:

$$\begin{aligned} max -\frac{1}{2}E_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\Big\{&((1-\gamma)\pi_{H,t} + \gamma\pi_{F,t})^2 + b_w\tilde{y}_t^2 \\ &+ 2\phi_{1,t}[\pi_{H,t} - \beta\pi_{H,t+1} - \kappa_y\tilde{y}_t - \kappa_\psi\psi_{F,t}] + 2\phi_{2,t}[\tilde{y}_t - \tilde{y}_{t+1} \\ &+ \frac{\omega_s}{\sigma}(r_t - \pi_{H,t+1} - \bar{rr}_t) - \frac{\gamma(\sigma\eta - \omega_\psi)}{\sigma}(\psi_{F,t+1} - \psi_{F,t})] \\ &+ 2\phi_{3,t}[\pi_{F,t} - \beta\pi_{F,t+1} - \lambda_F\psi_{F,t}] \\ &+ 2\phi_{4,t}[\psi_{F,t+1} - \psi_{F,t} - r_t + r_t^* - \pi_{t+1}^* + \pi_{F,t+1}]\Big\}\Bigg\}, \end{aligned}$$

where $\phi_{1,t+j}$, $\phi_{2,t+j}$, $\phi_{3,t+j}$, and $\phi_{4,t+j}$ are Lagrange multipliers associated with the constraints at time $t + j$. Notice that at this stage the Constraint (3) has been substituted.

The first order conditions of this problem read:

$$\pi_t(1 - \gamma) + (\phi_{1,t} - \phi_{1,t-1}) - \frac{\beta^{-1}\omega_s}{\sigma}\phi_{2,t-1} = 0, \tag{B1}$$

$$b_w\tilde{y}_t - \kappa_y\phi_{1,t} + \phi_{2,t} - \beta^{-1}\phi_{2,t-1} = 0, \tag{B2}$$

$$\frac{\omega_s}{\sigma}\phi_{2,t} - \phi_{4,t} = 0\,, \tag{B3}$$

$$-\kappa_\psi\phi_{1,t} + \frac{\gamma(\sigma\eta - \omega_\psi)}{\sigma}(\phi_{2,t} - \beta^{-1}\phi_{2,t-1}) - \lambda_F\phi_{3,t} + \beta^{-1}\phi_{4,t-1} - \phi_{4,t} = 0\,, \tag{B4}$$

$$\gamma\pi_t + \phi_{3,t} - \phi_{3,t-1} + \beta^{-1}\phi_{4,t-1} = 0\,. \tag{B5}$$

Therefore an optimal plan is defined, for any given policy weight b_w, as a bounded solution $\{\pi_{H,t}, \tilde{y}_t, \pi_{F,t}, r_t, \psi_{F,t}, e_t, \phi_{1,t}, \phi_{2,t}, \phi_{3,t}, \phi_{4,t}\}_{t=0}^{\infty}$ to the system of Equations (5), (13), (21), (11), (23), and (B1)–(B5). To complete the system of first order conditions we set the values of the predetermined Lagrange multipliers equal to their steady-state values (identified with a bar):

$$\phi_{1,-1} = \bar{\phi}_1, \phi_{2,-1} = \bar{\phi}_2, \phi_{3,-1} = \bar{\phi}_3, \phi_{4,-1} = \bar{\phi}_4\,.$$

B.1 Optimal Policy under Discretion

When the policymaker lacks a commitment device the problem will be to minimize $\pi_t^2 + b_w\,\tilde{y}_t^2$ period by period taking as given the private sector's expectation terms contained in Equations (3), (5), (11), (13), and (21)–(23). The first order conditions of such problems are:

$$\pi_t(1 - \gamma) + \phi_{1,t} = 0\,, \tag{B6}$$

$$b_w\tilde{y}_t - \kappa_y\phi_{1,t} + \phi_{2,t} = 0\,, \tag{B7}$$

$$\frac{\omega_s}{\sigma}\phi_{2,t} - \phi_{4,t} = 0\,, \tag{B8}$$

$$-\kappa_\psi\phi_{1,t} + \frac{\gamma(\sigma\eta - \omega_\psi)}{\sigma}\phi_{2,t} - \lambda_F\phi_{3,t} - \phi_{4,t} = 0\,, \tag{B9}$$

$$\gamma\pi_t + \phi_{3,t} = 0\,. \tag{B10}$$

Therefore a Markov-perfect (time consistent) solution is a set of processes $\{\pi_{H,t}, \tilde{y}_t, \pi_{F,t}, r_t, \psi_{F,t}, e_t, \phi_{1,t}, \phi_{2,t}, \phi_{3,t}, \phi_{4,t}\}_{t=0}^{\infty}$ that satisfies Equations (B6)–(B10) along with Equations (5), (13), (21), (11), and (23) at all dates for any given policy preference weight b_w. Conditions (B6)–(B10) above can be easily rearranged to obtain Condition (24) in the text.

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