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The Desirable Smooth Operator, Incomplete Pass Through and the "Zero Bound"

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Abstract

The typical New-Keynesian small-open-economy model has qualitative features and monetary-policy prescriptions similar to their original closed-economy counterparts – i.e. complete stabilization of domestic inflation is sufficient for optimal policy. We consider a version of the model here where that isomorphism no longer holds and where the zero-interest-rate lower bound matters. Under the commitment benchmark, the optimal interest-rate rule is intrinsically inertial. Under time-consistent policy, it is still optimal to delegate policy to an interest-rate smoothing central banker despite the fact that complete stabilization of domestic inflation is no longer possible. We thus extend the analysis of Woodford (1999) to a nontrivial small open economy setting. Our result is robust to alternative degrees of pass through, the types of shocks impinging the natural rate, and minor departures from optimal pricing behavior.

Keywords: Optimal monetary policy; interest-rate smoothing; small open economy; stabilization bias.

JEL classification: E32; E52; F41

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1. Introduction

The level of nominal interest rates for many industrialized small open economies tend to be highly and positively autocorrelated. For example, Espinosa-Vega and Rebucci (2003) document first-order autocorrelations for nominal interest rates in these countries that are near random walk. Furthermore, these rates are perfectly correlated with the respective countries' monetary policy rates. Often this feature is rationalized as central banks' preference for interest-rate smoothing. It may also be the case that history-dependence in policy rates arise naturally out of monetary policy that is *ex-ante* optimal, without any explicit desire for smoothing policy.[1] This result was shown by Woodford (1999) and Woodford (2003b) in the case of a closed-economy New-Keynesian (NK) model. However, it is well known that such policies are dynamically inconsistent. On the other hand time-consistent or discretionary optimal policy results in a Markov perfect equilibrium that possesses suboptimal short-run dynamics. This problem is often termed stabilization bias (see e.g. Dennis and Söderström 2002). Just as Rogoff (1985) considered the delegation of monetary policy to a conservative central banker as a solution to the well-known average inflation bias problem, Woodford (1999) advocates hiring an interest-rate-smoothing central bank delegate as a solution to the stabilization bias problem. This latter result will be conveniently labeled as the *Woodford proposition* below.

One might casually expect the important insight on the value of interest-rate smoothing of Woodford (1999) to carry through to small-open-economy monetary theory and policy. This would indeed be true in the case of typical NK small-open-economy models with complete exchange-rate pass through in the style of Clarida, Galí and Gertler (2001) and Galí and Monacelli (2004). Clarida et al. (2001) showed that the small-open-economy optimal monetary policy rule and resulting equilibrium is qualitatively the same as its closed economy counterpart.[2] However, such a conclusion may not be warranted in many small open economies that experience incomplete exchange rate pass through, and this question has not been theoretically analyzed for such economies. In fact, Monacelli (2003) shows that because of incomplete pass through, monetary policy via the interest rate path also affects the paths of inflation (domestic and imported goods price inflation) and output gap via the channel of the exchange rate and the deviation from the law of one price. Monacelli (2003) showed that it is no longer optimal to just achieve flexible domestic producer prices (which would have been sufficient in the closed-economy case), but there is a trade off between stabilizing domestic producer prices on the one hand, and stabilizing either the output gap or the law-of-one-price gap on the other.

We address the unanswered question of whether the *Woodford proposition* survives in a more general case of a small open economy with incomplete exchange-rate pass through where the optimal monetary policy is clearly one that cannot merely stabilize domestic goods inflation. This question is important since a large number of advanced industrialized countries, for instance Canada, Australia,

[1] A history-dependent central bank action describes the central bank's optimal stabilization plan simply because it affects current outcomes which are functions of anticipated policy, thereby acheiving the central bank's *ex ante* stabilization objective.

[2] Intuitively, with perfect exchange-rate pass through, any volatility in the exchange rate gets transmitted to aggregate demand immediately via the terms of trade and is thus captured in the output-gap stabilization objective of the central bank. Meanwhile, nominal rigidity in domestic goods prices can be dealt with by domestic-goods inflation targeting.

the United Kingdom, and New Zealand, are small open economies that face exactly this kind of problem where exchange rate pass through is less than complete. Furthermore, if the *Woodford proposition* survives in our nontrivial small open economy, one can more confidently rationalize the observed persistence in small open economy interest rates as possibly due to optimal interest rate smoothing.

We employ the model of Monacelli (2003) for our analysis. However, the analysis of Monacelli (2003) ignores the reality of a lower bound on the nominal interest rate and does not focus on the role of interest-rate inertia under commitment or discretion. We extend Monacelli's (2003) framework to take into account the zero-interest-rate lower bound on the small open economy. This additional constraint on the central bank allows us to discuss and extend the *Woodford proposition* to the case of a nontrivial small open economy.

The results of this paper are as follows. It is proved that the rule under commitment is one that is intrinsically inertial – i.e. it does not depend on the persistence of exogenous forcing processes. It is also shown that the interest-rate rules arising from discretion take the generic form of Taylor-type rules. However, the elasticities in these rules under discretionary policy are constrained by the model and central-bank preference parameters, reflecting the credibility constraint under a Markov perfect equilibrium. This suggests that, and this is shown in the numerical simulations, by delegating monetary policy to the right central banker "type" one can minimize the stabilization bias. Under time-consistent policy, it is still optimal to delegate policy to an interest-rate smoothing central banker despite the fact that complete stabilization of domestic inflation is no longer possible in our model setting. We thus extend the analysis of Woodford (1999) to a nontrivial small open economy setting. Our result is robust to alternative degrees of pass through, the types of shocks impinging the natural rate, and minor departures from optimal pricing behavior.

The remainder of the paper is organized as follows. We describe Monacelli's (2003) model briefly in Section 2. We then motivate why, in the nontrivial small open economy that we employ, optimal interest-rate smoothing or not can be crucial, in Section 3. Optimal monetary policy under commitment is considered and contrasted with alternative optimal discretionary policies in Section 4. We provide numerical examples showing that the *Woodford proposition* carries through to this economy as well in Section 5. We conclude in Section 6.

2. The uncanonized NK model

Monacelli's (2003) NK small-open-economy model can be described by the following set of log-linearized approximate equilibrium conditions. We outline the microfoundations of this linearized system in Appendix A.

$$\pi_t = (1-\gamma)\,\pi_{H,t} + \gamma\pi_{F,t} \tag{1}$$

$$\pi_{H,t} = \beta E_t \pi_{H,t+1} + \kappa_y \widetilde{y}_t + \kappa_\psi \psi_{F,t} \tag{2}$$

$$\pi_{F,t} = \beta E_t \pi_{F,t+1} + \lambda_F \psi_{F,t} \tag{3}$$

$$\widetilde{y}_t = E_t \widetilde{y}_{t+1} - \frac{\omega_s}{\sigma}\left(r_t - E_t \pi_{H,t+1} - r_t^n\right) + \Gamma_y E_t \left(\psi_{F,t+1} - \psi_{F,t}\right) \tag{4}$$

$$\psi_{F,t} = E_t \psi_{F,t+1} - r_t + r_t^* + E_t \pi_{F,t+1} + E_t \pi_{t+1}^* \tag{5}$$

The first identity (1) is the consumer price index inflation derived from a CES aggregator of domestic and imported goods prices. Domestic (2) and imported goods (3) inflation are, respectively, described by NK Phillips curves derived from the Calvo (1983) staggered price setting model. The dynamic IS curve (4) is a result of household intertemporal optimization and market clearing. Lastly, the dynamics of deviations from the law of one price (or LOP gap) is given by (5).[3] The coefficients of this system are nonlinear functions of underlying taste and technology parameters. Specifically, $\lambda_H = \theta_H^{-1}(1-\theta_H)(1-\beta\theta_H)$, $\lambda_F = \theta_F^{-1}(1-\theta_F)(1-\beta\theta_F)$, $\kappa_y = \lambda_H\left(\varphi + \frac{\sigma}{\omega_s}\right) > 0$, $\kappa_\psi = \lambda_H\left(1 - \frac{\omega_\psi}{\omega_s}\right) \geq 0$, $\Gamma_y = \frac{\gamma(1-\gamma)(\sigma\eta-1)}{\sigma} > 0$ and $\omega_s = 1 + \gamma(2-\gamma)(\sigma\eta - 1) \geq \omega_\psi = 1 + \gamma(\sigma\eta-1) > 0$. The "deep" parameters are $(\sigma, \varphi, \eta, \gamma, \theta_H, \theta_F)$, respectively denoting the constant-relative-risk-aversion coefficient for the utility of consumption, the inverse of the real-wage elasticity of labor supply, the elasticity of substitution between domestic and foreign goods, the foreign goods share in CPI, and the one period probabilities that domestic-goods firms and imports retailers do not change their prices in their Calvo (1983) optimal staggered-pricing model.

There are two exogenous stochastic processes given by technology shock in the rest of the world and its counterpart in the small open economy given by first-order Markov processes:

$$\begin{pmatrix} z_t^* \\ z_t \end{pmatrix} = \begin{pmatrix} \rho^* & 0 \\ 0 & \rho \end{pmatrix} \begin{pmatrix} z_{t-1}^* \\ z_{t-1} \end{pmatrix} + \boldsymbol{v}_t, \quad \boldsymbol{v}_t \sim i.i.d.\,(\mathbf{0}, \boldsymbol{\Sigma}) \tag{9}$$

The natural rate of interest depends on relative productivity shocks in the small open economy and the rest of the world:

$$r_t^n = -\frac{\sigma(1+\varphi)(1-\rho)}{\sigma + \varphi\omega_s}\left[\left(\frac{(\omega_s - 1)\varphi}{\sigma+\varphi}\right) z_t^* + z_t\right]. \tag{10}$$

Definition 1 *A rational expectations equilibrium in the small open economy is a set of bounded stochastic processes* $\left\{\pi_t, \pi_{H,t}, \widetilde{y}_t, \pi_{F,t}, \psi_{F,t}, r_t\right\}_{t\in\{0,\mathbb{Z}_+\}}$ *that satisfies the system of equations (1)-(5) for any given set of processes* $\{r_t^n, r_t^*, \pi_t^*, z_t, z_t^*\}_{t\in\{0,\mathbb{Z}_+\}}$.

[3] We can also construct the evolution of the nominal exchange rate using the uncovered interest-parity condition,

$$E_t e_{t+1} = e_t + r_t - r_t^* \tag{6}$$

and the terms of trade and the real exchange rate will be, respectively, defined by

$$s_t = \frac{\sigma}{\omega_s}\widetilde{y}_t + \left[\frac{\sigma(1+\varphi)}{\sigma+\varphi\omega_s}\right](z_t - z_t^*) + \frac{\sigma}{\omega_s}\left[\frac{\omega_\psi - \omega_s}{\sigma + \varphi\omega_s} - \omega_s\right]\psi_{F,t} \tag{7}$$

and

$$q_t = \psi_{F,t} + (1-\gamma)s_t \tag{8}$$

2.1. Relation to the canonical NK model

The Clarida et al. (2001) and Galí and Monacelli (2004) model is nested within this model. Specifically, when $\theta_F = 0$ and $\psi_{F,t} = 0$ for all t, the law of one price holds for imported goods, the relevant system becomes

$$\pi_{H,t} = \beta E_t \pi_{H,t+1} + \kappa_y \widetilde{y}_t \tag{11}$$

$$\widetilde{y}_t = E_t \widetilde{y}_{t+1} - \frac{\omega_s}{\sigma} \left(r_t - E_t \pi_{H,t+1} - r_t^n \right) \tag{12}$$

and (10), which is qualitatively similar to the canonical NK closed-economy model.

3. Policy objective trade-offs

In the complete pass-through canonical NK model given by (11)-(12), shocks to output gap via the natural rate, (10), can be completely offset by the nominal interest rate without the repercussion on domestic producer prices. Thus the role of optimal interest rate smoothing, either as a result of commitment or discretion, merely acts as a speed brake on the straightforward adjustment process, just as in the closed economy model of Woodford (1999). This is clearly not the case in the Monacelli (2003) model.

As argued by Monacelli (2003), the existence of an incomplete exchange-rate pass through to retail imports prices creates an endogenous cost-push shock, in the form of the LOP gap, $\psi_{F,t}$, to the aggregate supply relations in (2) and (3). Consider a one-unit domestic technology shock in (9). By inspecting the dynamic IS relation in (4) and (10), we can see that the output gap ought to decrease by the amount $k = (\sigma + \varphi\omega_s)^{-1} \times [(1+\varphi)(1-\rho)\omega_s + \omega_s(1+\varphi)]$, if all else including future expectations are held constant. The fall in output gap would cause both domestic and imported goods inflation to fall via the real marginal cost channel in (2) and (3), since output is demand determined. However, one may think such real technology shocks can be neutralized by cutting the interest rate, by the amount $\sigma\omega_s^{-1} \times k$ so that output gap in (4) remains unchanged. This would be true if there were no gaps in the law of one price. However, when $\theta_F > 0$, a fall in the interest rate by the said amount, would cause a positive LOP gap via (5). This will further feed through to decrease output gap in (4) since the composite parameter $\kappa_\psi > 0$, when $\eta > 1$. Furthermore, the positive LOP gap will cause both inflation measures to rise. Therefore, conditional on the parameterization of the model, there is a trade-off in the usual inflation-output space implied by the LOP gap which creates an endogenous cost-push shock under what would otherwise be efficient technology shocks. In summary, by attempting to neutralize shocks to output gap and thus domestic goods inflation, the central bank ends up trading off output gap with domestic and foreign goods inflation.

Thus, whether a central bank smooths the interest rate or not under optimal policy matters even more in the Monacelli (2003) kind of economy. On the one hand, if policy is not smoothed, one may expect more abrupt and larger trade-offs in terms of inflation volatility versus output gap or LOP gap volatility. On the other hand, if monetary policy is smoothed, one may obtain the opposite. We will show that relative to the benchmark commitment case, the outcome favors optimal interest-rate smoothing because it helps to reduce the trade-offs under discretion (which were nonexistent in the typical NK model), in Section 5.

4. Optimal monetary policy and the zero bound

In this section, we begin by characterizing what is meant as "optimal policy". As the benchmark we consider the optimal commitment policy. Against this, we also consider time-consistent optimal policies and a version of an interest rate conservative central bank, as in Woodford's proposition.[4]

We retain Monacelli's (2003) assumption that the central bank's *ex ante* loss function is

$$W = E_0 \sum_{t=0}^{\infty} \beta^t L_t \tag{13}$$

where $\beta \in (0,1)$ and the loss per period is $L_t = \pi_t^2 + b_w \widetilde{y}_t^2$.[5] However, unlike Monacelli (2003), we allow for an empirically relevant zero-interest-rate floor. Given that we deal with welfare measures that are defined up to the second order, the zero-interest-rate lower bound can be built in by the following constraints

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^t r_t \right\} \geq 0 \tag{14}$$

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^t r_t^2 \right\} \leq \left(1 + \frac{1}{k^2}\right) \left[E_0 \left\{ \sum_{t=0}^{\infty} \beta^t r_t \right\} \right]^2 . \tag{15}$$

as in Woodford (2003a). These two constraints say that the "average" value of the sequence $\{r_t\}_{t\in\{0,\mathbb{Z}_+\}}$ must be nonnegative, and its fluctuations are bounded by k standard deviations above zero. Woodford (2003a) shows that problem of minimizing (13) subject to (14), (15) and the structural equations (1)-(5) can be replaced by one where the period loss function is given by

$$L_t = \pi_t^2 + b_w \widetilde{y}_t^2 + b_r \left(r_t - r^*\right)^2 \tag{16}$$

where $r^* > 0$. The weights $b_w > 0$ and $b_r > 0$ denote the relative concern of the central bank for output gap and interest rate variability (when (14), (15) bind) respectively. One may envision that

[4] It should be noted that even when the output level in the long run is made efficient, stabilization bias (a short-run business cycle phenomenon) can still exist when the central bank cannot optimally commit to a once-and-for-all policy. To abstract from the problem of an average inflation bias it is assumed, as shown in Galí and Monacelli (2004), that fiscal policy in the long run provides a subsidy to real wage of $\tau = \frac{1}{\varepsilon}$ where ε is the common elasticity of substitution between differentiated goods. This yields output at steady state which equals the first-best equilibrium outcome so that the target output gap is zero. Having done this, the focus can then be solely on the welfare effects of the stabilization bias problem.

[5] In the canonical two-equation NK model, a quadratic loss with output gap and domestic goods inflation as arguments can be derived from a quadratic approximation of the household's lifetime utility measure. Even then, Galí and Monacelli (2004) show that this analytical derivation can be done only when specific restrictions on preference parameters are imposed (i.e. when $\sigma = \eta = \gamma = 1$). This approach is not possible here when $\theta_F \neq 0$. Thus we follow Monacelli (2003) and Svensson (2000) in arguing that our choice of loss function reflects the fact that all inflation-targeting small open economies have chosen to target a CPI measure of inflation rather than the producer price measure, π_H. Furthermore, as our discussion in Section 3. showed, it is no longer feasible for the central bank to just stabilize π_H. It also has to take into account the LOP gap or, equivalently, π_F. Thus a natural argument for the loss function would have to include the overall CPI measure, π_t.

these weights have been chosen by society and given to the central bank at some initial "constitutional design" stage.

4.1. Commitment and the problem of time inconsistency

When the central bank can commit to minimizing (13) and (16) subject to the constraints of the evolution of the economy in (1)-(5), it behaves like a Stackelberg leader. The first-order conditions for the central bank's problem are then:

$$(1-\gamma)\,\pi_t + \phi_{1,t} - \phi_{1,t-1} - \frac{\omega_s}{\beta\sigma}\phi_{2,t-1} = 0 \tag{17}$$

$$b_w \widetilde{y}_t - \kappa_y \phi_{1,t} + \phi_{2,t} - \beta^{-1}\phi_{2,t-1} = 0 \tag{18}$$

$$b_r\,(r_t - r^*) + \frac{\omega_s}{\sigma}\phi_{2,t} - \phi_{4,t} = 0 \tag{19}$$

$$-\kappa_\psi \phi_{1,t} + \Gamma_y\left(\phi_{2,t} - \beta^{-1}\phi_{2,t-1}\right) - \lambda_F \phi_{3,t} + \beta^{-1}\phi_{4,t-1} - \phi_{4,t} = 0 \tag{20}$$

$$\gamma\pi_t + \phi_{3,t} - \phi_{3,t-1} + \beta^{-1}\phi_{4,t-1} = 0 \tag{21}$$

with the initial conditions $\phi_{1,-1} = \phi_{2,-1} = \phi_{3,-1} = \phi_{4,-1} = 0$.

The existence of lagged Lagrange multipliers in (17)-(21) implies that endogenous variables and in particular the optimal interest-rate instrument under commitment must not only react to current shocks, but also past movements of endogenous variables. This creates intrinsic policy inertia, independent of the serial correlation of exogenous stochastic processes as Woodford (1999) had shown in the case of a typical closed-economy New Keynesian model. This is stated in Proposition 1 below.

Proposition 1 *In a rational expectations (RE) equilibrium under the optimal pre-commitment problem of minimizing (13)-(16) subject to (1)-(6), the resulting interest rate rule is backward and forward looking in terms of current and past RE forecasts of domestic and foreign technology shocks:*

$$r_t = (1-\rho_r)\,r^* + \rho_r r_{t-1} - \boldsymbol{\Theta}_b \sum_{s=0}^{t-1} \mathbf{N}^s \mathbf{C} \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} \mathbf{M}^j \mathbf{z}_{t-s-1} - \boldsymbol{\Theta}_f \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} \mathbf{M}^j \mathbf{z}_t. \tag{22}$$

where $\boldsymbol{\Theta}_b$, $\boldsymbol{\Theta}_f$, $\mathbf{N}$, $\mathbf{C}$, $\mathbf{H}$, and $\mathbf{F}$ are matrices obtain under the RE equilibrium. It is also intrinsically inertial and the inertia coefficient ρ_r is independent of the structure of serial correlation in $\mathbf{z}_t$.

Proof. See Appendix B. ■

It can also be seen in Appendix B that $\boldsymbol{\Theta}_b$ and $\boldsymbol{\Theta}_f$ are decreasing in absolute terms with the central banker's preference for interest rate stability, b_r, in the case of pre-commitment. In other words, when the central bank places greater weight on interest-rate variability, reacts less aggressively to current and expected future domestic and foreign productivity shocks.

4.2. Discretionary optimal policy

Consider the case when the central bank cannot commit to the once and for all optimal plan. In this case, the central bank under discretion has an incentive to disregard the lagged constraints in (17)-(21) the conduct of its optimal policy and this is consistent with the beliefs of the private sector in a Markov perfect equilibrium. Effectively, in each period, the central bank will just minimize (16) subject to the constraints (1)-(6). The resulting first-order conditions now are:

$$(1-\gamma)\,\pi_t + \phi_{1,t} = 0 \tag{23}$$

$$b_w \widetilde{y}_t - \kappa_y \phi_{1,t} + \phi_{2,t} = 0 \tag{24}$$

$$b_r\,(r_t - r^*) + \frac{\omega_s}{\sigma}\phi_{2,t} - \phi_{4,t} = 0 \tag{25}$$

$$-\kappa_\psi \phi_{1,t} + \Gamma_y \phi_{2,t} - \lambda_F \phi_{3,t} - \phi_{4,t} = 0 \tag{26}$$

$$\gamma \pi_t + \phi_{3,t} = 0 \tag{27}$$

Definition 2 *A Markov perfect equilibrium is the set of sequences*

$$\left\{\pi_t, \pi_{H,t}, \widetilde{y}_t, \pi_{F,t}, \psi_{F,t}, r_t, e_t, \phi_{1,t}, \phi_{2,t}, \phi_{3,t}, \phi_{4,t}\right\}_{t\in\{0,\mathbb{Z}_+\}}$$

that satisfies (1)-(6) and (23)-(27) for all $t \in \{0, \mathbb{Z}_+\}$*, for any given set of exogenous stochastic processes* $\left\{r_t^n, r_t^*, \pi_{t+1}^*, z\,_t, z_t^*\right\}_{t\in\{0,\mathbb{Z}_+\}}$.

Under the case of optimal discretion, one can find an analytical expression for the interest-rate rule in the model. This turns out to be a Taylor-type rule where the rule reacts to both CPI inflation and output gap. However, the elasticity of policy with respect to these arguments are constrained by the private and policy-preference parameters, reflecting the credibility constraint under a Markov perfect equilibrium. This is summarized below.

Proposition 2 *The Markov perfect equilibrium that solves the problem in Definition 2 is characterized by an optimal Taylor-type rule:*

$$r_t = r^* + \Phi_\pi \pi_t + \Phi_y \widetilde{y}_t \tag{28}$$

where $\Phi_\pi = b_r^{-1}\left\{(1-\gamma)\left[\kappa_\psi + \kappa_y \sigma^{-1}\left(1+\gamma\left(\sigma\eta - 1\right)\right) + \gamma\lambda_F\right]\right\}$ *and* $\Phi_y = b_w b_r^{-1}\sigma^{-1}\left[1+\gamma\left(\sigma\eta-1\right)\right]$ *are positive.*

There is no intrinsic inertia in the optimal interest-rate policy (28) since no lagged Lagrange multiplier terms appear in the first-order condition for the central bank's optimal choice. This is simply because the central banker in each period has no incentive to be bound by the constraints from past periods.

4.3. Delegation to an interest rate smoother

In this section, interest-rate smoothing under discretionary policy is considered as a solution to the stabilization bias problem. Intuitively, this approximates the intrinsic inertia in policy found in the case of pre-commitment. Suppose now, instead of attempting to force the central bank to commit to minimizing society's lifetime loss function, and realizing that the central bank will cheat by acting in discretion anyway, society delegates policy making to a central banker with an additional preference for interest rate smoothing.

Specifically, assume that the central banker (under discretion) is one who minimizes

$$L_t^{CBsmooth} = \pi_t^2 + b_w \widetilde{y}_t^2 + b_{\triangle r} \left(r_t - r_{t-1} \right)^2 \tag{29}$$

subject to the constraints of private variables in (1)-(6). Notice that rather than having an objective with an interest-rate target or variability term, $b_{\triangle r} > 0$ involves a a concern for changes in the interest rate. Since this is also given in quadratic form, it means that the larger the changes in interest rate between two periods, the more the central bank is penalized in terms of its loss per period, $L_t^{CBsmooth}$. The first-order conditions are the same as (23)-(27), except that (25) is replaced with:

$$b_{\triangle r} \left(r_t - r_{t-1} \right) + \frac{\omega_s}{\sigma} \phi_{2,t} - \phi_{4,t} = 0 \tag{30}$$

Proposition 3 *The Markov perfect equilibrium in the case of the interest-rate-smoothing central banker is characterized by an optimal difference Taylor-type rule of the form*

$$r_t = r_{t-1} + \Phi_\pi \pi_t + \Phi_y \widetilde{y}_t \tag{31}$$

and $\Phi_\pi = b_{\triangle r}^{-1} \left\{ (1-\gamma) \left[\kappa_\psi + \kappa_y \sigma^{-1} \left(1 + \gamma \left(\sigma\eta - 1 \right) \right) + \gamma \lambda_F \right] \right\}$ *and* $\Phi_y = b_w b_{\triangle r}^{-1} \sigma^{-1} \left[1 + \gamma \left(\sigma\eta - 1 \right) \right]$ *are positive.*

Proof. This is a straightforward result from amending Proposition 2 for interest-rate growth in the first-order conditions; specifically in (30). ■

However, notice that now an additional pre-determined state variable r_{t-1} enters the credibility constrained optimal rule. This is simply an artefact of the central banker's explicit interest rate smoothing objective which constrains the optimal time-consistent policy. Further, the concern for interest-rate changes $b_{\triangle r}$ affects the optimal weights Φ_π and Φ_y such that a greater concern for smoother interest rates entails less response to CPI inflation and output gap, *ceteris paribus.*

5. Simulation results

In this section we show that the Woodford proposition can be extended to this nontrivial small open economy. The welfare and business cycle effect of delegating monetary policy to a central banker with an explicit taste for interest-rate smoothing (29) is considered. This is considered alongside equilibrium outcomes under the original social loss function (13)-(16) and also under an optimally delegated version of (16). Then, some robustness examples for optimal policies are considered for different degrees of exchange-rate pass through, alternative assumptions of exogenous shocks and the existence of some backward-looking inflation dynamics. Following Jensen (2002), our welfare statistic will be measured as the square root of the difference in society's loss function value under a given discretionary policy, W_D, and society's loss function value under the assumption that a central bank can commit, once and for all, to minimizing society's true social loss, W_C:

$$\widetilde{\pi} = \sqrt{W_D - W_C}. \tag{32}$$

This has the interpretation of the welfare gain of moving from a discretionary targeting regime to one with full commitment to society's welfare, in terms of the amount of compensation in inflation required to achieve some target inflation rate.

The benchmark parameter values are set out as follows. The private sector parameters are the same as Monacelli (2003). The common rate of time preference is set as $\beta = 0.99$. The coefficient of relative risk aversion is set as $\sigma = 1$, implying a log period utility in consumption. The elasticity of substitution between home and foreign goods is given by $\eta = 1.5$. Labor supply elasticity is given by $\varphi = 3$ while price stickiness in both domestic and retail imports sectors are assumed equal, and they take on the standard value of $\theta_H = \theta_F = 0.75$. This implies average price-stickiness of 4 quarters. The degree of openness in the economy, governed by the imports share in the consumption basket is given by $\gamma = 0.4$. There are only two exogenous stochastic processes given by technology shocks domestically and abroad. The persistence parameter for both processes are $\rho = \rho^* = 0.9$ and their standard deviations are assumed to be one, $\sigma_z = \sigma_z^* = 1$. Finally society's loss function (16) is parameterized as $b_w = 0.5$, following Monacelli (2003), and we also set a lower value of $b_r = 0.2$. The loss function parameters are not inconsistent with those used in the applied literature.

5.1. A desirable and credible smooth operator

Table 1 summarizes the effect on our measure of social loss and the volatility (standard deviation) of the variables in the model under the different policy regimes, given the benchmark parameterization of the model economy. The variables are the nominal one-period interest rate, r_t, the change in this interest rate, $\triangle r_t$, output gap, $\widetilde{y}_t$, nominal exchange rate, e_t, CPI inflation, π_t, and the real exchange rate, q_t. Where applicable, the last two rows of the table refer to society's loss function value and the measure of stabilization bias, respectively. Column (a) of Table 1 shows the equilibrium outcomes under the pre-commitment case. This will be used as a yardstick against which columns (b), (c) and (d) will measure. These, respectively, are the cases where the central bank acts in discretion under society's preferences, where society optimally delegates to a central banker who acts in discretion but shares the same functional form of society in (16), and where society optimally delegates to a central banker who acts in discretion but has an interest-rate smoothing objective (29). In the last two columns, (c) and (d), of the tables that follow any asterisked central bank preference parameters denote an optimally chosen set of policy preferences under policy delegation.[6]

[6] We conduct a set of grid searches over a subset of the parameter space for either (b_w, b_r) or $(b_w, b_{\triangle r})$ given by $[0, 1] \times [0, 1]$ with 2500 points. The second-moment statistics are computed in the frequency domain using codes provided

In Table 1, it can be seen that when the central bank is charged with minimizing the intertemporal "social loss", the time consistent (discretionary) solution [Column (b)] generates a greater social loss than the case with commitment policy. Recall that the implied form of the interest-rate rule in this case is (28). Furthermore, the equilibrium under discretion yields greater volatility in most of the variables in the short run.

Now consider optimally delegating the task of discretionary policy to a central banker (or committee) that places different weights on the target variables in the same loss function as society's. Column (c) shows that society's loss is greatly reduced but is still about four times the loss under pre-commitment, or that the gain from moving from discretion to pre-commitment is less, but it cannot outperform the latter. It is also interesting to note that the optimal weights on output gap and interest rate are less than those of society's. This can have the interpretation of a Rogoff (1985) conservative, but in the sense of a short-run stabilization bias.

Finally, when one considers an interest-rate smoothing regime for discretionary policy, social loss is reduced and the volatilities of the key variables are also much less than pure discretion under (b) and (c). That is, the gain from having pre-commitment is further weakened, when one considers optimally delegating the discretionary policy making to an interest-rate smoothing central banker [Column (d)]. This is the case where the implied interest-rate rule is a difference Taylor-type rule of the form in (31). In summary, discretionary flexible inflation targeting by an interest-rate smoothing central banker, can reduce the stabilization bias arising out of discretionary monetary policy.

5.2. Some robustness experiments

5.2.1. Degree of exchange-rate pass through to imports prices

Tables 2 and 3 retain the benchmark parameter values of the model, except for the degree of exchange-rate pass through, θ_F. Here, we consider if the previous conclusion about the regimes, especially the one under discretion with interest-rate smoothing, holds for high and low exchange-pass through. In these cases, we consider new sets of optimized weights for the delegation cases [columns (c) and (d)] when θ_F changes. In Table 2, we have the case of high pass through, $\theta_F = 0.4$.[7] Table 3 shows the case of a low degree of pass through, $\theta_F = 0.99$. Comparison of these results can be made with the benchmark case in Table 1.

It can be seen that the same general pattern arises, regardless of the degree of exchange-rate pass through. Pure discretion in monetary policy under society's loss function is the worse off. However, delegation of policy, under discretion, to a central banker who cares about smaller interest-rate changes outperforms the other discretionary policy regimes considered. Specifically, the distance, in terms of social loss or the gain from pre-commitment, between an equilibrium under a central banker with a

by Harald Uhlig and are described in Uhlig (1999). In each case, the model is solved using linearized perturbation methods as described in Uhlig (1999). We focus on linear-quadratic economies in the spirit of recent New Keynesian work in the monetary literature. However, it would be interesting, for future work, to consider more global nonlinear solution methods, such as that employed in Lim and McNelis (2004) and Lim and McNelis (2005).

[7] A stable and unique rational expectations equilibrium could not be attained for $\theta_F \in (0, 0.4)$, for all policy regimes, given the other parameters of the model.

smoothing objective, and one under pre-commitment is reduced.

5.2.2. Individual exogenous shocks

A second set of robustness experiments is presented in Tables 4-6. Taking the parameterization of central bank preferences as given from Tables 1-3, we now consider "shutting off" one exogenous shock at a time. Case 1 in Tables 1-3 refer to the case when only domestic productivity shocks exist, so that $\sigma_z = 1$ and $\sigma_z^* = 0$. Case 2 in the same tables assume the scenario when only productivity shocks from the rest of the world matter, or $\sigma_z = 0$ and $\sigma_z^* = 1$. Again, the same general conclusions in favor of discretionary interest-rate smoothing arise in these cases.

5.2.3. Existence of rule-of-thumb pricing

Finally we consider the robustness of our previous conclusion to the existence of backward-looking inflation dynamics. Retaining the parameterization of the policy weights from the purely forward-looking benchmark model in Table 1, we consider allowing for hybrid New Keynesian Phillips curves in both the domestic and imported goods sectors. These essentially have a lagged term for inflation as well as a forward-looking term. These equations are:

$$\pi_{H,t} = \omega_0^H E_t \{\pi_{H,t+1}\} + \omega_1^H \pi_{H,t-1} + \omega_2^H mc_{H,t}. \tag{33}$$

$$\pi_{F,t} = \omega_0^F E_t \{\pi_{F,t+1}\} + \omega_1^F \pi_{F,t-1} + \omega_2^F \psi_{F,t}. \tag{34}$$

where $\omega_0^j = \beta\theta_j / \left\{\theta_j + \left(1-\lambda_r^j\right)[1-\theta_j(1-\beta)]\right\}$, $\omega_1^j = \left(1-\lambda_r^j\right) / \left\{\theta_j + \left(1-\lambda_r^j\right)[1-\theta_j(1-\beta)]\right\}$, and $\omega_2^j = \left[\lambda_r^j (1-\theta_j)(1-\beta\theta_j)\right] / \left\{\theta_j + \left(1-\lambda_r^j\right)[1-\theta_j(1-\beta)]\right\}$, for $j = H, F$. Appendix C explains how these Phillips curves are obtained. Notice that when the fraction of rule-of-thumb price setters is zero or $\lambda_r^j = 1$, (33) and (34) collapse to the benchmark model given by (47) and (50), respectively. Also, $\partial\omega_1^j / \partial\lambda_r^j = -\theta_j / \left\{\theta_j + \left(1-\lambda_r^j\right)[1-\theta_j(1-\beta)]\right\}^2 < 0$ implying that as the proportion of rule-of-thumb firms increase, the weight on lagged inflation, ω_1, will increase. Furthermore, the sum of the coefficients on the lead and lag inflation terms, $\omega_0^j + \omega_1^j \in [\beta, 1]$. Given that usually, $\beta \simeq 1$, this suggests approximately vertical long-run Phillips curves.

Table 7 applies the policy regimes and weights (optimally selected weights in the case of delegation) from the benchmark case in Table 1 to the model with some fraction of rule-of-thumb price makers in the domestic and imported goods sectors. In this example, the fraction of forward-looking firms are set to $\lambda_r^j = 0.8$, for $j = H, F$, implying that each period with a probability of 0.2, each firm is backward-looking. In attempting to study cases where $\lambda_r^j < 0.8$ for $j = H, F$, we find that there are no numerically stable and unique rational expectations equilibria across all targeting regimes such that we can make uniform comparisons. Therefore we set $\lambda_r^H = \lambda_r^F = 0.8$ and interpret this as a small deviation from full forward-looking behavior in the benchmark model.

The same conclusion is obtained in the case of Table 7. Again, having some intrinsic inertia in the inflation processes does not seem to alter the benefit of delegating discretionary monetary policy to an interest-rate smoothing central banker. It would be interesting to consider the result in the light of a completely backward-looking Phillips curve model, but that would not be in the spirit of the class of New Keynesian models emphasized here.

5.3. Optimal policy inertia and dynamics

We now analyze the stabilization bias problem in terms of the magnitude, direction and persistence of dynamic adjustments in the model. Consider a positive domestic technology shock. This is shown in Figure 1. The solid lines correspond to the case when optimal policy is conducted with the supposed pre-commitment to society's loss function. The lines marked with crosses describe the equilibrium under the optimally delegated central banker with no smoothing behavior. Finally the circled lines represent discretionary policy under optimal delegation with an interest-rate smoothing central bank.

Consider first the case of pre-commitment to society's lifetime loss. Generally, the amplitude of the impulse responses under this case are much smaller than both cases of discretion. Given a positive domestic technology shock, the direct effect through the production function should increase the level of output gap. However, for a given level of nominal interest rate, the technology shock lowers the natural interest rate, resulting in a larger gap between the nominal and natural interest rates. This has a tendency to depress the output gap initially. This can be seen by inspecting the IS equation in (4). Since policy responds to output-gap deviations, the nominal interest rate falls, and this creates a positive output gap eventually. Given a fall in the nominal interest rate, there is a currency depreciation resulting in the nominal exchange rate deviation being positive under uncovered interest rate parity. Alternatively, one can observe from (7) that a positive technology shock has the Samuelson-Balassa effect of improving the small open economy's terms of trade and therefore creating a depreciation of its currency. A depreciation of the domestic currency which is persistent, creates an expectation that future imports prices will be falling as demand switches from imports to domestic goods. This causes domestic inflation to rise boosted by the rise in output gap, while imports inflation falls negating the tendency of a depreciation to create a positive LOP gap. In fact a negative LOP gap is obtained which reinforces the fall in imports inflation. This can be verified by inspecting equations (3)-(6).

When the optimally chosen central bank has the incentive to "cheat" under discretion, and this is anticipated by the private agents, it ends up allowing for a smaller positive effect of a domestic technology increase on output gap, but, a larger negative effect on inflation, compared to the commitment benchmark. Part of this is also because under discretion, there is a bias toward stabilizing the LOP gap which has a trade-off effect on output gap and inflation, in contrast to the commitment case. However, when one considers allowing for the case of optimally delegating discretionary policy to a policy maker who has the additional preference for interest-rate smoothing, it can be seen that the impulse responses tend to track those of the outcomes under commitment much better. Here the discretionary interest-rate smoother foregoes some of the bias toward output gap and LOP gap stabilization. This is a desirable property if the central bank were to act with discretion. The same can be seen when we consider the case of an exogenous technology shock in the rest of world, in Figure

2.

Thus, while pure discretionary policy without interest-rate smoothing carries a large trade off between stabilizing domestic inflation, output gap, interest rate and the LOP gap, optimally delegating policy to an interest-rate smoother is seen to dampen such a trade off by bringing the equilibrium dynamics of the economy closer to that under the desired commitment outcome.

6. Conclusion

In this paper, the role of optimal interest-rate smoothing is considered in the context of a small open economy model that faces incomplete exchange-rate pass through to import prices. It was shown that Woodford's (1999) conclusion about optimal monetary policy inertia still carries through in the small-open-economy setting that breaks the closed–and-open-economy monetary policy isomorphism. The paper proceeded from the benchmark of assuming that the central bank can solve a pre-commitment policy problem. However, if it is accepted that the central bank cannot credibly commit to that policy and thus acts in discretion, this creates too much stabilization on the central bank's part. Such a stabilization bias manifested itself in the form of greater uncertainty around the macroeconomic variables in the model. The bias is also measured as a larger loss in terms of the central bank's mandated loss function.

A possible solution, as was proposed by Woodford (1999), is to hire a central banker whose preferences include interest-rate smoothing even though this is not shared by society's preferences. It was shown in the paper that allowing for interest-rate smoothing under discretion results in a difference rule for the interest rate. That is, optimal (discretionary) policy in such a case involves setting the change in interest rate in response to CPI inflation and output gap. The reason for having an interest-rate conservative central banker is that it tends to introduce intrinsic inertia into the interest rate process, thus approximating the desired pre-commitment outcome. While pure discretionary policy without interest-rate smoothing carries a large trade off between stabilizing domestic inflation, output gap, interest rate and the LOP gap, optimally delegating policy to an interest-rate smoother is seen to dampen such a trade off. Therefore, it was found that the stabilization bias under discretion was greatly reduced when one delegates policy to a central banker with a taste for interest-rate smoothing. This conclusion survives under alternative degrees of exchange-rate pass through, shocks and also under minor departures from optimal pricing behavior by firms.

APPENDIX

A The private sector model

The private sector of the model consists of the household sector, imperfectly competitive domestic goods firms, foreign goods importers, the central bank, and exogenous processes for the rest of the world.

A1. Household sector

The representative household maximizes

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N^{1+\varphi}}{1+\varphi} \right] \tag{35}$$

subject to the sequence of constraints given by

$$\int_0^1 \left[P_{H,t}\left(i\right) C_{H,t}\left(i\right) + P_{F,t}\left(i\right) C_{F,t}\left(i\right) \right] di + E_t Q_{t,t+1} B_{t+1} \leq B_t + W_t N_t + T_t; \quad t \in \{0, \mathbb{Z}_+\} \tag{36}$$

The notation E_0 denotes the usual mathematical expectations operator, conditioned on the available information set at time 0. The prices of home and foreign goods of type i are respectively given by $P_{H,t}\left(i\right)$ and $P_{F,t}\left(i\right)$, B_{t+1} is the nominal value of assets held at the end of period t, $W_t N_t$ is the total wage income and T_t is a lump-sum tax or transfer. The stochastic discount factor is $Q_{t,t+1}$. The consumption index C_t is linked to a continuum of domestic, $C_{H,t}\left(i\right)$, and foreign goods, $C_{F,t}\left(i\right)$ which exist on the interval of $[0, 1]$ through the following indexes

$$C_t = \left[(1-\gamma)^{\frac{1}{\eta}} C_{H,t}^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}} C_{F,t}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta-1}{\eta}}, \tag{37}$$

$$C_{H,t} = \left[\int_0^1 C_{H,t}\left(i\right)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}, C_{F,t} = \left[\int_0^1 C_{F,t}\left(i\right)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{38}$$

Thus the elasticity of substitution between home and foreign goods is given by $\eta > 0$ and the elasticity of substitution between goods within each goods category (home and foreign) is $\varepsilon > 0$. Optimal allocation of the household expenditure across each good type gives rise to the demand functions:

$$C_{H,t}\left(i\right) = \left(\frac{P_{H,t}\left(i\right)}{P_{H,t}} \right)^{-\varepsilon} C_{H,t}, C_{F,t}\left(i\right) = \left(\frac{P_{F,t}\left(i\right)}{P_{F,t}} \right)^{-\varepsilon} C_{F,t} \tag{39}$$

for all $i \in [0, 1]$ where $P_{j,t} = \left(\int_0^1 P_{j,t}\left(i\right)^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}}$, $j = H, F$ and $C_{H,t} = (1-\gamma) \left(\frac{P_{H,t}}{P_t} \right)^{-\eta} C_t$, and $C_{F,t} = \gamma \left(\frac{P_{F,t}}{P_t} \right)^{-\eta} C_t$. The consumer price index can be solved as $P_t = \left[(1-\gamma) P_{H,t}^{1-\eta} + \gamma P_{F,t}^{1-\eta} \right]^{\frac{1}{1-\eta}}$. Another intratemporal condition relating labor supply to the real wage must also be satisfied

$$C_t^{\sigma} N_t^{\varphi} = \frac{W_t}{P_t} \tag{40}$$

Finally, intertemporal optimality for the household decision problem must satisfy the stochastic Euler equation

$$\beta E_t \left\{ \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \left(\frac{P_t}{P_{t+1}} \right) \right\} = Q_{t,t+1} \tag{41}$$

where $Q_{t,t+1}$ is the stochastic discount factor.

A2. Domestic production

There is a continuum of monopolistically competitive firms defined on $[0,1]$. Firms utilize a constant returns-to-scale technology, $Y_t(i) = Z_t N_t(i)$, where $Z_t = \exp(z_t)$ is a total productivity shifter. Cost minimization leads to the first-order condition

$$MC_{H,t}(i) Z_t = W_t \tag{42}$$

Given (42) it can be seen that nominal marginal cost is common for all firms such that $MC_{H,t}(i) = MC_{H,t}$ for all $i \in [0,1]$. In our analysis on optimal monetary policy, it is assumed that fiscal policy provides for an employment subsidy of τ to deliver the first-best allocation under flexible prices. Therefore, (42) can be rewritten, after integrating across all firms, as

$$mc_{H,t} = \frac{(1-\tau) W_t}{Z_t P_{H,t}}. \tag{43}$$

A3. Domestic pricing

The retail side of the firms producing domestic goods change prices according to a discrete-time version of Calvo's (1983) model. The signal for a price change is a stochastic time-dependent process governed by a geometric distribution. In a symmetric equilibrium all firms that get to set their price in the same period choose the same price. Thus prices evolve according to

$$P_{H,t} = \left[(1-\theta_H) \left(P_{H,t}^{new} \right)^{1-\varepsilon} + \theta_H \left(P_{H,t-1} \right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}}. \tag{44}$$

Thus, when setting $P_{H,t}^{new}$, each firm will seek to maximize the value of expected discounted profits:

$$\max_{\left\{ P_{H,t}^{new} \right\}_{t \in \{0, \mathbb{Z}_+\}}} E_t \left\{ \sum_{k=0}^{\infty} Q_{t,t+k} \theta_H^k \left[P_{H,t}^{new} - MC_{H,t+k}(i) \right] C_{H,t+k} \left(P_{H,t}^{new}, i \right) \right\} \tag{45}$$

subject to $C_{H,t+k}(i) = \left(\frac{P_{H,t}^{new}}{P_{H,t+k}} \right)^{-\varepsilon} C_{H,t+k}$. The optimal pricing strategy is thus one of choosing an optimal path of price markups as a function of rational expectations forecast of future demand and marginal cost conditions,

$$P_{H,t}^{new} = P_{H,t} \left(\frac{\varepsilon}{\varepsilon - 1} \right) \frac{E_t \sum_{k=0}^{\infty} Q_{t,t+k} \theta_H^k \left(\frac{P_{H,t}}{P_{H,t+k}} \right)^{-1-\varepsilon} \left(\frac{MC_{H,t+k}}{P_{H,t+k}} \right) C_{H,t+k}}{E_t \sum_{k=0}^{\infty} Q_{t,t+k} \theta_H^k \left(\frac{P_{H,t}}{P_{H,t+k}} \right)^{-\varepsilon} C_{H,t+k}}. \tag{46}$$

Notice that if the chance for stickiness in price setting is nil, $\theta_H = 0$ for all $k \in \{0, \mathbb{Z}_+\}$, the first order condition in (46) reduces to $mc_{H,t} = \left(1 - \varepsilon^{-1}\right)$, for all t, which says that the optimal price is a constant markup over marginal cost, or that the real marginal cost is constant over time. This is the same result as that for a static model of a firm with monopoly power. Log-linearizing the pricing decision and straightforward algebra produce the NK Phillips curve for domestic goods:

$$\pi_{H,t} = \beta E_t \{\pi_{H,t+1}\} + \lambda_H mc_{H,t}. \tag{47}$$

where $\lambda_H = \theta_H^{-1}(1-\theta_H)(1-\beta\theta_H)$.

A4. Imports retailer

Let ϵ_t denote the level of the nominal exchange rate. There exists local firms acting as retailers who purchase imports at the marginal cost equal to the imports price in domestic dollar terms, $\epsilon_t P_{F,t}^*(j)$, and re-sell them domestically at a markup price, $P_{F,t}^{new}$. It is the stickiness in the domestic price of imported goods that will cause a persistent and potentially large gap in what would otherwise be the law of one price. Thus the local retailer importing good j solves

$$\max_{\{P_{F,t}^{new}\}_{t\in\{0,\mathbb{Z}_+\}}} E_t \left\{ \sum_{k=0}^{\infty} Q_{t,t+k}\theta_F^k \left[P_{F,t}^{new} - \epsilon_{t+k} P_{F,t+k}^*(j)\right] C_{F,t+k}(j) \right\} \tag{48}$$

such that $C_{F,t+k}(j) = \left(\frac{P_{F,t}^{new}}{P_{F,t+k}}\right)^{-\varepsilon} C_{F,t+k}$. The optimal pricing strategy is thus

$$P_{F,t}^{new} = P_{F,t}\left(\frac{\varepsilon}{\varepsilon-1}\right) \frac{E_t \sum_{k=0}^{\infty} Q_{t,t+k}\theta_F^k \left(\frac{P_{F,t}}{P_{F,t+k}}\right)^{-1-\varepsilon} \left(\frac{\epsilon_{t+k}P_{F,t+k}^*}{P_{F,t+k}}\right) C_{F,t+k}}{E_t \sum_{k=0}^{\infty} Q_{t,t+k}\theta_F^k \left(\frac{P_{F,t}}{P_{F,t+k}}\right)^{-\varepsilon} C_{F,t+k}}$$

given the evolution of the aggregate retail imports price index as

$$P_{F,t} = \left[(1-\theta_F)\left(P_{F,t}^{new}\right)^{1-\varepsilon} + \theta_F\left(P_{F,t-1}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}.$$

Let e_t, $p_{F,t}^*$ and $p_{F,t}$ denote the log deviations of the nominal exchange rate, foreign price of imports and domestic retail price of imports respectively. The law-of-one-price gap in log-deviation terms is measured as

$$\psi_{F,t} = e_t + p_{F,t}^* - p_{F,t}. \tag{49}$$

A first-order approximation to the pricing dynamics will result in a similar aggregate supply schedule

$$\pi_{F,t} = \beta E_t\{\pi_{F,t+1}\} + \lambda_F \psi_{F,t}. \tag{50}$$

where $\lambda_F = \theta_F^{-1}(1-\theta_F)(1-\beta\theta_F)$. Notice that if the domestic dollar price of foreign goods exceed the domestic retail price of foreign goods, or $\psi_{F,t} > 0$, ceteris paribus, $\pi_{F,t} > 0$.

A5. Market clearing conditions

In the rest of the world, it is assumed that in the limit of being a closed economy, the home goods price of the rest of the world equals its CPI, or $P^*_{H,t} = P^*_t$ and consumption equals output, $C^*_t = Y^*_t$. Market clearing in the small open economy requires that

$$Y_t(i) = C_{H,t}(i) + C^*_{H,t}(i) \tag{51}$$

$$= \left(\frac{P_{H,t}(i)}{P_{H,t}}\right)^{-\varepsilon}\left[\left(\frac{P_{H,t}}{P_t}\right)^{-\eta}(1-\gamma)\,C_t + \left(\frac{P_{H,t}}{\epsilon_t P^*_t}\right)^{-\eta}\gamma^* Y^*_t\right] \tag{52}$$

A6. Dynamics and policy in the rest of the world

The rest of the world maintains a first-best flexible price equilibrium. Specifically the aggregate supply equivalent of (47) in the rest of the world, combining with labor supply decisions, yields $mc^*_t = (\sigma+\varphi)\,y^*_t - (1+\varphi)\,z^*_t$, and under the natural flexible price level of output in the world economy, $mc^*_t = 0$, implying $\pi^*_t = 0$, for all t. Thus output in the rest of the world equals its natural output

$$y^*_t = \left(\frac{1+\varphi}{\sigma+\varphi}\right) z^*_t. \tag{53}$$

From the IS equation for the rest of the world,

$$y^*_t = E_t y^*_{t+1} - \frac{1}{\sigma}\left(r^*_t - E_t\pi^*_{t+1}\right) = \rho\left(\frac{1+\varphi}{\sigma+\varphi}\right) z^*_t - \frac{1}{\sigma} r^*_t \tag{54}$$

making use of (9) and (53) in (54) yields the natural rate of interest in the rest of the world as

$$r^*_t = -\sigma\left(\frac{1+\varphi}{\sigma+\varphi}\right)(1-\rho)\,z^*_t. \tag{55}$$

B Proof of Proposition 1

The system of forward-looking private-sector variables (1)-(6) together with the predetermined Lagrange multipliers can be written in the canonical form

$$\begin{pmatrix} E_t\mathbf{x}_{t+1} \\ \boldsymbol{\phi}_t \end{pmatrix} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix}\begin{pmatrix} \mathbf{x}_t \\ \boldsymbol{\phi}_{t-1} \end{pmatrix} + \begin{pmatrix} \mathbf{F} \\ \mathbf{0}_4 \end{pmatrix}\mathbf{z}_t \tag{56}$$

where $\mathbf{x}_t = \begin{pmatrix} \pi_{H,t} & \widetilde{y}_t & \pi_{F,t} & \psi_{F,t} \end{pmatrix}'$, $\boldsymbol{\phi}_t = \begin{pmatrix} \phi_{1,t} & \phi_{2,t} & \phi_{3,t} & \phi_{4,t} \end{pmatrix}'$, and $\mathbf{z}_t = \begin{pmatrix} z^*_t & z_t \end{pmatrix}'$. In a rational expectations (RE) equilibrium given by Definition 1, the unique and bounded solution for the forward-looking part of the model can be found by "solving forward" to yield

$$\mathbf{x}_t = \mathbf{G}\boldsymbol{\phi}_{t-1} - \sum_{j=0}^{\infty}\mathbf{H}^{-(j+1)}\mathbf{F}E_t\mathbf{z}_{t+j} \tag{57}$$

where $\mathbf{G}$ and $\mathbf{H}$ contain coefficients that are determined in the RE equilibrium. The predetermined Lagrange multipliers can be solved backward to obtain

$$\boldsymbol{\phi}_t = \mathbf{C}\mathbf{x}_t + \mathbf{D}\boldsymbol{\phi}_{t-1} = \mathbf{N}\boldsymbol{\phi}_{t-1} - \mathbf{C}\sum_{j=0}^{\infty}\mathbf{H}^{-(j+1)}\mathbf{F}E_t\mathbf{z}_{t+j} \tag{58}$$

where $\mathbf{N} = \mathbf{CG} + \mathbf{D}$. By recursive backward substitution of (58), and given the initial conditions $\boldsymbol{\phi}_{-1} = \mathbf{0}_{4\times1}$, this can be written as

$$\boldsymbol{\phi}_t = -\sum_{s=0}^{t} \mathbf{N}^s \left(\mathbf{C} \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} E_{t-s} \mathbf{z}_{t-s+j} \right). \tag{59}$$

From the first-order condition (19) of the central bank's problem, we have $b_r (r_t - r^*) + \frac{\omega_s}{\sigma} \phi_{2,t} - \phi_{4,t} = 0$ which, making use of the solution (58) and lagging (19) by one period, can be re-written as

$$\begin{aligned} & b_r (r_t - r^*) \\ &= \begin{pmatrix} 1 \\ -\frac{\omega_s}{\sigma} \end{pmatrix}' \left\{ \begin{bmatrix} N_{21}\phi_{1,t-1} + N_{22}\phi_{2,t-1} + N_{23}\phi_{3,t-1} + N_{24}\left(b_r (r_{t-1} - r^*) + \frac{\omega_s}{\sigma}\phi_{2,t-1}\right) \\ N_{41}\phi_{1,t-1} + N_{42}\phi_{2,t-1} + N_{43}\phi_{3,t-1} + N_{44}\left(b_r (r_{t-1} - r^*) + \frac{\omega_s}{\sigma}\phi_{2,t-1}\right) \end{bmatrix} \right. \\ & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad + \left. \begin{pmatrix} \mathbf{C}_2 \\ \mathbf{C}_4 \end{pmatrix} \right\} \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} E_t \mathbf{z}_{t+j}. \end{aligned}$$

where N_{ij} refers to the (i,j)-th element of the matrix $\mathbf{N}$ and $\mathbf{C}_i$ refers to the i-th row of matrix $\mathbf{C}$. Using (59) we can re-write this as

$$(r_t - r^*) = \rho_r (r_{t-1} - r^*) - \boldsymbol{\Theta}_b \sum_{s=0}^{t-1} \mathbf{N}^s \mathbf{C} \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} E_{t-s} \mathbf{z}_{t+j-s-1} - \boldsymbol{\Theta}_f \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} E_t \mathbf{z}_{t+j}$$

where

$$\begin{aligned} \rho_r &= N_{44} - \frac{\omega_s}{\sigma} N_{24}, \\ \boldsymbol{\Theta}_b &= b_r^{-1} \begin{pmatrix} 1 \\ -\frac{\omega_s}{\sigma} \end{pmatrix}' \begin{pmatrix} N_{21} & \left(N_{22} + \frac{\omega_s}{\sigma} N_{24}\right) & N_{23} \\ N_{41} & \left(N_{42} + \frac{\omega_s}{\sigma} N_{44}\right) & N_{43} \end{pmatrix} \begin{pmatrix} \mathbf{I}_3 & \mathbf{0}_{3\times1} \end{pmatrix}, \\ \boldsymbol{\Theta}_f &= b_r^{-1} \begin{pmatrix} 1 \\ -\frac{\omega_s}{\sigma} \end{pmatrix}' \begin{pmatrix} \mathbf{C}_2 \\ \mathbf{C}_4 \end{pmatrix}. \end{aligned}$$

In the model, it was assumed that $\mathbf{z}_t$ follows a first-order Markov process given by the transition matrix $\mathbf{M}$ where $\mathbf{M}$ is a stable matrix. Therefore, the interest rate process can be further solved in terms of the primitive shocks as (22), given below:

$$r_t = (1 - \rho_r) r^* + \rho_r r_{t-1} - \boldsymbol{\Theta}_b \sum_{s=0}^{t-1} \mathbf{N}^s \mathbf{C} \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} \mathbf{M}^j \mathbf{z}_{t-s-1} - \boldsymbol{\Theta}_f \sum_{j=0}^{\infty} \mathbf{H}^{-(j+1)} \mathbf{F} \mathbf{M}^j \mathbf{z}_t.$$

The optimal interest-rate process under the pre-commitment policy results in an inertial rule so long as $N_{44} - \frac{\omega_s}{\sigma} N_{24} \neq 0$. This rule is both forward and backward looking in terms of past and current forecasts of foreign and domestic technology shocks, since $\boldsymbol{\Theta}_b \neq 0$ and $\boldsymbol{\Theta}_f \neq 0$. Finally, since the coefficient on lag interest rate, ρ_r, is independent of $\mathbf{M}$, the inertia in policy under pre-commitment in this small open-economy-model is not an artefact of serial correlation in the exogenous stochastic processes $\mathbf{z}_t$.

C Hybrid Phillips curves

As an alternative to the purely forward-looking Phillips curve model, we apply the approach of Amato and Laubach (2003) in generalizing the New-Keynesian Phillips curve for the domestic and imported goods sectors. The modification essentially allows for a fraction of domestic and foreign goods firms to set prices as a function of their own historical prices. Specifically, we have the following assumption. Suppose now, at the beginning of each period, nature draws from fixed a geometric distribution and determines with probability $\lambda_r^j \in (0,1)$, and $j = H, F$, that a firm will get to set price according to the Calvo model, so that the optimal price for domestic and foreign goods firms will be, respectively:

$$P_{F,t}^{opt} = P_{F,t}\left(\frac{\varepsilon}{\varepsilon-1}\right)\frac{E_t\sum_{k=0}^{\infty}Q_{t,t+k}\theta_F^k\left(\frac{P_{F,t}}{P_{F,t+k}}\right)^{-1-\varepsilon}\left(\frac{\epsilon_{t+k}P_{F,t+k}^*}{P_{F,t+k}}\right)C_{F,t+k}}{E_t\sum_{k=0}^{\infty}Q_{t,t+k}\theta_F^k\left(\frac{P_{F,t}}{P_{F,t+k}}\right)^{-\varepsilon}C_{F,t+k}} \tag{60}$$

$$P_{H,t}^{opt} = P_{H,t}\left(\frac{\varepsilon}{\varepsilon-1}\right)\frac{E_t\sum_{k=0}^{\infty}Q_{t,t+k}\theta_H^k\left(\frac{P_{H,t}}{P_{H,t+k}}\right)^{-1-\varepsilon}\left(\frac{MC_{H,t+k}}{P_{H,t+k}}\right)C_{H,t+k}}{E_t\sum_{k=0}^{\infty}Q_{t,t+k}\theta_H^k\left(\frac{P_{H,t}}{P_{H,t+k}}\right)^{-\varepsilon}C_{H,t+k}} \tag{61}$$

Otherwise each type respectively will end up, with probability $1-\lambda_r^j$, setting a price according to the rule of thumb: $P_{j,t}^{rot} = P_{j,t-1}^{new}\left(\frac{P_{j,t-1}}{P_{j,t-2}}\right)$; $j = H, F$. This basically says that rule-of-thumb price setters will base their current pricing strategy on last period's aggregate price, $P_{j,t-1}^{new}$, which includes forward-looking and backward-looking prices, times gross inflation between two periods. We assume that the new aggregate price is given by the index

$$P_{j,t}^{new} = \left[\left(1-\lambda_r^j\right)\left(P_{j,t}^{rot}\right)^{1-\varepsilon} + \lambda_r^j\left(P_{j,t}^{opt}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} \tag{62}$$

Some algebraic manipulation will produce the more general New-Keynesian Phillips curve for domestic and foreign goods, respectively, as (33) and (34).

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Table 1: Targeting Regimes, delegation and welfare: Benchmark economy

	Commitment	**Discretion**		
	(a) Social	(b) Social	(c) Delegation	(d) Smoothing
	$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.25$	$b_w^* = 0.41$
	$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.28$
Outcomes				
Social Loss ($\times 100$)	0.105	1.166	0.486	0.280
Pre-commitment gain, $\widetilde{\pi}$	0	1.030	0.617	0.418
Standard deviation:				
interest rate, r_t	0.045	0.148	0.119	0.079
interest rate change, $\triangle r_t$	0.029	0.117	0.093	0.052
output gap, $\widetilde{y}_t$	0.022	0.022	0.022	0.031
nominal exchange rate, e_t	1.787	2.409	2.221	1.894
CPI inflation, π_t	0.020	0.084	0.043	0.033
real exchange rate, q_t	0.897	0.803	0.819	0.814

Table 2: Targeting Regimes, delegation and welfare under high pass through, $\theta_F = 0.4$

	Commitment	**Discretion**		
	(a) Social	(b) Social	(c) Delegation	(d) Smoothing
	$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.3$	$b_w^* = 0.44$
	$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.2$
Outcomes				
Social Loss ($\times 100$)	0.139	0.419	0.269	0.195
Pre-commitment gain, $\widetilde{\pi}$	0	0.529	0.361	0.237
Standard deviation:				
interest rate, r_t	0.067	0.117	0.104	0.084
interest rate change, $\triangle r_t$	0.045	0.092	0.081	0.060
output gap, $\widetilde{y}_t$	0.017	0.018	0.019	0.022
nominal exchange rate, e_t	1.890	2.198	2.105	1.955
CPI inflation, π_t	0.019	0.036	0.019	0.018
real exchange rate, q_t	0.880	0.879	0.880	0.879

Table 3: Targeting Regimes, delegation and welfare under low pass through, $\theta_F = 0.99$

	Commitment	**Discretion**		
	(a) Social	(b) Social	(c) Delegation	(c) Smoothing
	$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.9$	$b_w^* = 0.26$
	$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.1$
Outcomes				
Social Loss ($\times 100$)	0.174	0.728	0.339	0.241
Pre-commitment gain, $\widetilde{\pi}$	0	0.744	0.406	0.259
Standard deviation:				
interest rate, r_t	0.069	0.153	0.105	0.087
interest rate change, $\triangle r_t$	0.049	0.120	0.082	0.061
output gap, $\widetilde{y}_t$	0.024	0.041	0.012	0.026
nominal exchange rate, e_t	1.637	2.456	2.075	1.875
CPI inflation, π_t	0.022	0.042	0.034	0.024
real exchange rate, q_t	1.273	1.387	2.075	1.348

Table 4: Targeting Regimes under benchmark pass through, $\theta_F = 0.75$, with alternative shocks

		Commitment	**Discretion**		
		(a) Social	(b) Social	(c) Delegation	(d) Smoothing
		$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.25$	$b_w^* = 0.41$
		$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.28$
Outcomes					
Social Loss ($\times 100$):	Case 1	0.062	1.019	0.356	0.154
	Case 2	0.043	0.148	0.130	0.125
Pre-commitment gain, $\widetilde{\pi}$:	Case 1	0	0.970	0.542	0.303
	Case 2	0	0.324	0.295	0.286
Standard deviation:					
interest rate, r_t:	Case 1	0.038	0.127	0.094	0.066
	Case 2	0.025	0.076	0.073	0.043
interest rate change, $\triangle r_t$:	Case 1	0.027	0.100	0.074	0.044
	Case 2	0.011	0.060	0.057	0.029
output gap, $\widetilde{y}_t$:	Case 1	0.019	0.005	0.007	0.019
	Case 2	0.010	0.022	0.020	0.024
nominal exchange rate, e_t:	Case 1	0.431	1.273	0.935	0.720
	Case 2	1.735	2.046	2.012	1.752
CPI inflation, π_t:	Case 1	0.013	0.083	0.042	0.022
	Case 2	0.016	0.008	0.004	0.024
real exchange rate, q_t:	Case 1	0.552	0.537	0.564	0.570
	Case 2	0.707	0.597	0.594	0.581

Note:

a. Case 1 corresponds to $\sigma_z^* = 0$ and $\sigma_z = 1$ and Case 2 is when $\sigma_z^* = 1$ and $\sigma_z = 0$.

b. Optimized parameters $b_w^*, b_r^*, b_{\triangle r}^*$ are w.r.t. benchmark case with all shocks in Table 1.

Table 5: Targeting Regimes under low pass through, $\theta_F = 0.4$, with alternative shocks

		Commitment	**Discretion**		
		(a) Social	(b) Social	(c) Delegation	(c) Smoothing
		$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.3$	$b_w^* = 0.44$
		$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.2$
Outcomes					
Social Loss ($\times 100$):	Case 1	0.071	0.300	0.166	0.114
	Case 2	0.069	0.120	0.103	0.081
Pre-commitment gain, $\widetilde{\pi}$:	Case 1	0	0.479	0.308	0.207
	Case 2	0	0.226	0.184	0.110
Standard deviation:					
interest rate, r_t:	Case 1	0.050	0.093	0.079	0.066
	Case 2	0.045	0.071	0.067	0.052
interest rate change, $\triangle r_t$:	Case 1	0.035	0.073	0.062	0.047
	Case 2	0.028	0.056	0.053	0.037
output gap, $\widetilde{y}_t$:	Case 1	0.016	0.004	0.010	0.012
	Case 2	0.006	0.018	0.017	0.018
nominal exchange rate, e_t:	Case 1	0.504	0.934	0.790	0.697
	Case 2	1.822	1.990	1.951	1.826
CPI inflation, π_t:	Case 1	0.009	0.035	0.019	0.014
	Case 2	0.016	0.006	0.001	0.010
real exchange rate, q_t:	Case 1	0.616	0.617	0.620	0.617
	Case 2	0.628	0.625	0.624	0.626

Note:

a. Case 1 corresponds to $\sigma_z^* = 0$ and $\sigma_z = 1$ and Case 2 is when $\sigma_z^* = 1$ and $\sigma_z = 0$.

b. Optimized parameters $b_w^*, b_r^*, b_{\triangle r}^*$ are w.r.t. benchmark case with all shocks in Table 2.

Table 6: Targeting Regimes under low pass through, $\theta_F = 0.99$, with alternative shocks

		Commitment	**Discretion**		
		(a) Social	(b) Social	(c) Delegation	(c) Smoothing
		$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.9$	$b_w^* = 0.26$
		$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.1$
Outcomes					
Social Loss ($\times 100$):	Case 1	0.157	0.433	0.183	0.179
	Case 2	0.017	0.295	0.157	0.062
Pre-commitment gain, $\widetilde{\pi}$:	Case 1	0	0.525	0.161	0.148
	Case 2	0	0.527	0.374	0.212
Standard deviation:					
interest rate, r_t:	Case 1	0.067	0.131	0.086	0.079
	Case 2	0.013	0.080	0.061	0.037
interest rate change, $\triangle r_t$:	Case 1	0.047	0.103	0.067	0.055
	Case 2	0.011	0.062	0.048	0.026
output gap, $\widetilde{y}_t$:	Case 1	0.021	0.039	0.012	0.024
	Case 2	0.012	0.011	0.001	0.011
nominal exchange rate, e_t:	Case 1	0.715	1.310	0.855	0.833
	Case 2	1.473	2.077	1.891	1.679
CPI inflation, π_t:	Case 1	0.021	0.011	0.017	0.016
	Case 2	0.008	0.040	0.029	0.017
real exchange rate, q_t:	Case 1	0.816	1.121	0.953	0.941
	Case 2	0.977	0.817	0.886	0.966

Note:
a. Case 1 corresponds to $\sigma_z^* = 0$ and $\sigma_z = 1$ and Case 2 is when $\sigma_z^* = 1$ and $\sigma_z = 0$.
b. Optimized parameters $b_w^*, b_r^*, b_{\triangle r}^*$ are w.r.t. benchmark case with all shocks in Table 3.

Table 7: Rule-of-Thumb Pricing as Deviation from Benchmark, $\lambda_r^H = \lambda_r^F = 0.8$

	Commitment	**Discretion**		
	(a) Social	(b) Social	(c) Delegation	(d) Smoothing
	$b_w = 0.5$	$b_w = 0.5$	$b_w^* = 0.25$	$b_w^* = 0.41$
	$b_r = 0.2$	$b_r = 0.2$	$b_r^* = 0.1$	$b_{\triangle r}^* = 0.28$
Outcomes				
Social Loss ($\times 100$)	0.115	2.272	0.744	0.288
Pre-commitment gain, $\widetilde{\pi}$	0	1.469	0.793	0.416
Standard deviation:				
interest rate, r_t	0.046	0.190	0.136	0.079
interest rate change, $\triangle r_t$	0.033	0.144	0.104	0.053
output gap, $\widetilde{y}_t$	0.021	0.032	0.021	0.030
nominal exchange rate, e_t	1.771	2.766	2.356	1.856
CPI inflation, π_t	0.022	0.122	0.060	0.034
real exchange rate, q_t	0.906	0.800	0.822	0.820

Note:
a. Policy weights are from Table 1.

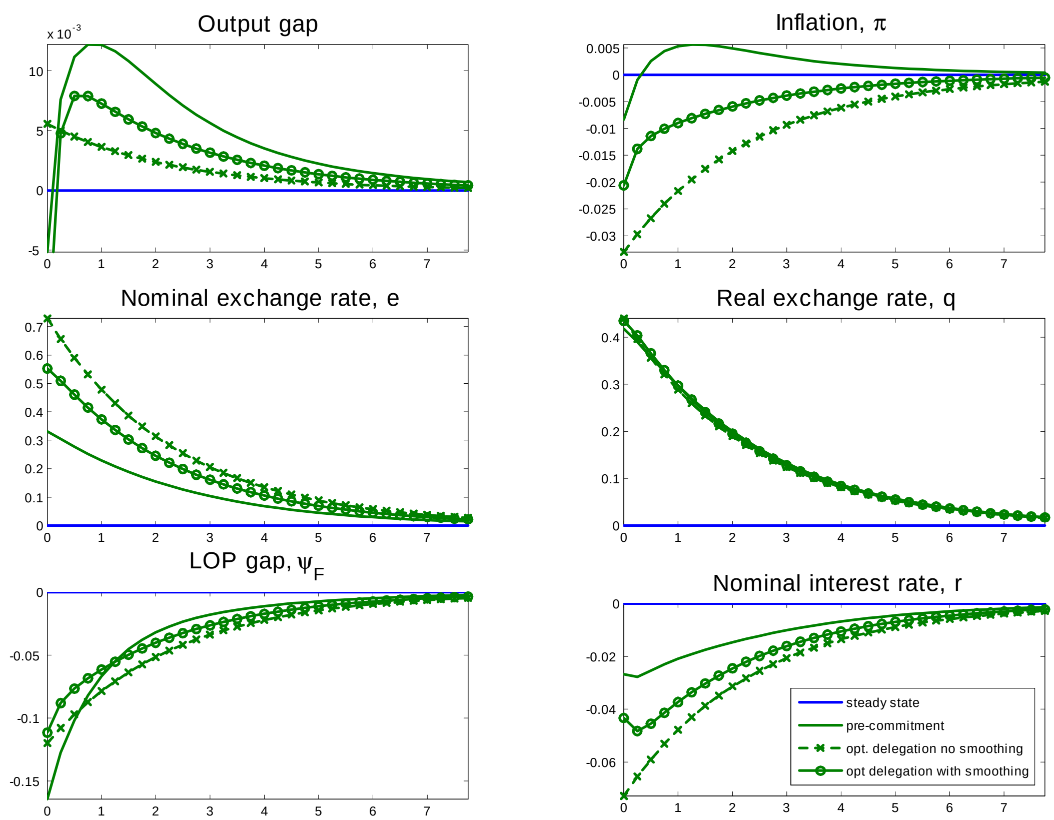

Figure 1: Impulse responses to domestic technology shock: benchmark economy.

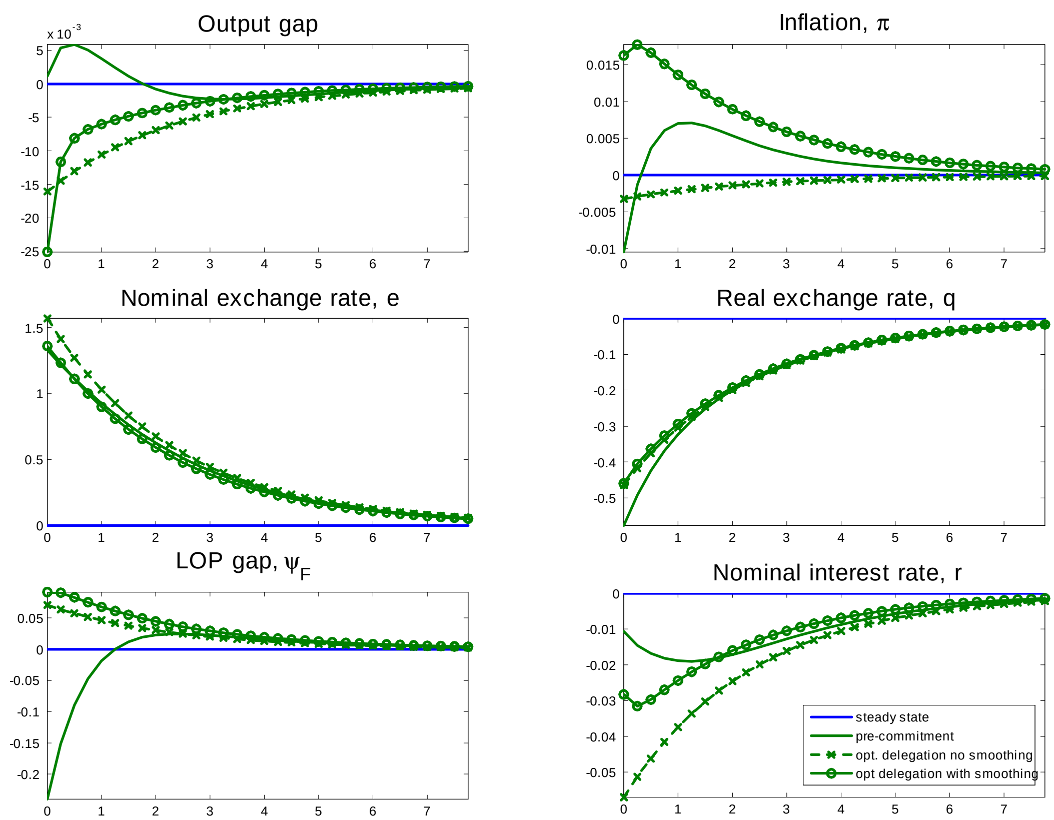

Figure 2: Impulse responses to foreign technology shock: benchmark economy.