PRICING POLICIES AND INFLATION DYNAMICS

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Abstract

The paper proposes a New Keynesian monetary model where firms set pricing policies that feature forward-looking optimal indexation of the rate of price growth. The model shares several desirable features with the popular alternative of backward-looking automatic indexation to aggregate inflation. Most importantly, in response to persistent monetary shocks it generates a gradual and persistent reaction of the inflation rate. But under backward-looking indexation gradual and persistent inflation dynamics are also observed for very transitory monetary shocks and for technology shocks, while under optimal indexation inflation dynamics are highly dependent on agents' rational assessment of the nature and persistence of shocks.

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1 Introduction

A large and growing body of research in monetary theory uses the assumption of nominal rigidities embedded in dynamic general equilibrium models with rational expectations. Comprehensive surveys of this literature and its successes can be found in Taylor (1998), Clarida, Galí and Gertler (1999), Lane (2001), Galí (2003) and Woodford (2003). The resurgence of this model class is based both on much improved theoretical foundations and on empirical arguments. The time-dependent price adjustment formulations of Taylor (1980), Rotemberg (1982) and Calvo (1983) made it possible to incorporate nominal rigidities into rational expectations models with forward-looking optimizing agents. Empirical support came from evidence showing that monetary policy has significant short-run real effects, such as Christiano, Eichenbaum and Evans (1996, 1998) and Leeper, Sims and Zha (1996).

Whether the inflation specifications derived from this model class can fully account for the short-run empirical properties of inflation and output has recently been much debated.[1] Mankiw (2001) notes that they do not generate the empirically observed delayed and gradual initial response of inflation to monetary policy shocks, a phenomenon that we will refer to as *inflation inertia*. Fuhrer and Moore (1995) show that they also do not generate the observed very prolonged steady state deviations of inflation following shocks, a phenomenon that is generally referred to as *inflation persistence*. Persistence is a general property of the inflation process, but inertia has mainly been identified in response to monetary policy shocks, a fact that will be important in our evaluation of alternative pricing assumptions.[2] Finally, this model class implies that inflation-stabilization policies have minimal real costs. This is also inconsistent with a large body of empirical evidence (Gordon (1982, 1997)) which shows that disinflationary policies give rise to *recessions*.

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[1] See Rudd and Whelan (2006, 2007) for critical reviews.

[2] For example, Dedola and Neri (2007) find no evidence of inflation inertia following technology shocks.

In this paper we use a tractable generalization of the Calvo (1983) staggered pricing model first introduced in an open economy continuous time setting by Calvo, Celasun and Kumhof (2002, 2007). The model contains the basic Calvo (1983) model as a special case. But it is also capable of generating inflation inertia, inflation persistence and recessionary disinflations. Its main difference to conventional treatments is in its specification of firms' price setting behavior, where we assume that once a firm receives an opportunity to change its pricing policy, it jointly and optimally chooses an initial price level and an unconditional rate at which it will update its price in the future. In this specification, which we refer to as the optimal indexation model, an unexpected and credibly permanent decline in the steady state inflation rate targeted by monetary policy entails a slow and drawn-out inflation response and output losses. The main reason is that for such a shock the model's inflation process is mainly driven by a slow-moving state variable, the weighted average of historically chosen updating rates. The real interest rate increase induced by the slow inflation response gives rise to a recession.

Similar to Christiano, Eichenbaum and Evans (2005) and many other papers in this literature, our motivation for nominal rigidities is based on costs of reoptimization, such as costs of information gathering, decision making, negotiation and communication. The implication is that firms can *change* prices every quarter, but that they *reoptimize* their pricing policies much more infrequently. In the meantime they must therefore follow a pricing policy that does not respond to news about the aggregate state of the economy. The critical question for inflation dynamics turns out to be what class of pricing policies the model allows.

Before turning to that question, we emphasize that the bulk of the direct empirical evidence on price setting is concerned with the average frequency of price changes, not with the average frequency of reoptimizations or with the form of pricing policies between reoptimizations. Examples are Bils and Klenow (2004), Klenow and Kryvtsov (2005), and Golosov and Lucas (2003), who find an average frequency of price changes of once every 1.5 quarters for consumer prices. The assumption that prices between reoptimizations change on a quarterly basis is therefore preferable to the assumption that they do not change at all, especially because much of the empirical macro literature suggests working with a calibration in which reoptimizations are more than one year apart. The choice of a particular form of pricing policy between reoptimizations on the other hand is almost impossible to validate by recourse to price data. This is because there is great heterogeneity in pricing behavior across firms (ECB (2005)), and more importantly because a large part of an individual firm's pricing behavior is driven by idiosyncratic factors rather than by its response to aggregate conditions. But it *is* possible to distinguish and choose between alternative pricing assumptions by comparing their macroeconomic implications, and that is the course we take in this paper.

In the existing literature there are now a number of approaches to specifying the form of pricing policies permitted by the model. We focus our comparison on two especially popular ones. The first and earlier approach (Yun (1996)), which we will refer to as the Calvo-Yun model, has firms choosing only their initial price level and thereafter updating their prices at the current steady state inflation rate. This implies that only the aggregate price level is sticky while inflation is flexible. The model therefore exhibits no inflation inertia whatsoever, and disinflations are not recessionary. This led the literature (Christiano, Eichenbaum and Evans (2005)) to adopt another specification where firms again choose only their initial price level, but where they subsequently update their prices at the lagged aggregate inflation rate. We will refer to this approach, which does produce highly inertial and persistent inflation and costly disinflations, as the backward indexation model.[3] But this model has been criticized by Rudd and Whelan (2007) because, at least as far as price setting is concerned, its microfoundations are weak, and it is as open to the Lucas critique as the traditional econometric Phillips curve models it seeks to replace. Our paper will confirm

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[3] The 'hybrid' New Keynesian model, first introduced by Clarida, Galí and Gertler (1999) and Galí and Gertler (1999), can be derived from the same microfoundations. It also allows for an intermediate case where a fraction of agents indexes to steady state inflation and another fraction indexes to lagged aggregate inflation.

this critique, by showing that the backward indexation model exhibits inflation inertia and persistence that is not only high but also almost invariant to the nature and persistence of the underlying shocks. More importantly, we show that the optimal indexation model provides an alternative that is capable of addressing the shortcomings of the Calvo-Yun model as well as the backward indexation model, to the extent that these shortcomings arise mainly when monetary shocks are highly persistent, as in a disinflation. On the other hand, when monetary shocks are transitory, or under technology shocks, optimizing price setters behave very similarly to Calvo-Yun agents. This greater ability of optimal indexation to respond to the nature of shocks is due to the fact that it imposes fewer constraints on firms' optimization problem, by giving them a larger number of choice variables. As such it is somewhat less arbitrary or ad hoc than the alternatives. It is also better suited to confront the empirical evidence, which points to a substantial decline in U.S. inflation persistence since the early 1980s.

Any model adopting the Calvo (1983) timing assumption for pricing policies is a model of inattention, of random duration, to news about the state of the economy. This is so because firms do not revise their pricing policies in response to new information that arrives between random reoptimization opportunities. The seminal work on rational inattention of Reis (2006) improves dramatically on random inattention, first by making the end date of a given pricing policy part of firms' optimization problem (which features a fixed cost of reoptimizing), and second by allowing agents to choose any arbitrary, rather than log-linear, price paths. But the benefit of the more restricted optimal indexation model, with random inattention and log-linear firm specific price paths, is that the state space of the economy is dramatically simplified. Standard linearization methods can therefore be applied to solve for the equilibrium dynamics in a fully microfounded stochastic model. Similar comments apply in relation to the work on sticky information of Mankiw and Reis (2002), where the beliefs of agents that last updated their information arbitrarily far in the past are state variables. The number of state variables is therefore infinite, and standard solution methods of the type used in this paper cannot be used.[4] We will show in this paper that, despite our simplifying assumptions about the timing and form of pricing decisions, some of the most important macroeconomic phenomena that we seek to explain, inflation inertia, inflation persistence and recessionary disinflations, do arise in the optimal indexation model. The critical assumption leading to this result is the existence, rather than the precise form, of firm-specific price paths. This assumption implies that inflation will at all times be determined not only by current price setters, as in the Calvo-Yun model, but also by the firm-specific inflation rates chosen by historic price setters who have not updated their information about the stance of monetary policy.

This also means that the predictions of our model for a disinflation share an important feature with models of learning about monetary policy. In particular, a measure of expected inflation lags actual inflation for a long period during a disinflation, as in the influential paper of Erceg and Levin (2003). Under learning the reason is a lack of stability and credibility of monetary policy, while under optimal indexation the reason is the high persistence of monetary policy shocks. Given that periods of unstable or non-credible monetary policies are often characterized by persistent changes in the inflation target, we see learning and optimal indexation as highly complementary approaches that can contribute to explaining similar phenomena.

The rest of the paper is organized as follows. Section 2 contains a detailed exposition of the optimal indexation model, and a brief discussion of the pricing blocks of the alternative Calvo-Yun and backward indexation models. Section 3 discusses model calibration and solution, presents impulse responses to develop intuition, and then compares inflation inertia and inflation persistence in the three models in more depth by examining the initial jumps and autocorrelation functions of inflation. Section 4 concludes.[5]

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[4] Another example is Burstein (2006), who provides a state-dependent pricing model in which firms can set nonlinear price paths. Because of this nonlinearity, the model cannot be solved with conventional perturbation methods. Instead the paper focuses on the perfect foresight case and uses a nonlinear solution method.

[5] A separate Technical Appendix contains detailed derivations of optimality conditions.

2 The Model

The economy consists of a continuum of measure one of identical price-taking infinitely-lived households, a continuum indexed by $j \in [0,1]$ of monopolistically competitive infinitely-lived firms, and a government. All our main results can be obtained using a simple baseline model with sticky prices and flexible wages. We will at one point briefly discuss a sticky wage and sticky price economy, but to conserve space the algebra for that case is only presented in the Technical Appendix.

2.1 Households

Households maximize lifetime utility, which depends on their per capita consumption c_t, labor effort L_t, and real money balances M_t/P_t (where M_t is nominal money and P_t is the aggregate price index). Their objective function is

$$Max \quad E_t \Sigma_{k=0}^{\infty} \beta^k \left\{ \ln\left(C_{t+k}\right) - \frac{\kappa}{1+\gamma} L_{t+k}^{1+\gamma} + \frac{a}{1-\epsilon} \left(\frac{M_{t+k}}{P_{t+k}} \right)^{1-\epsilon} \right\} , \tag{1}$$

where E_t is the expectations operator, β is the discount factor, γ is the inverse of the Frisch elasticity of labor supply, and ϵ determines the interest elasticity of money demand. Households exhibit internal habit persistence in consumption, with habit parameter ν:[6]

$$C_t = c_t - \nu c_{t-1} \quad . \tag{2}$$

Consumption c_t is a CES aggregator over individual varieties $c_t(j)$, with elasticity of substitution $\sigma > 1$:

$$c_t = \left[\int_0^1 c_t(j)^{\frac{\sigma-1}{\sigma}} dj \right]^{\frac{\sigma}{\sigma-1}} \quad . \tag{3}$$

The aggregate price index P_t is the consumption based price index associated with this consumption aggregator,

$$P_t = \left[\int_0^1 P_t(j)^{1-\sigma} dj \right]^{\frac{1}{1-\sigma}} \quad , \tag{4}$$

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[6] Habit persistence is not essential for our main results. Its only role is to produce more reasonable, U-shaped instead of V-shaped, output responses.

where $P_t(j)$ is the price of variety j. In addition to money households hold one period nominal government bonds B_t with gross nominal return i_t. Their income consists of nominal wage income W_tL_t determined in a competitive labor market, lump-sum profit redistributions from firms $\int_0^1 \Pi_t(j)dj$, and lump-sum transfers from the government $P_t\tau_t$. Households' budget constraint is

$$B_t = i_{t-1}B_{t-1} + M_{t-1} - M_t + W_tL_t + \int_0^1 \Pi_t(j)dj + P_t\tau_t - P_tc_t \quad . \tag{5}$$

We denote the multiplier of this budget constraint by Λ_t, and let $\lambda_t = \Lambda_t P_t$. Then the first-order conditions with respect to $c_t(j)$, c_t, L_t and B_t are

$$c_t(j) = c_t \left(\frac{P_t(j)}{P_t}\right)^{-\sigma} \quad , \tag{6}$$

$$C_t^{-1} - \beta\nu E_t C_{t+1}^{-1} = \lambda_t \quad , \tag{7}$$

$$\kappa L_t^{\gamma} = \lambda_t w_t \quad , \tag{8}$$

$$\lambda_t = \beta i_t E_t \left(\frac{\lambda_{t+1}}{\pi_{t+1}}\right) \quad , \tag{9}$$

where $w_t = W_t/P_t$ and $\pi_t = P_t/P_{t-1}$. Because the central bank will be assumed to follow an interest rate rule, the first-order condition for money is redundant. We proceed to linearize conditions (7) - (9) and (2) around the steady state. A hat above a variable denotes its log deviation from steady state, e.g. $\hat{x}_t = \ln(x_t/\bar{x})$, where $\bar{x}$ is the steady state of x_t. We assume that the inflation target π_t^* of the central bank follows a unit root process $\pi_t^* = \pi_{t-1}^*\varepsilon_t^{\pi^*}$, and note that linearization of inflation rates is always performed around the current inflation target, for example $\hat{\pi}_{t+1} = \ln(\pi_{t+1}) - \ln(\pi_t^*)$. The linearized first-order conditions are

$$\frac{\beta\nu}{1-v}E_t\hat{c}_{t+1} = \frac{1+\beta\nu^2}{1-v}\hat{c}_t - \frac{v}{1-v}\hat{c}_{t-1} + (1-\beta\nu)\hat{\lambda}_t \quad , \tag{10}$$

$$E_t\left(\hat{\lambda}_{t+1} - \hat{\pi}_{t+1}\right) = \hat{\lambda}_t - \hat{\imath}_t \quad , \tag{11}$$

$$\hat{w}_t + \hat{\lambda}_t = \gamma\hat{L}_t \quad . \tag{12}$$

2.2 Firms

Each firm $j \in [0,1]$ sells a distinct product variety. Heterogeneity in price setting decisions and therefore in demand for individual products arises because each firm receives its price changing opportunities at different, random points in time. Following Calvo (1983) it is assumed that these opportunities follow a geometric distribution, so that the probability $(1-\delta)$ of a firm's receiving a new opportunity is independent of how long ago it was last able to change its price. It is also independent across firms, so that it is straightforward to determine the aggregate distribution of prices. We assume that firms' output $y_t(j)$ is produced via linear production functions in labor input $\ell_t(j)$:

$$y_t(j) = z_t \ell_t(j) \quad . \tag{13}$$

Aggregate output y_t is defined as

$$y_t = \left(\int_0^1 y_t(j)^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma}{\sigma-1}} \quad . \tag{14}$$

For productivity z_t we assume $\bar{z} = 1$ and the following law of motion:

$$\hat{z}_t = \rho^z \hat{z}_{t-1} + \hat{\varepsilon}_t^z \quad . \tag{15}$$

Firms have market power and therefore set the prices of their varieties $P_t(j)$ to maximize profits taking into account consumers' demand for their variety (6):

$$y_t(j) = c_t \left(\frac{P_t(j)}{P_t} \right)^{-\sigma} \quad . \tag{16}$$

Under optimal indexation, when a firm j gets an opportunity to decide on its pricing policy, it chooses both its current price level V_t^j and the rate v_t^j at which it will update its price from today onwards until the time it is next allowed to change its policy. At any time $t+k$ when the time t policy is still in force, its price is therefore

$$P_{t+k}(j) = V_t^j (v_t^j)^k \quad . \tag{17}$$

Firms discount nominal profits expected in period $t+k$ by the intertemporal marginal rate of substitution and by δ^k, the probability that their period t pricing policy will still be in force k periods from t. Nominal revenue and the nominal wage bill at t equal $P_t(j)y_t(j)$ and $W_t\ell_t(j)$. Firms' problem is therefore

$$\underset{V_t^j, v_t^j}{Max} \quad E_t\Sigma_{k=0}^{\infty}\left(\delta\beta\right)^k\lambda_{t+k}\left[\frac{P_{t+k}(j)y_{t+k}(j)}{P_{t+k}} - w_{t+k}\ell_{t+k}(j)\right] \quad , \tag{18}$$

subject to (13), (16) and (17). Note that in stating the optimality conditions the firm specific index j can be dropped because all firms that get a price changing opportunity at time t will behave identically. Let $p_t \equiv V_t/P_t$. We scale all inflation rates by the inflation target π_t^*, with notation $\breve{v}_t = v_t/\pi_t^*$, $\breve{\pi}_t = \pi_t/\pi_t^*$. Using this we can define cumulative aggregate normalized inflation as $\breve{\Pi}_{t,k} = \Pi_{j=1}^k\breve{\pi}_{t+j}$ for $k \geq 1$ ($\equiv 1$ for $k = 0$). The first-order condition with respect to V_t is then

$$p_t = \mu\frac{E_t\Sigma_{k=0}^{\infty}\left(\delta\beta\right)^k\lambda_{t+k}y_{t+k}(j)\frac{w_{t+k}}{z_{t+k}}}{E_t\Sigma_{k=0}^{\infty}\left(\delta\beta\right)^k\lambda_{t+k}y_{t+k}(j)\left(\frac{(\breve{v}_t)^k}{\breve{\Pi}_{t,k}}\right)} \quad , \tag{19}$$

and with respect to v_t we have

$$p_t = \mu\frac{E_t\Sigma_{k=0}^{\infty}\left(\delta\beta\right)^k k\lambda_{t+k}y_{t+k}(j)\frac{w_{t+k}}{z_{t+k}}}{E_t\Sigma_{k=0}^{\infty}\left(\delta\beta\right)^k k\lambda_{t+k}y_{t+k}(j)\left(\frac{(\breve{v}_t)^k}{\breve{\Pi}_{t,k}}\right)} \quad , \tag{20}$$

where $\mu = \sigma/(\sigma - 1)$. Before analyzing these conditions further we need to describe government policy and define equilibrium.

2.3 Government

The government's fiscal policy is assumed to be Ricardian. In particular, we assume that the government budget is balanced period by period through lump-sum taxes/transfers, and that the initial stock of government bonds is zero. The budget constraint is therefore simply:

$$\tau_t = \frac{M_t - M_{t-1}}{P_t} \quad . \tag{21}$$

We assume that the central bank pursues the following interest rate rule for its policy instrument i_t:

$$i_t = \frac{\pi_t^*}{\beta}E_t\left(\frac{\pi_{t+1}}{\pi_t^*}\right)^{\phi}\left(\frac{y_t}{y_t^n}\right)^{\theta}\left(h_t\right)^{\phi-1} \quad . \tag{22}$$

The first component on the right-hand side equals the long-run gross nominal interest rate at the current inflation target π_t^*. Permanent disinflations correspond to shocks $\varepsilon_t^{\pi^*}$ to the unit root process of this target. The law of motion for the inflation target is

$$\hat{\pi}_t^* = \hat{\pi}_{t-1}^* + \hat{\varepsilon}_t^{\pi^*} \ . \tag{23}$$

The nominal interest rate responds to expected one-period ahead[7] deviations of inflation from its target, and to deviations of output from the natural or flexible price rate of output y_t^n, with response coefficients ϕ and θ. The natural rate of output is given by the solution for output of the flexible price version of our model economy. Finally, h_t is a zero mean autocorrelated monetary policy shock with law of motion

$$\hat{h}_t = \rho^h \hat{h}_{t-1} + \hat{\varepsilon}_t^h \quad . \tag{24}$$

The coefficient of this shock in the monetary policy rule $(\phi - 1)$ ensures that a permanent shock of given size to h_t has the same long run effect on inflation as a shock of the same size to the inflation target π_t^*. After normalizing the nominal interest rate by the inflation target ($\check{i}_t = i_t/\pi_t^*$), the rule (22) can be linearized (noting that $E_t \hat{\varepsilon}_{t+1}^{\pi^*} = 0$) as

$$\hat{\imath}_t = \phi E_t \hat{\pi}_{t+1} + \theta \left(\hat{y}_t - \hat{y}_t^n \right) + (\phi - 1) \hat{h}_t \quad . \tag{25}$$

In the literature an alternative to this rule is very popular, namely one that adds a lag of the interest rate, also known as interest rate smoothing, as in Clarida, Galí and Gertler (1999). We have therefore checked the robustness of our results to that alternative, and found that all our main results are unaffected, except for one detail concerning inflation persistence. For that one case we will work with the following alternative specification:

$$\hat{\imath}_t = \rho^i \hat{\imath}_{t-1} + \left(1 - \rho^i\right) \left(\phi E_t \hat{\pi}_{t+1} + \theta \left(\hat{y}_t - \hat{y}_t^n \right) + (\phi - 1) \hat{h}_t \right) \quad . \tag{26}$$

Furthermore, rule (25) is supported empirically by the work of Rudebusch (2002, 2006), who shows that interest rate smoothing would imply a large amount of forecastable variation

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[7] We have also considered an alternative rule where the nominal interest rate instead responds to current inflation. While this changes some details, our main results are unaffected.

in interest rates at horizons of more than three months, which is contradicted by evidence from the term structure of interest rates. Highly persistent shocks are shown not to imply a large forecastable variation. Rudebusch and Wu (2007) estimate a monetary policy rule that allows for both interest rate smoothing and autocorrelated shocks, after embedding that rule in a macro-finance model that directly exploits such term structure information. They find an interest rate smoothing parameter near zero and a coefficient of monetary policy shock autocorrelation very close to one.[8]

We define a *government policy* as a set of stochastic processes $\{i_s, \tau_s\}_{s=t}^{\infty}$ such that, given stochastic processes $\{M_s, P_s, y_s, z_s, h_s\}_{s=t}^{\infty}$, the conditions (21) and (22) hold for all $s \geq t$.

2.4 Equilibrium

A list of stochastic processes $\{B_s, M_s, c_s, L_s, y_s, y_s^n, c_s(j), \ell_s(j), y_s(j), j \in [0,1]\}_{s=t}^{\infty}$ is an *allocation*, and a list of stochastic processes $\{P_s, W_s, P_s(j), V_s^j, v_s^j, j \in [0,1]\}_{s=t}^{\infty}$ is a *price system*. *Shock processes* are a list of stochastic processes $\left\{\varepsilon_t^{\pi^*}, \varepsilon_s^h, \varepsilon_s^z\right\}_{s=t}^{\infty}$. Then equilibrium is defined as follows:

An equilibrium given initial conditions π_{-1}^*, h_{-1}, z_{-1} *and* P_{-1} *is an allocation, a price system, a government policy and shock processes such that*

(a) given the government policy, the price system and shock processes, the allocation solves the household's problem of maximizing (1) *subject to (2), (3) and* (5)*,*

(b) given the government policy, shock processes, the restrictions on price setting, and the sequences $\{P_s, W_s, c_s\}_{s=0}^{\infty}$*, the sequences* $\{V_s^j, v_s^j, j \in [0,1]\}_{s=0}^{\infty}$ *solve firms' problem of maximizing* (18)*,*

(c) the goods market clears for all goods and at all times, $y_t(j) = c_t(j) \quad \forall t, \forall j \in [0,1]$,

(d) the labor market clears at all times, $L_t = \int_0^1 \ell_t(j) dj \quad \forall t$,

(e) the bond market clears at all times, $B_t = 0 \quad \forall t$.

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[8] Rudebusch and Wu (2007) stress that such shocks represent responses by the Fed to a variety of persistent determinants beyond inflation and output. On the other hand, Charles Goodhart pointed out to us that they may also represent the effects on interest rates of autocorrelated inflation forecast errors.

It is straightforward to show that $\bar{L} = \bar{c} = \bar{y}$, and that

$$\hat{z}_t + \hat{L}_t = \hat{y}_t = \hat{c}_t \ . \tag{27}$$

2.5 Linearized Price Dynamics

Aggregate price dynamics can be derived by linearizing the price index (4) to obtain

$$\hat{\pi}_t = \frac{1-\delta}{\delta}\hat{p}_t + \hat{\psi}_t \quad , \tag{28}$$

$$\hat{\psi}_t = \delta\hat{\psi}_{t-1} + (1-\delta)\hat{v}_{t-1} - \hat{\varepsilon}_t^{\pi^*} \quad . \tag{29}$$

The state variable $\hat{\psi}_t$ is, in deviation form and allowing for changes in the inflation target, the weighted average of all those past firm-specific inflation rates that are still in force between periods $t-1$ and t, and which therefore enter into period t aggregate inflation.[9]

The two components of equation (28) reflect the reasons for inflation inertia in this model. Large jumps in current prices $\hat{p}_t$ can in principle cause large and immediate jumps in inflation. But when shocks to monetary policy are persistent, new price setters optimally respond mainly through changes in their updating rate $\hat{v}_t$. In that case inflation is dominated by the state variable $\hat{\psi}_t$, which moves slowly because it represents the continuing effects of price updating decisions made prior to the shock.

The complete pricing block of the optimal indexation model can be derived by combining (28) and (29) with linearized versions of the optimality conditions (19) and (20). Instead of the usual one-equation New Keynesian Phillips curve it consists of three equations, (29) for the state variable $\hat{\psi}_t$, and the following two difference equations for $\hat{\pi}_t$ and $\hat{v}_t$:

$$E_t\hat{v}_{t+1} = \hat{v}_t + \frac{(1-\delta\beta)^2}{(\delta\beta)^2}\frac{\delta}{1-\delta}\left(\hat{\psi}_t - \hat{\pi}_t\right) + \frac{(1-\delta\beta)^2}{(\delta\beta)^2}\left(\hat{w}_t - \hat{z}_t\right) \ , \tag{30}$$

$$E_t\hat{\pi}_{t+1} = \hat{\pi}_t\left(\frac{2}{\beta} - \delta\right) + \hat{v}_t\left((1-\delta)(1+\delta)\right) + \hat{\psi}_t\left(\delta(1+\delta) - \frac{2}{\beta}\right) - \left(\frac{2(1-\delta)(1-\delta\beta)}{(\delta\beta)}\right)\left(\hat{w}_t - \hat{z}_t\right) \ . \tag{31}$$

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[9] Note that $\hat{v}_{t-1}$ is defined as the firm-specific inflation rate from $t-1$ to t. This differs from the timing convention for the aggregate inflation rate from $t-1$ to t, which is $\hat{\pi}_t$. This convention is adopted because, unlike $\hat{\pi}_t$, $\hat{v}_{t-1}$ is decided on and therefore known at $t-1$.

To summarize, the dynamic behavior of the economy can be characterized by the aggregate demand block (10)-(12), the aggregate supply block (29)-(31), the market clearing condition (27), the monetary policy rule (25), and the exogenous shock processes (15), (23) and (24).[10]

Except for the aggregate supply block the Calvo-Yun and backward indexation models are identical to the above. The New Keynesian Phillips curve for the Calvo-Yun case is

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{(1-\delta\beta)(1-\delta)}{\delta} \left(\hat{w}_t - \hat{z}_t \right) \ . \tag{32}$$

Note that this is unaffected by unit root shocks to the inflation target, because this model variant assumes that following such shocks all agents immediately start updating at the same rate as the new target. Such shocks therefore do not give rise to any transitional dynamics.[11] On the other hand, for the backward indexation case we obtain

$$\left(\hat{\pi}_t - \hat{\pi}_{t-1} \right) = \beta E_t \left(\hat{\pi}_{t+1} - \hat{\pi}_t \right) + \frac{(1-\delta\beta)(1-\delta)}{\delta} \left(\hat{w}_t - \hat{z}_t \right) - \hat{\varepsilon}_t^{\pi^*} \ . \tag{33}$$

The main additional equations for the case of sticky wages consist of a system of equations for wage inflation identical in form to (29)-(33), but with the marginal cost term being replaced by the difference between the marginal rate of substitution and the real wage.

3 Inflation Dynamics

3.1 Calibration and Solution

To study the properties of the model we calibrate parameter values for the quarterly frequency. We follow the literature in assuming $\beta = 0.99$. The value for the habit parameter $\nu = 0.7$ follows Boldrin, Christiano and Fisher (2001). The parameter γ, which represents the inverse of the Frisch elasticity of labor supply, is set equal to 1.[12] A key issue is the

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[10] We have established numerically that this system has a unique rational expectations solution for $\phi > 1$ but that it exhibits multiplicity for $\phi < 1$. For the current specification of preferences and technologies, the stability properties of our model are therefore the same as those of the conventional New Keynesian system.

[11] See the Technical Appendix for details on the treatment of unit root shocks.

[12] Pencavel (1986) reports that most microeconomic estimates of the Frisch elasticity are between

interpretation of the price stickiness parameter δ. In each of the three models we consider, actual price changes take place every quarter in accordance with a pricing policy, and δ does not simply refer to the frequency of such price changes. Instead it represents an assumption about the frequency of comprehensive pricing policy reviews that take into account recent macroeconomic shocks such as changes in the central bank's inflation target. For our baseline calibration we assume that the length of this interval is five quarters, or $\delta = 0.8$, and similarly for the sticky wages case we assume that $\delta_w = 0.8$. While these may seem high, they are in fact a little lower than the estimates reported for comparable models in Smets and Wouters (2003) and Christiano, Eichenbaum and Evans (2005). As can be seen in equations (29)-(31), the markup of price over marginal cost does not affect the linearized dynamics of the model. For the sticky wages case we assume a wage markup parameter μ_w of 1.2, similar to the estimates of Rotemberg and Woodford (1997) and Amato and Laubach (1999). For the monetary policy rule we adopt the coefficients originally used by Taylor (1993), namely $\phi = 1.5$ and $\theta = 0.5$. Rudebusch (2006) estimates similar coefficients for an interest rate rule without smoothing. We present one illustrative example for the case of interest rate smoothing, where we will assume $\rho^i = 0.7$. For the monetary policy shock baseline we assume a persistence of $\rho^h = 0.98$, again based on Rudebusch (2006). But because ρ^h is a key parameter in our model, we will explore the sensitivity of our results to other values. We illustrate the technology shock for a persistence of $\rho^z = 0.98$. This is close to the unit root assumption which is becoming more common in applied work.[13]

We first solve the model by the algorithm of King and Watson (2002), and use impulse responses to display the dynamic response of the economy to permanent shocks to the inflation target $\hat{\varepsilon}_t^{\pi^*}$, to monetary policy shocks $\hat{\varepsilon}_t^h$, and to technology shocks $\hat{\varepsilon}_t^z$. Having gained intuition from those experiments we then analyze two aspects of inflation dynamics

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0 and 0.45, but in the business cycle literature it is common to assume a unitary elasticity. As discussed by Chang and Kim (2005), a low Frisch elasticity makes it difficult to explain cyclical fluctuations in hours worked, and they present a heterogenous agent model in which aggregate labor supply is considerably more elastic than individual labor supply.

[13] For an example and discussion, see Juillard, Kamenik, Kumhof and Laxton (2007).

in more detail. Inflation inertia refers to a delayed and gradual initial change in inflation following a shock. We capture this notion by displaying the initial jump in inflation, scaled by the size of the shock, against the persistence of the shock. A model with the highest degree of inertia displays the smallest initial jump in inflation, while in models without any inertia the maximum jump in inflation occurs in the period of the shock. Inflation persistence refers to persistent deviations of inflation from its long run value following a shock. We therefore plot the autocorrelation functions of inflation under the different models, again as a function of shock persistence.

In the figures below the solid lines represent the results of the optimal indexation model and are labelled OPT, the dotted lines represent those of the Calvo-Yun model and are labelled CY, and the broken lines represent those of the backward indexation model and are labelled BWI.

3.2 Impulse Responses

The first monetary policy shock we consider is a permanent change in π_t^* from 5% to 4% per annum. Figure 1 clearly illustrates the shortcomings of the Calvo-Yun model mentioned in the Introduction. In that model, because firms are assumed to immediately start updating their prices at the new steady state inflation rate, inflation instantaneously drops to its new target level. It is therefore neither inertial nor persistent. And because the ex-ante real interest rate never changes, consumption, output and employment remain flat, i.e. disinflations are not recessionary.

By contrast, in the optimal indexation model inflation exhibits both inertia and persistence. The key factor generating this result is that, following the shock, aggregate inflation is expected to be lower than its initial value for a long period of time, in this example forever. The importance of this factor derives from the fact that, given the concavity of their profit function, firms maximize profits by keeping the deviations of their price path from the market average price path as small as possible over the expected length of the policy.[14] When as in Figure 1 firms expect a long run change in trend inflation rather than a short lived jump in inflation, they minimize the deviations of their price path by changing the long-run component of their pricing policies v_t rather than their initial price level p_t. That in turn slows down the response of aggregate inflation, because v_t enters the inflation process through ψ_t, a slow-moving state variable. This reason for inertia is different from one that is commonly stressed in the literature, which relies on a slow response of marginal cost to shocks. In our model inflation is inertial and persistent despite the fact that marginal cost w_t/z_t is perfectly flexible. Adding nominal wage rigidities as in Erceg and Levin (2003) does however help in one important respect. The consensus view is that an initial increase in the nominal interest rate is required to start to bring down inflation, but in the baseline model in Figure 1 that increase is small at only 5 basis points. Figure 2 therefore explores the case of sticky wages and prices, and here we find that nominal interest rates initially have to rise by 35 basis points for a 100 basis points reduction in inflation. The remainder of this paper returns to the flexible wage case.

The initially high nominal interest rate is required due to the large initial deviation of inflation from its new steady state combined with a high response coefficient ϕ to such deviations in the monetary policy rule. Given the slow adjustment of inflation, the immediate consequence is a steep rise in the real interest rate. This causes consumption, output and therefore labor demand to drop, i.e. we observe the recession that is associated with disinflations in the data. This in turn lowers the real wage, which exerts downward pressure on prices so that inflation begins to fall. Both the drop in inflation and the recession then start to lower the nominal and the real interest rate. Once this process is complete the recession ends and inflation drops to its new target. An output sacrifice is therefore unavoidable in bringing down inflation. The sacrifice ratio in this deliberately simple version of the model

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[14] It can in fact be shown that the profit maximization problem amounts to choosing a price path that minimizes the distance between the firm specific and the aggregate price paths in a weighted least squares sense. See Calvo, Celasun and Kumhof (2002).

is modest at only 0.30%, but adding nominal wage rigidities, capital accumulation with investment adjustment costs, and a higher parameter δ, can produce much larger real effects while still displaying qualitatively identical inflation dynamics.

Finally, backward indexation displays very similar dynamics to optimal indexation. In fact, for our particular calibration inflation is less inertial and persistent under backward indexation, and consequently output losses are smaller, with a sacrifice ratio of only 0.10%. As we will emphasize further below, this specification does not have many clear advantages over optimal indexation in explaining the dynamics of inflation.

Insert Figure 1 here

Insert Figure 2 here

To understand the differences in price setting behavior between optimal and backward indexation it is instructive to follow the relative price paths of the first cohorts of firms that get to change their pricing policies following the inflation target shock in Figure 1. Under backward indexation there is limited inflation inertia because firms respond to the shock by lowering their initial price level p_t relative to the average price level of competitors. We see in Figure 1 that this strategy is also followed by subsequent cohorts, so that aggregate inflation falls over time. For the first cohort, indexation to aggregate inflation ensures that after the initial period their relative price rises, until eventually it stabilizes at a value that need not be equal to one. Under optimal indexation there is more inflation inertia because of a substantially smaller reliance on an initial price drop p_t. Instead firms choose an intermediate updating rate v_t of around 4.5% for their price path that strikes a balance between initially high aggregate inflation of 5%, and later low aggregate inflation approaching 4%. As a result their relative price gradually falls further below one until aggregate inflation has declined to 4.5% in period 6, and then starts to rise, eventually to above one, as aggregate inflation drops further.[15] Gradual relative price changes therefore substitute for the larger up-front change

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[15] Like Calvo (1983) models without inflation updating the model therefore implies that very old pricing policies exhibit high relative prices. But this problem is far less severe because of indexation. For example, the first cohort in Figure 1 has around a 1% chance of its pricing policy surviving

under backward indexation.

The bottom right panel of Figure 1 (and of subsequent figures) compares actual inflation to a measure of expected inflation under optimal indexation, defined as

$$\hat{\pi}_t^e = (1-\delta)\Sigma_{k=0}^{\infty}\delta^k E_{t-k}\hat{\pi}_t \ . \tag{34}$$

This formula averages the expectations of cohorts of agents who last reset their pricing policies k periods ago, and who therefore last updated their information and expectations for today's inflation at that time. The weights attached to each cohort in (34) correspond to the fraction of such pricing policies that are currently still in force. These old expectations matter under optimal indexation, as they are still reflected in current updating rates of old pricing policies. While the expectation $\hat{\pi}_t^e$ is not directly comparable to standard measures of inflation expectations, it behaves quite similarly in one key respect - it lags actual inflation for a long time during the disinflation. Its dynamics in Figure 1 therefore closely resembles the learning dynamics in Erceg and Levin (2003).[16] The reason in the case of learning is unstable or non-credible monetary policy rather than persistent changes in the inflation target per se. But the two are clearly closely related, and we therefore see the two models as highly complementary.

The importance of a prolonged expected change in aggregate inflation suggests that the effect of a highly persistent monetary policy shock should be very similar to that of a permanent shock. In our second monetary policy experiment we therefore assume that the steady state inflation rate remains at 5% per annum while there is a persistent ($\rho^h = 0.98$) monetary policy shock of equal impact size to the inflation target shock of Figure 1. Figure 3 shows that for the optimal indexation and backward indexation models the economy indeed responds similarly to the previous case, except of course in the very long run. But the Calvo-Yun model now performs very differently, exhibiting not only prolonged inflation deviations

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for five years, but even at that time its price is only 0.4% above the average market price.

[16] There are of course also significant differences to learning models. Most importantly, with learning short run expected inflation falls more quickly than long run expected inflation, while the opposite is true under optimal indexation.

but also output deviations from steady state. This discontinuity arises because the presence of a discount factor in the New Keynesian Phillips curve (32) makes the model behave very differently depending on whether there are persistent inflation deviations from steady state or whether the steady state itself has changed. This unappealing feature follows directly from the rigidity of the updating assumption in that model. Furthermore, the Calvo-Yun model again does not imply an inertial response of inflation, the maximum jump in inflation occurs in the period of the shock.

Insert Figure 3 here

Figure 4 displays impulse responses for a more transitory monetary policy shock, with $\rho^h = 0.7$. Because in this case the expected change in aggregate inflation is of a very short duration, price setters in the optimal indexation model react mostly through the short-term, initial price level component of their pricing policies. This is identical to the behavior of agents in the Calvo-Yun model, whose only option is to react through this variable. As a result pricing is almost identical for the two models. Therefore the real effects are also very similar. We observe a recession that is both more shallow and shorter than for a highly persistent shock of equal impact size. It is the backward indexation model that displays very different dynamics for this case. The key observation is that inflation inertia and persistence are built into this model, regardless of the persistence of the underlying shock, thereby denying price setters the option to rationally take the transitory nature of a shock into account. We will explore this shortcoming more systematically in the following subsections.

Insert Figure 4 here

The effects of different assumptions about pricing policies must affect the response of inflation not only to monetary policy shocks but also to all shocks that affect marginal cost. In Figure 5 we therefore study, as an example, the effects of a persistent ($\rho^z = 0.98$) one percent increase in the level of technology z_t. The structure of the problem is such that persistent shocks to markups of price over marginal cost would have identical effects. The real effects of technology shocks are familiar and qualitatively similar across all models. Because the technology shock is highly persistent, there is a similarly persistent increase in output, which thereafter returns to its long run level in a very gradual fashion. Consequently the real interest rate gradually approaches its long run level from below. This is in turn reflected in the longer run behavior of the nominal interest rate and of inflation, which is highly persistent in all three models. But as we will see below, the optimal indexation model again implies much less inflation persistence for more transitory shocks. Moreover, the behavior of inflation inertia differs significantly across models even for high levels of shock persistence. The shock immediately reduces real marginal cost, the driving force of inflation. But while for both the Calvo-Yun model and the optimal indexation model the maximum response of inflation occurs in the first period, the backward indexation model again displays its built-in inertia. This is problematic because, as mentioned in the Introduction, the literature has documented inflation inertia primarily for monetary policy shocks and not for technology shocks.

Insert Figure 5 here

3.3 Inflation Inertia

Figure 6 studies the extent of inflation inertia generated by the three models in more detail. It uses the ratio of the impact jump in inflation to the size of the shock as a proxy for the inertia or slowness of the inflation response to shocks, with a smaller ratio corresponding to more inertia. It shows how this ratio changes with increasing degrees of monetary policy or technology shock persistence.

The first panel of Figure 6 studies monetary policy shocks. We observe that, as expected from Figures 3 and 4, for low shock persistence the initial jump in inflation is small, simply because the cumulative impulse to disinflation is small. For the same reason, as shock persistence increases the initial jump in inflation increases for all three pricing models. But it increases only little for the backward indexation model, because inertia in this model is built into the structure rather than reflecting optimal choices. At the other extreme we find the Calvo-Yun model, where the initial jump in inflation increases monotonically and steeply in the persistence of shocks. At the limit, for permanent shocks the jump in inflation exactly equals the size of the shock, the case considered in Figure 1. In the Calvo-Yun model there is therefore no inertia whatsoever, for any shock the largest jump in inflation always occurs in the first period. The optimal indexation case is intermediate, reflecting the assumption that agents can respond rationally to the persistence of shocks by making their pricing response more or less inertial. For transitory shocks there is therefore even less inertia than in the Calvo-Yun model. This is because agents optimally respond to a short-lived dip in inflation by initially lowering their price substantially and subsequently letting it grow at a slightly faster rate than aggregate prices. But for more persistent shocks (approximately $\rho^h > 0.8$) optimal indexation generates more inertia than Calvo-Yun, and for highly persistent shocks such as those in Figures 1 and 3 it even generates more inertia than the backward indexation model.[17] As we saw in our discussion of Figure 1, this is because for such shocks it is optimal to respond mostly through the inflation updating component of pricing policies.

The second panel of Figure 6 studies technology shocks. For transitory shocks we observe similar relative levels of inflation inertia as under monetary policy shocks. But the empirically relevant range of technology shocks is at high levels of persistence, and here we observe, as suggested by Figure 5, much smaller initial changes in inflation (by a factor of at least two) under backward indexation. The reason is, as for monetary policy shocks, the fact that inertia is built into this model as a structural rather than an optimizing feature. But this is not innocuous, because as mentioned in the Introduction the literature has not identified inertial inflation behavior in response to technology shocks.

Insert Figure 6 here

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[17] Some details of the rankings in Figure 6 depend on the specific calibration, especially on the parameters of the monetary policy rule. But the overall conclusions are robust.

3.4 Inflation Persistence

Figures 7 and 8 study the degrees of inflation persistence generated by the three models in more detail. They use inflation autocorrelation functions (ACF) and inflation AR1 coefficients to represent persistence or the time it takes for inflation to return to its long run value following a shock. Figure 7 considers monetary policy shocks and Figure 8 technology shocks. Each figure contains three plots, one for each pricing model, that show a family of ACF corresponding to shock persistence between 0.99 and 0.1 (0.5 for technology shocks). A fourth plot shows only the AR1 coefficients against shock persistence along the horizontal axis, but it does so for all three pricing models to facilitate comparison.

For monetary policy shocks in Figure 7, inflation persistence under both the optimal indexation and the Calvo-Yun model is almost the same as the persistence of the underlying shock. But under backward indexation inflation persistence is, again, built into the structure rather than reflecting optimal choices. This is not troubling for highly persistent shocks, where all three models predict highly persistent inflation. But at the other extreme, even for shocks that are nearly white noise the AR1 coefficient of inflation under backward indexation is 0.82.

Similar but not identical results obtain for technology shocks. For the empirically relevant range of highly persistent technology shocks inflation is implausibly persistent under backward indexation, it essentially follows a unit root process. But under optimal indexation its maximum autocorrelation is considerably lower at around 0.86, with a much higher sensitivity to the persistence of the underlying shocks.

The fact that the autocorrelation of inflation under backward indexation is nearly independent of the autocorrelation of underlying shocks is not a desirable feature of an otherwise optimizing rational expectations model. It is also problematic in the light of empirical evidence on inflation persistence. Taylor (2000) estimates the largest autoregressive root of inflation for the years prior to the Volcker disinflation (1960-1979) and following that disinflation (1982-1999), and found that the confidence interval for the earlier period was $(0.94, 1.05)$, while it was only $(0.50, 0.86)$ for the later period. Figure 9 shows the autocorrelation functions of inflation for the periods analyzed by Taylor (2000), but allowing for a different mean of inflation in the two subperiods, and with the second period extended to include the most recent data. The results broadly confirm Taylor (2000). Clearly, unless one allows for strongly time-varying structural parameters (such as δ), which is theoretically not appealing, the backward indexation model has difficulties accounting for inflation dynamics in both subperiods. The Calvo-Yun model is not a promising alternative because it does not generate inflation inertia for monetary policy shocks, which is a feature of the data at all times. The optimal indexation model on the other hand exhibits moderate persistence when monetary policy is characterized mostly by small and transitory shocks as in recent years, and much higher persistence when monetary policy shocks are larger and more persistent, as they were up to the end of the Volcker disinflation.

Insert Figure 7 here

Insert Figure 8 here

Insert Figure 9 here

In Figures 7 and 8, inflation under optimal indexation (and Calvo-Yun indexation) exhibits little persistence beyond the persistence of the underlying shocks. It is in this dimension that a modest degree of interest rate smoothing leads to a different conclusion. This is shown in Figure 10, which plots the AR1 coefficients for inflation in a similar fashion to Figure 7, but under the assumption that $\rho^i = 0.7$. Interest rate smoothing does generate some inflation persistence even for monetary policy shocks with very little serial correlation, but the difference to the backward indexation case is still very large, with coefficients just above 0.5 for optimal indexation and everywhere above 0.91 for backward indexation.

Insert Figure 10 here

4 Conclusion

In this paper we have presented a monetary model with nominal rigidities and optimizing, forward-looking households and firms that have full information about the state of the economy. The model differs from conventional alternatives in this class in one key respect - firms set pricing policies instead of price levels. The paper is motivated by some important shortcomings of the conventional alternatives, namely their inability to generate inflation inertia, inflation persistence and recessionary disinflations without resorting to some variant of a backward-looking price setting specification.

The model, which we refer to as the optimal indexation model, does generate all of these effects in response to persistent shocks to monetary policy. The reason is the ability of price setters to separately determine two components of their pricing policies, their initial price level and a long-run or inflation updating component. The presence of firm-specific inflation updating introduces a state variable into aggregate inflation dynamics despite the absence of backward looking behavior. This is distinct from another frequently stressed reason for inflation inertia and persistence, a slow response of marginal cost to shocks.

The main shortcoming of the alternative Calvo-Yun model is its inability to generate inflation inertia and recessionary disinflations, while the main shortcoming of the alternative backward indexation model is the fact that it generates high inflation inertia and persistence irrespective of both the nature and persistence of the underlying shocks. The greater flexibility of price setters under optimal indexation means that this model is not subject to either of these limitations.

Future work will be directed towards estimating richer versions of the optimal indexation model that include capital accumulation. Juillard, Kamenik, Kumhof and Laxton (2007) is a first step in this direction, but much work remains to be done, particularly a comparison of fit between the optimal and backward indexation models.

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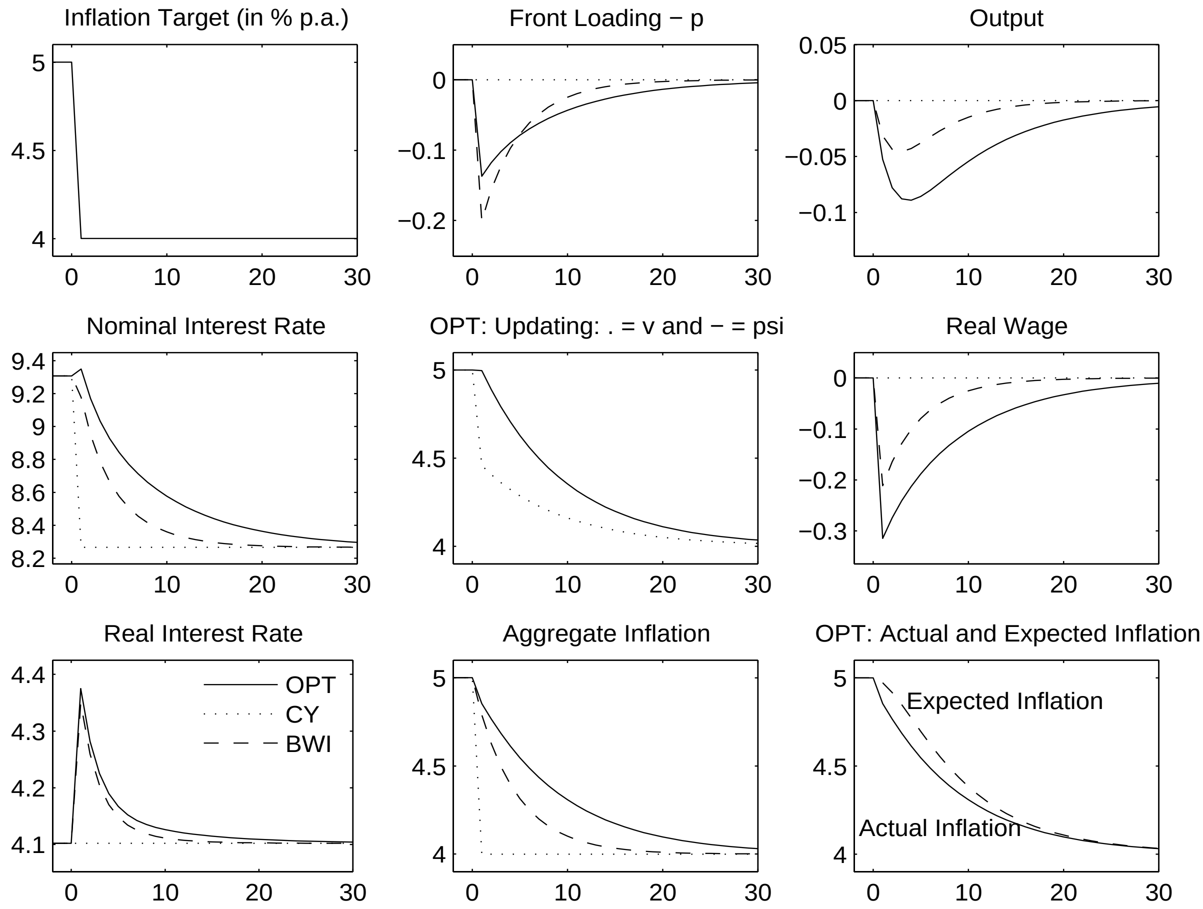


Figure 1 : Permanent Disinflation in the Baseline Model

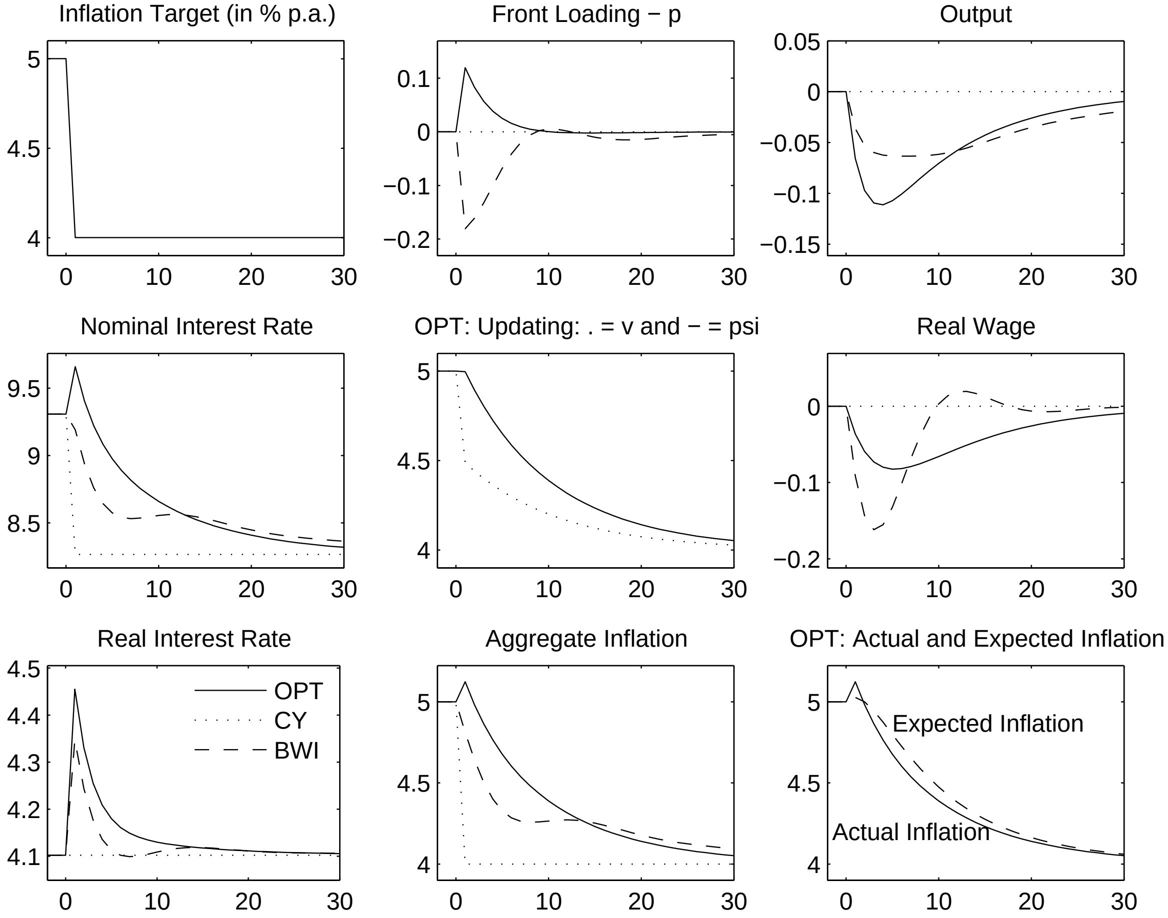


Figure 2 : Permanent Disinflation under Sticky Wages and Prices

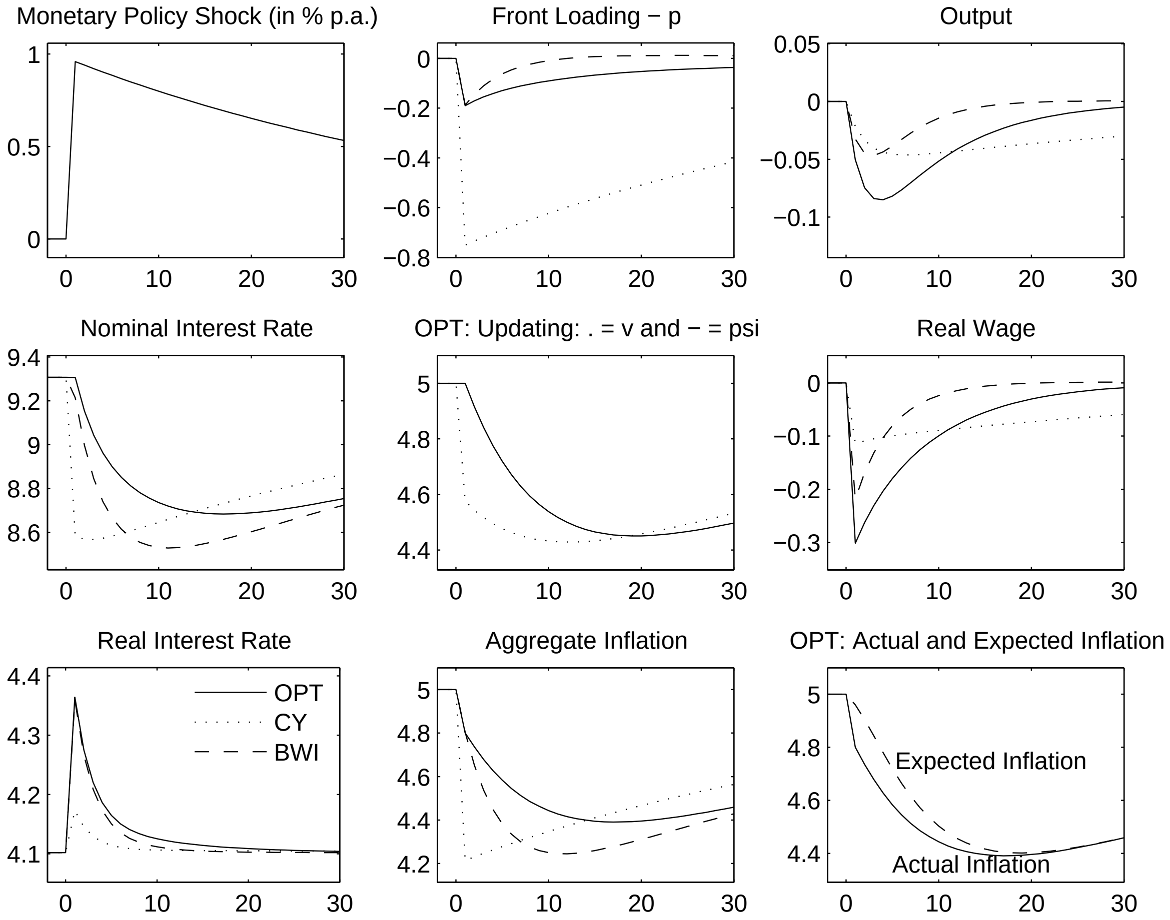


Figure 3 : Persistent Monetary Policy Shock $\rho^h = 0.98$

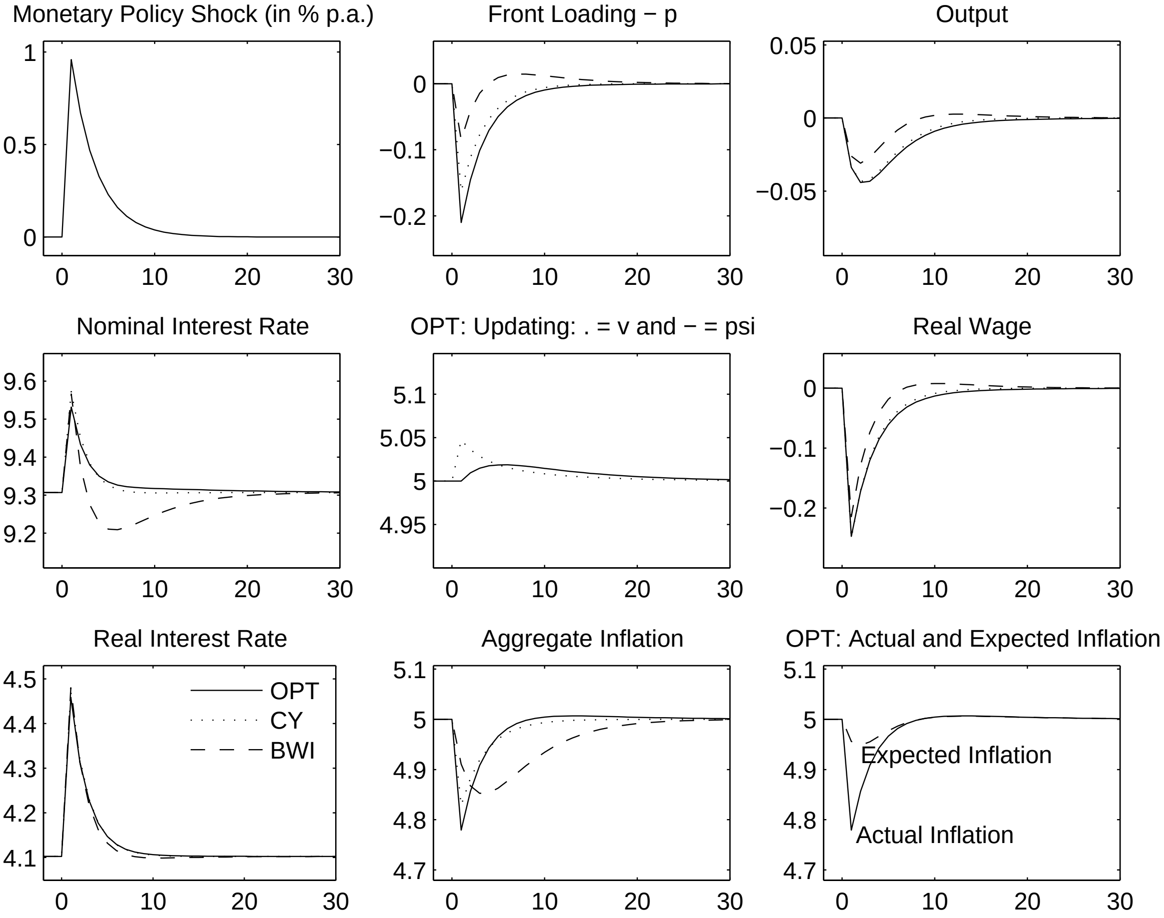
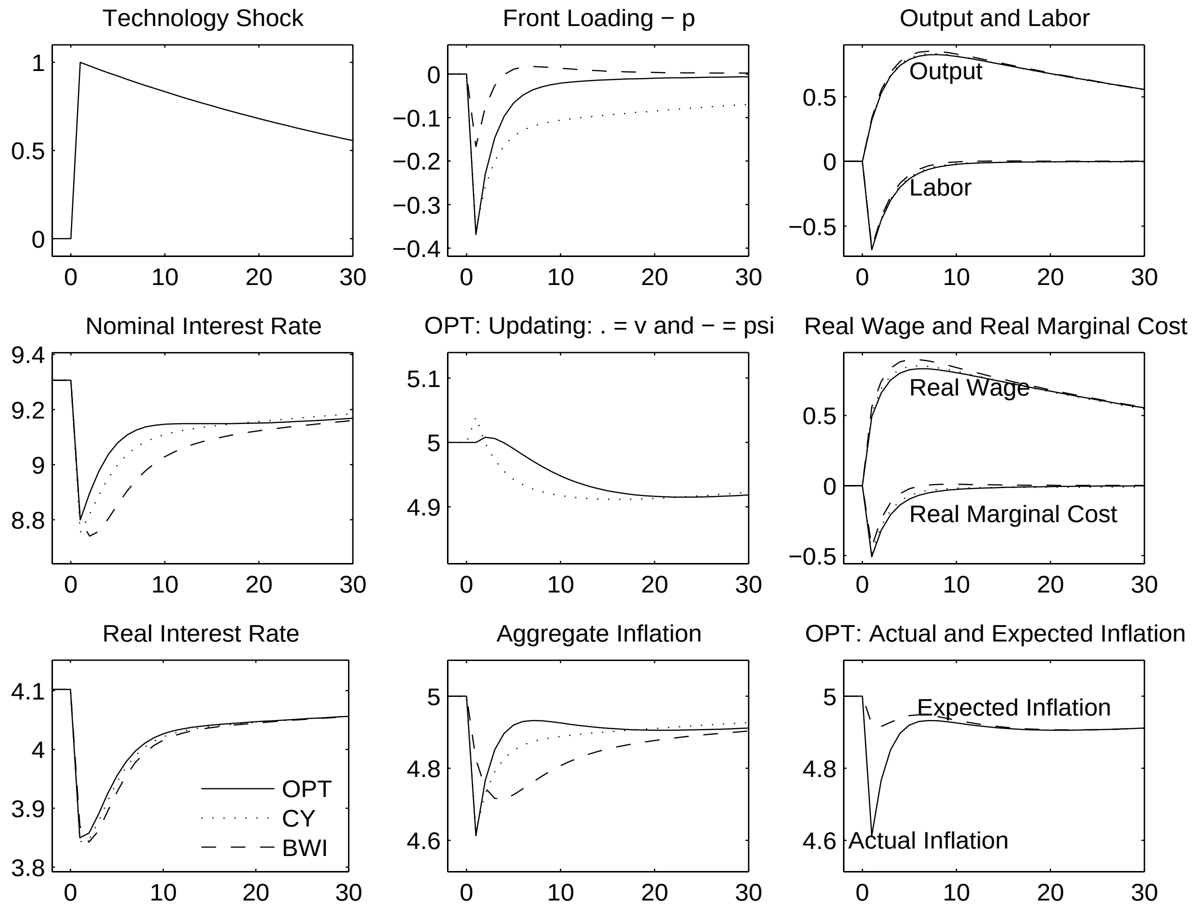


Figure 4 : Transitory Monetary Policy Shock $\rho^h = 0.7$


Technology Shock

Front Loading − p

Output and Labor

Nominal Interest Rate

OPT: Updating: . = v and − = psi

Real Wage and Real Marginal Cost

Real Interest Rate

Aggregate Inflation

OPT: Actual and Expected Inflation

Figure 5 : Persistent Technology Shock $\rho^z = 0.98$

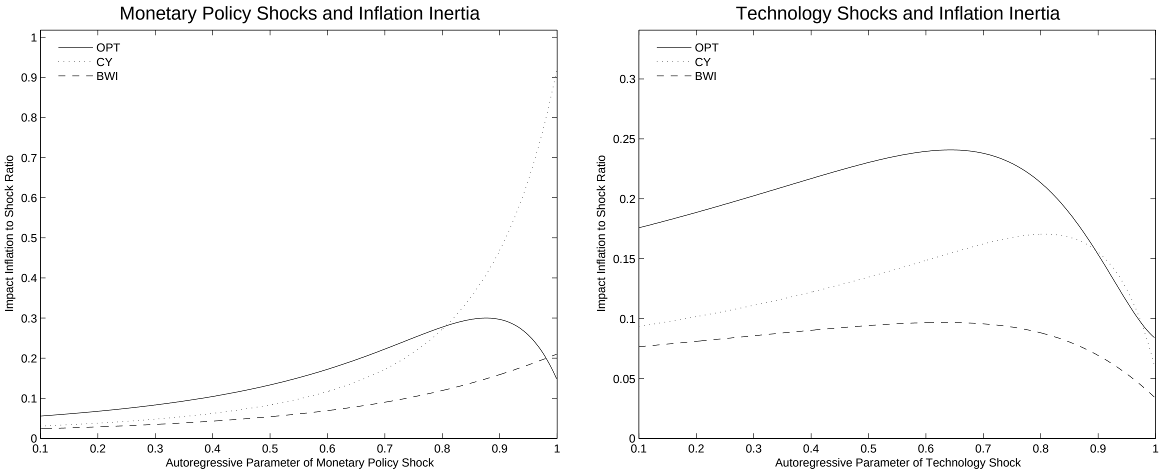
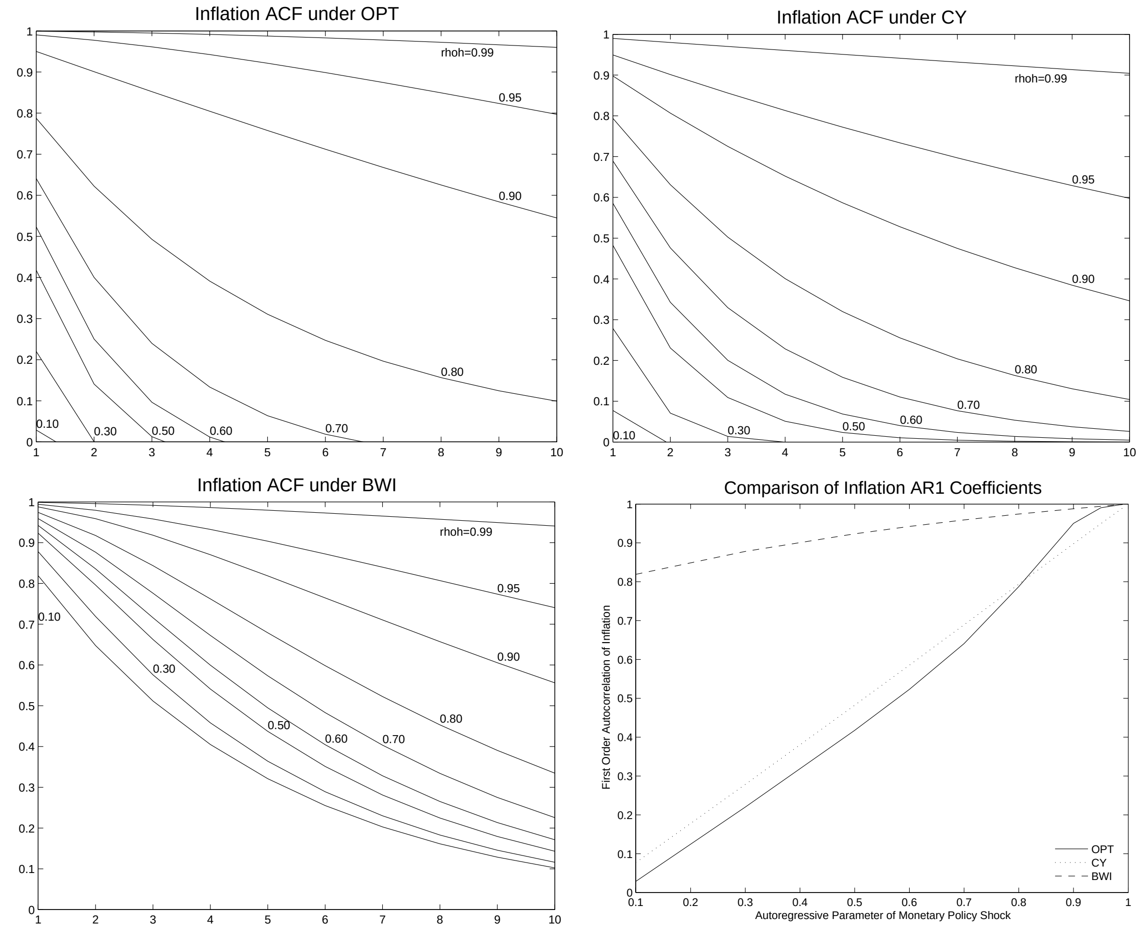


Figure 6 : Inflation Inertia

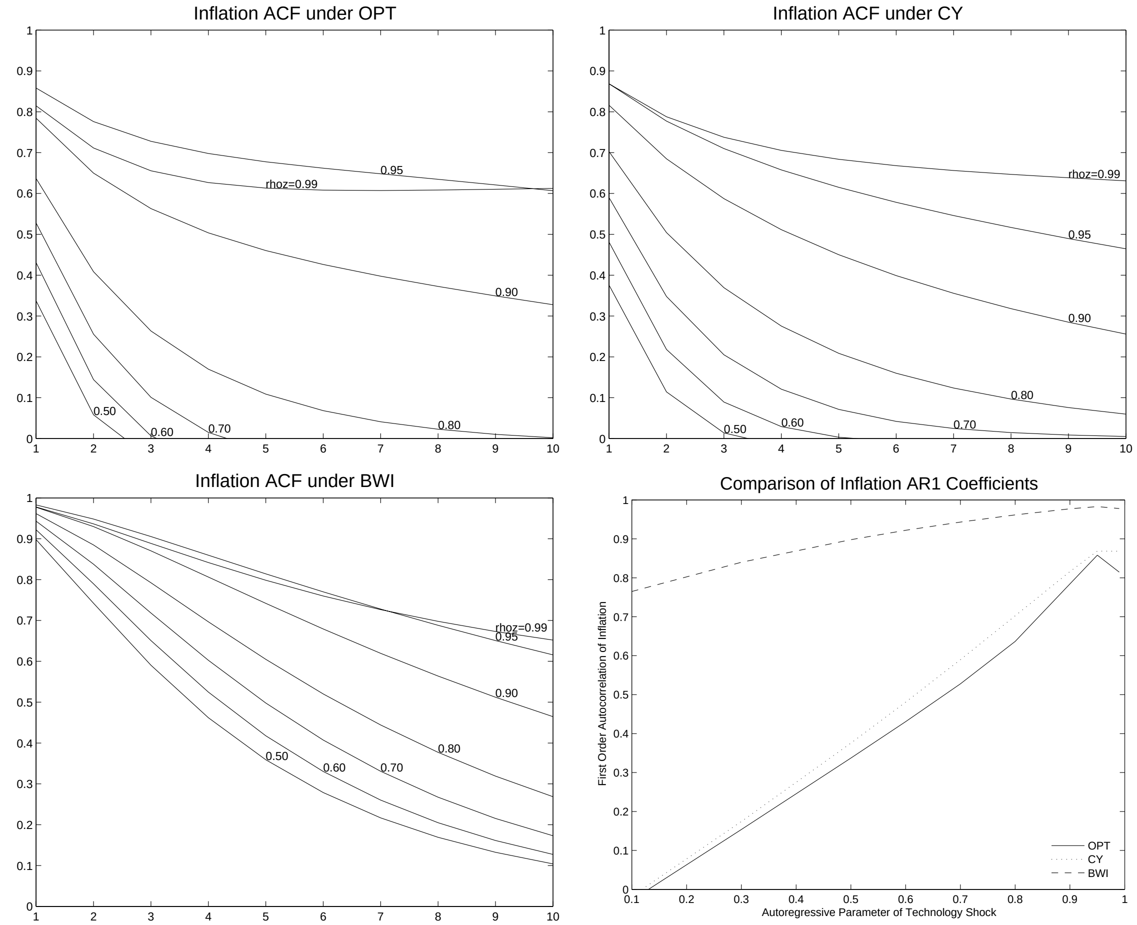

Inflation ACF under OPT

Inflation ACF under CY

Inflation ACF under BWI

Comparison of Inflation AR1 Coefficients

Figure 7 : Inflation Persistence under Monetary Policy Shocks



Inflation ACF under OPT

Inflation ACF under CY

Inflation ACF under BWI

Comparison of Inflation AR1 Coefficients

Figure 8 : Inflation Persistence under Technology Shocks

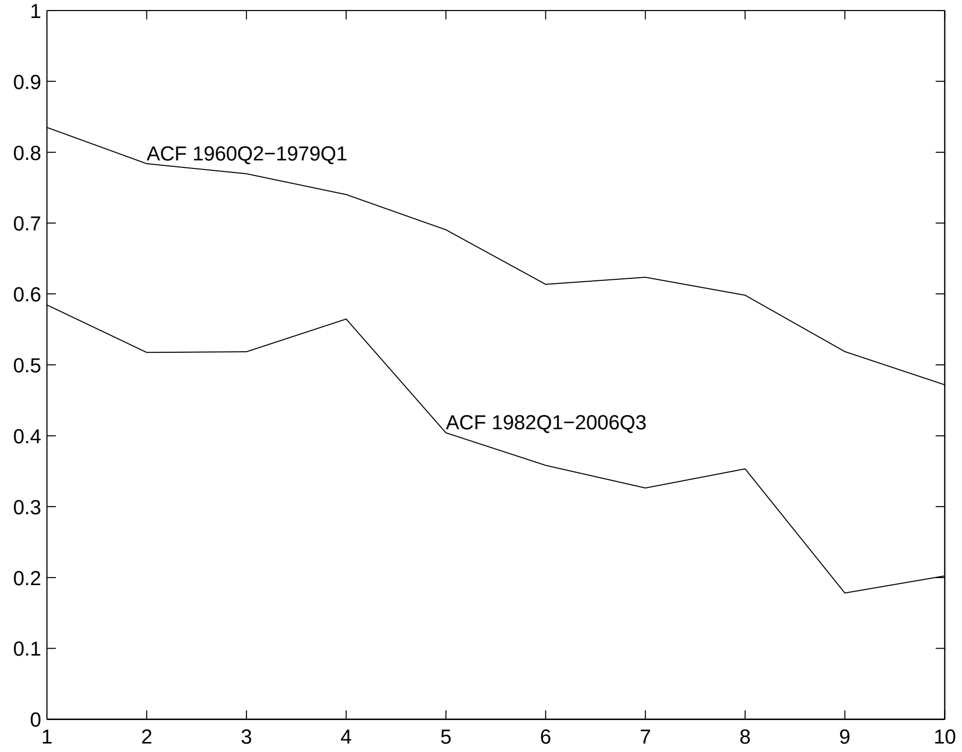


Figure 9 : ACF of U.S. Inflation

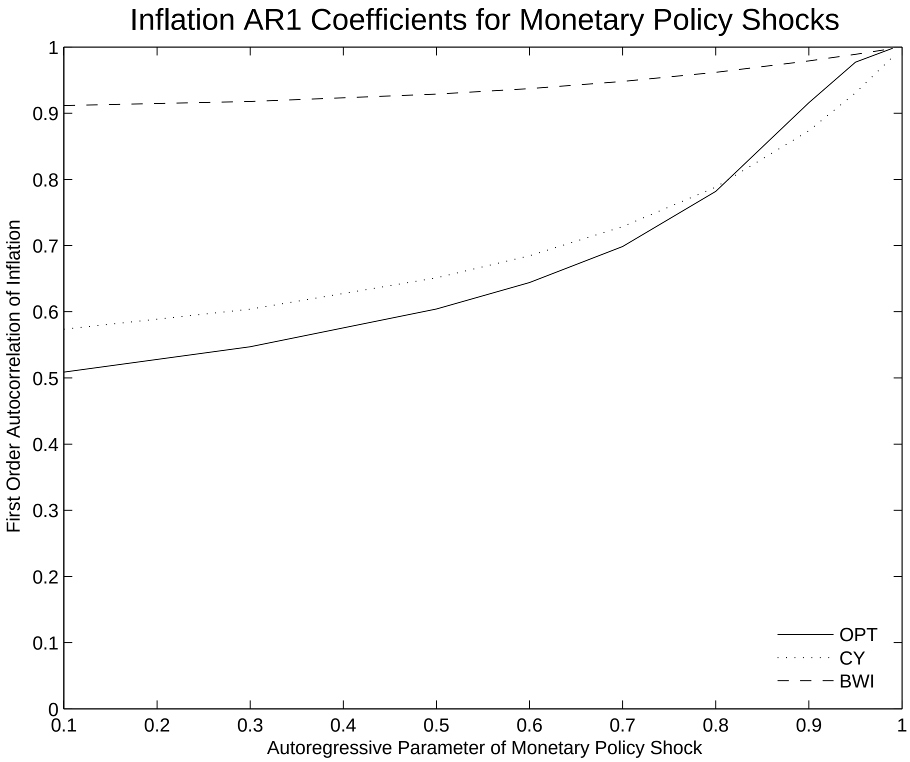


Figure 10 : Inflation Persistence under Interest Rate Smoothing