Speed Limit Policies: The Output Gap and Optimal Monetary Policy

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1 Introduction

Recent work on the design of monetary policy reflects a general consensus on the appropriate objectives of monetary policy. As articulated by Svensson, "....there is considerable agreement among academics and central bankers that the appropriate loss function both involves stabilizing inflation around an inflation target and stabilizing the real economy, represented by the output gap" (Lars E. O. Svensson 1999a). Such a loss function forms a key component of "The Science of Monetary Policy" (Richard Clarida, Jordi Galí, and Mark Gertler 1999), and has been widely used in recent work on policy design (e.g., Bennett T. McCallum and Edward Nelson 1999, 2000, Henrik Jensen 2001, Svensson and Michael Woodford 1999, David Vestin 2000, Marianne Nessén and Vestin 2000, and McCallum 2001). Woodford (1999a) has derived the assumptions under which a quadratic loss function in inflation and the output gap is the correct approximation to the utility of the representative agent.

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Despite this apparent agreement about the objectives of policy, it is not clear that inflation and output gap stabilization are the objectives central banks either should or actually do pursue in the conduct of policy. Several recent papers (Svensson 1999b, Robert Dittman and William Gavin 1999, Vestin 2000) have argued that price level targeting has desirable properties. Vestin, for example, finds that a policy of stabilizing the output gap and the price level dominates one focused on inflation and output gap stabilization. Yet, while the formal charters of several central banks (e.g., the Reserve Bank of New Zealand and the ECB) cite price stability as the primary or sole objective of monetary policy, no central bank has actually made price stability, as opposed to low and stable inflation, its practical objective. Similarly, actual statements from the Federal Reserve suggest that inflation and the output gap may not be the variables on which the Fed actually focuses. For example, in justifying interest rate increases during 2000, the press releases from the Federal Open Market Committee emphasized the *growth* in output relative to the *growth* in potential, rather than the output gap itself (the *level* of output relative to the *level* of potential).[1] In remarks at the Wharton Public Policy Forum in April 22, 1999, Fed Governor Edward M. Gramlich also described monetary policy in terms of a focus on demand growth relative to growth in potential output:

> "Solving a standard model of the macroeconomy, such a policy would effectively convert monetary policy into what might be called 'speed limit' form, where policy tries to ensure that aggregate demand grows at roughly the expected rate of increase of aggregate supply, which increase can be more easily predicted."
>
> ".. the monetary authority is happy with the cocktail party temperature at present but moves against anything that increases its warmth. Should demand growth threaten to outrun supply growth (the party to warm up), the seeds of

[1] For example, following rate increases during the first half of 2000, the FOMC stated that

> The Federal Open Market Committee voted today to raise its target for the federal funds rate by 25 basis points to 5-3/4 percent. .... The [Federal Open Market] Committee remains concerned that over time, increases in demand will continue to exceed the growth in potential supply. (Feb., 2, 2000)
>
> The Federal Open Market Committee voted today to raise its target for the federal funds rate by 50 basis points to 6-1/2 percent. .... Increases in demand have remained in excess of even the rapid pace of productivity-driven gains in potential supply... (May 16, 2000)

accelerating inflation may be planted and monetary policy should curb the growth in demand by raising interest rates."

Growth in demand relative to growth in potential is equal to the *change* in the output gap, and the purpose of this paper is to examine what role changes in the output gap – a speed limit policy in Gramlich's words – should play in the design of monetary policy. Gramlich's comments suggest measurement error is one factor favoring a speed limit policy. Measurement error in the gap can be critical for policy implementation, and Orphanides (2000) has argued that this mismeasurement contributed to the excessive inflation of the 1970s. If the growth rate of potential is measured more accurately than its level, first differencing the log level of the estimated gap will reduce the variance of the remaining measurement error. I ignore this attribute of a speed limit policy, however, to focus on an aspect of such policies that has not previously been identified. In a standard, forward-looking New Keynesian model, Woodford (1999a) has emphasized that pure discretion, in which the central bank minimizes the social loss function but is unable to precommit, leads to inefficient stabilization in the face of cost shocks. It is this inefficiency that is reduced if the central bank follows a speed limit policy.

The reason for this result can be traced to Woodford's demonstration that an optimal precommitment policy imparts inertia when expectations are forward looking. By imparting inertia into policy actions, the central bank's current actions directly affect the public's expectations of future inflation. A central bank concerned with social loss but operating under discretion will fail to introduce any inertia. When the central bank strives to stabilize the change in the output gap, however, the lagged output gap becomes an endogenous state variable. This introduces inertia into monetary policy, even under discretion.

This suggests that there may be an important role for the change in the output gap in policy design. At the very least, it suggests that a closer examination of the role of the output gap as a policy objective is called for. To carry out this examination, I employ a parameterized New Keynesian model and evaluate a speed limit policy against other alternative policies. I find that a policy based on targeting the change in the output gap dominates inflation targeting unless inflation adjustment is predominately backward looking. A speed limit policy dominates price level targeting unless inflation is predominately forward looking. And while optimal inflation targeting involves appointing a weight-conservative central banker who values inflation stability more highly than does society, society can do even better by appointing a *liberal* central banker who highly values stability in output gap changes.

2 The basic model under precommitment, discretion, and speed limit policies

The basic New Keynesian model has been developed by Tack Yun (1996), Julio Rotemberg and Woodford (1997), and Marvin Goodfriend and Robert King (1997). Clarida, Galí, and Gertler (1999), Woodford (1999, 2000), McCallum and Nelson (1999), Svensson and Woodford (1999), among others, have popularized it as a useful framework for monetary policy analysis. As discussed by Clarida, Galí, and Gertler (1999), it is convenient to treat the output variable as the policy instrument; the aggregate demand specification can then be used to solve for the nominal interest rate that achieves the desired output value. In this case, only the inflation adjustment equation and the policy objectives are necessary for deriving optimal policies.

Most recent models of inflation adjustment have employed the Calvo specification of staggered price adjustment based on the optimizing behavior of monopolistically competitive firms in the presence of price stickiness, but John Roberts (1995) shows that other basic models of price adjustment lead to similar expressions for inflation (see also Carl E. Walsh 1998). With sticky prices, firms must base their pricing decisions on real marginal costs and their expectations of future price inflation. As a consequence, current inflation is given by[2]

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \kappa x_t + e_t \tag{1}$$

where x is the output gap, e is a cost shock, and β is the discount factor ($0 < \beta < 1$).

The second aspect of the model specification is the social loss function. As is standard in this literature, this is taken to be a function of inflation and output gap variability:

$$L_t = \mathrm{E}_t \sum_{i=0}^{\infty} \beta^i \left(\pi_{t+i}^2 + \lambda x_{t+i}^2 \right). \tag{2}$$

[2]Details on the derivation of equation (1) and all other results can be found in a longer version of this paper available at http://econ.ucsc.edu/~walshc/.

This specification reflects the widespread agreement over the objectives of monetary policy alluded to by Svensson (1999a).

2.1 Optimal precommitment and discretion

Woodford (1999a), Clarida, Galí, and Gertler (1999) McCallum and Nelson (2000), and Richard Dennis (2002) discuss optimal precommitment and discretionary policies in this basic model. As these authors demonstrate, under both pure discretion and optimal precommitment, the central bank's first order condition for the current period is given by

$$\kappa\pi_t = -\lambda x_t \tag{3}$$

while, under precommitment, the first order conditions for future periods take the form

$$\kappa \mathrm{E}_t \pi_{t+i} = -\lambda \mathrm{E}_t \left(x_{t+i} - x_{t+i-1} \right), \qquad i \geq 1. \tag{4}$$

The inherent time-inconsistency of the precommitment policy is revealed by the fact the first order conditions for t and $t+i$ differ for $i \geq 1$. At time t, the central bank sets $\pi_t = -(\lambda/\kappa)x_t$ and promises to set $\pi_{t+1} = -(\lambda/\kappa)(x_{t+1} - x_t)$. But when period $t+1$ arrives, a central bank that reoptimizes will again obtain $\pi_{t+1} = -(\lambda/\kappa)x_{t+1}$, condition (3) updated to $t+1$, as its optimal setting for inflation.

An alternative definition of an optimal precommitment policy requires that the central bank implement condition (4) for all periods, including the current period. Woodford (1999a) has labeled this the "timeless perspective" approach to precommitment. That is, under the optimal precommitment policy, inflation and the output gap satisfy

$$\pi_{t+i} = -\left(\frac{\lambda}{\kappa}\right)\left(x_{t+i} - x_{t+i-1}\right) \tag{5}$$

and equation (1) for all $i \geq 0$. One can think of such a policy as having been chosen in the distant past, and the current values of the inflation rate and output gap are the values chosen from that earlier perspective to satisfy the two conditions (1) and (4). Svensson and Woodford

(1999) and McCallum and Nelson (2000) provide further discussion of the timeless perspective, and the latter argue that this approach agrees with the one commonly used in many studies of precommitment policies.[3]

From a given initial period t, it is not necessarily the case that the optimal timeless precommitment policy leads to a lower expected present value of the social loss function than pure discretion. Simulations by McCallum and Nelson (2000) using a calibrated model shows, however, that the loss is higher under discretion.[4] Precommitment policies introduce an inertia into output and inflation that is absent under pure discretion, and this inertia improves the trade-off between inflation variability and output gap variability. In the face of a positive cost shock ($e_t > 0$), a central bank acting in a discretionary environment can only offset the inflation effects of this shock by creating a negative output gap. A central bank able to precommitment, however, can also affect $\mathrm{E}_t\pi_{t+1}$. By keeping output below potential (a negative output gap) for several periods into the future after a positive cost shock, the central bank is able to lower expectations of future inflation. A fall in $\mathrm{E}_t\pi_{t+1}$ at the time of the positive inflation shock improves the trade-off between inflation and output gap stabilization faced by the central bank.

Under optimal discretion, a serially uncorrelated cost shock causes inflation to rise and the output gap to fall, but both return to baseline one period after the shock. None of the persistence generated by precommitment occurs under discretion.

2.2 A speed limit policy

Much of the recent literature on monetary policy design has assumed the central bank can commit to a policy rule, and optimal rules or rules constrained to take simple forms (such as Taylor rules) are evaluated. Less well understood is how the gains of commitment in forward looking models might be obtained even if the central bank must operate with discretion. An

[3]Dennis (2002) argues that the optimal timeless precommitment policy is not unique. There is a third approach to defining a commitment policy in this class of models. In the model consisting of equation (1), the only state variable is the current cost-push shock realization e_t. The logic employed in the Barro-Gordon literature defined a commitment policy as the choice of a rule expressing the policy instrument as a function of the current state. This would correspond to the choice of a rule of the form $x_t = be_t$ that minimizes the loss function subject to equation (1). Woodford (1999) shows that such a policy is suboptimal when expectations are forward-looking.

[4]Dennis and Söderström (2002) use calibrated and estimated models to compare discretionary outcomes with those arising under the fully optimal precommitment policy (i.e., the policy consistent with (3) and (4)).

exception is Jensen (2001) who considers the optimal assignment of a nominal income growth objective to the central bank (in addition to inflation and output gap objectives). He numerically calculates the optimal weights on the nominal income growth and inflation objectives that society should assign to a central bank operating under discretion. Thus, rather than assume the central bank can commit to a simple rule, Jensen evaluates how changing the *objectives* of the central bank might affect output and inflation. This approach parallels that used to develop solutions to the traditional average inflation bias arising under discretion (e.g., Kenneth Rogoff 1985, Walsh 1995, and Svensson 1997). Similarly, Vestin (2000) shows that assigning the central bank a price *level* target rather than an inflation objective can improve over pure discretion in a forward looking model.[5] Woodford (1999a) suggests that adding an interest rate smoothing objective to the central bank's loss function can improve outcomes by introducing inertia.

Some intuition for the role alternative policy objectives might play can be obtained by examining the form of the central bank's first order condition with alternative objectives. For example, a central bank faced with the single-period problem of minimizing $\pi_t^2 + \lambda z_t^2$ for some objective z would set $\kappa\pi_t + \lambda z_t = 0$. If z denotes the output gap, this becomes $\kappa\pi_t + \lambda x_t = 0$, which is just equation (3). If z is equal to the change in the output gap, a central bank faced with the single-period problem of minimizing $\pi_t^2 + \lambda z_t^2$ would set $\kappa\pi_t + \lambda (x_t - x_{t-1}) = 0$, the condition that holds along the timeless perspective optimal precommitment path.[6] This suggests a central bank concerned with stabilizing inflation and the change in the output gap would introduce inertia similar to that arising under a precommitment policy. A positive cost shock, for example, initially leads to a rise in inflation and a fall in the output gap. Under pure discretion, the gap returns to zero the next period, and the change in the output gap in the period following the shock is positive as output rebounds from the temporary contraction. A central bank that is concerned with stabilizing the change in the gap will continue to maintain a contractionary policy to dampen this increase in the gap, returning the gap to zero gradually.

The first order condition under the timeless precommitment policy suggests another

[5] Previously, Svensson (1999b) had shown that price level targeting had desirable properties in a model with a Lucas-type aggregate supply function.

[6] Hence, a completely myopic central bank that focuses only on miminizing its single-period objective function at each point in time would deliver the optimal precommitment policy if it targets the change in the output gap rather than the gap itself.

potential policy objective. If p_t denotes the log price level and L the lag operator, (4) can be written as $(1-\text{L})p_t = -(\lambda/\kappa)(1-\text{L})x_t$. Dividing by (1−L) yields $p_t = -(\lambda/\kappa)\, x_t$. This last condition, as Clarida, Galí, and Gertler (1999) have noted, is the first order condition obtained if the central bank minimizes a single-period loss function of the form $p_t^2 + \lambda x_t^2$. Hence, a policy of stabilizing the price level and the output gap may also mimic the timeless precommitment policy. Despite the implication that a price level objective might lead to policies that mimic optimal precommitment, no central bank has formally adopted such an objective. In contrast, the earlier quotations from Federal Reserve Governor Gramlich suggest the Fed may be following a speed limit policy.

These arguments are heuristic only, but they do provide some insight into why a speed limit policy that focuses on the change in the gap (or a price level policy) might have some desirable properties. To formally evaluate such policies, however, we need to set up the central bank's full intertemporal decision problem when it is assigned a speed limit objective.

Suppose the central bank is assigned inflation and gap change objectives. In this case, it chooses monetary policy under discretion to minimize

$$L_t^{sl} = \text{E}_t \sum_{i=0}^{\infty} \beta^i \left[\pi_{t+i}^2 + \lambda \left(x_{t+i} - x_{t+i-1}\right)^2\right] \tag{6}$$

subject to (1).[7]

In choosing x_t to affect $x_t - x_{t-1}$, the central bank's policy choice will be a function of x_{t-1}. This introduces the lagged output gap as an endogenous state variable. Private agents will base their forecasts of future values of x_{t+i} and π_{t+i} on x_{t-1} and e_t. In an optimal closed-loop equilibrium, the central bank takes the process through which private agents form their expectations as given. In this case, the central bank recognizes that expectational terms such as $\text{E}_t\pi_{t+1}$ will depend on the state variables at time t and that these state variables may be affected by policy actions at time t or earlier.

Under either optimal precommitment or discretion with a speed limit objective, the equilibrium output gap will be a linear function of the lagged gap and the cost shock. Under

[7] Suppose potential output follows a deterministic trend: $\bar{y}_t = \bar{y}_0 + \delta t$. Then, $x_t - x_{t-1} = (y_t - \bar{y}_t) - (y_{t-1} - \bar{y}_{t-1}) = y_t - y_{t-1} - \delta$, where $y_t - y_{t-1}$ is the growth rate of real output, so in this case a speed limit policy is equivalent to a policy of stabilizing inflation and the growth rate of output relative to trend.

the timeless precommitment policy, denote this solution for x_t as

$$x_t^c = a_x^c x_{t-1} + b_x^c e_t,$$

while under discretion with a speed limit objective, denote the solution as

$$x_t^{sl} = a_x^{sl} x_{t-1} + b_x^{sl} e_t.$$

Outcomes under the two alternative policy regimes can be compared by examining the equilibrium values of the coefficients appearing in these two equations.[8] It can be shown that the coefficient a_x^c is the solution less than one in absolute value of a quadratic equation that can be written as[9]

$$c(a_x^c) \equiv (1 - \beta a_x^c) \left(\frac{1 - a_x^c}{a_x^c} \right) = \left(\frac{\kappa^2}{\lambda} \right). \tag{7}$$

In contrast, a_x^{sl} is given by the solution less than one in absolute value of a fourth order polynomial equation that can be written as

$$sl(a_x^{sl}) \equiv (1 - \beta a_x^{gc})^3 \left(\frac{1 - a_x^{sl}}{a_x^{sl}} \right) = \left(\frac{\kappa^2}{\lambda} \right). \tag{8}$$

Only the first factor on the left side differs in the definitions of $c(\ )$ and $sl(\ )$. Both functions $c(\ )$ and $sl(\ )$ are decreasing functions of a_x^i for $0 < a_x^i < 1$. Since $0 < 1 - \beta a_x^i < 1$, $(1 - \beta a_x^i)^3 < 1 - \beta a_x^i$. It follows that $a_x^{sl} < a_x^c$. The optimal discretionary speed limit policy imparts some persistence to output, unlike pure discretion, but it imparts less persistence than under the timeless perspective precommitment policy.

While analytical solutions to (7) and (8) are not available, some further insights can be gained by inspection. For example, consider delegating monetary policy to a central bank following a speed limit policy but with a weight λ^{cb} on the change in the output gap objective.

[8] Under pure discretion, $x_t^d = b_x^d e_t$ where $b_x^d = -\kappa/(\lambda + \kappa^2)$.

[9] Details are contained in an appendix available from the author.

Equation (8) can then be rewritten as

$$(1-\beta a_x^{sl})\left(\frac{1-a_x^{sl}}{a_x^{sl}}\right)=\left(\frac{\kappa^2}{\hat{\lambda}}\right) \tag{9}$$

where $\hat{\lambda}=\lambda^{cb}(1-\beta a_x^{sl})^2$. If $\hat{\lambda}=\lambda$, (7) and (9) imply that $a_x^c=a_x^{sl}$. In this case, discretion under a speed limit policy imparts exactly the same degree of inertia to the gap as optimal precommitment does. $\hat{\lambda}=\lambda$ occurs when $\lambda^{cb}=\lambda/(1-\beta a_x^{sl})^2>\lambda$; optimal inertia is obtained if the central bank places *more* weight on its output objective than the social loss function does. A Rogoff "liberal" is required.[10] However, the optimal precommitment policy is not replicated exactly. It can be shown that if $\lambda^{cb}=\lambda/(1-\beta a_x^{sl})^2$ so that $a_x^c=a_x^{sl}$, the output gap reaction to an inflation shock is given by

$$b_x^{sl}=-\left(1-\beta a_x^{sl}\right)\left(\frac{\kappa}{\lambda\left[1+\beta(1-a_x^{sl})\right]+\kappa^2}\right)$$

and $\left|b_x^{sl}\right|<|b_x^c|$. Thus, the speed limit policy that imparts the correct amount of inertia responds too little to the cost shock. A speed limit policy that reduced the amount of inertia (lowering a_x^{sl} by appointing a somewhat less liberal central banker) would improve the response to cost shocks.

2.3 Simulation results

To further evaluate outcomes under discretion, numerical methods are employed to solve the model under alternative assumptions about the policy regime (commitment versus discretion) and the objective function of the central bank. Details of the solution procedures are provided in Paul Söderlind (1999).[11]

[10] The term liberal is used loosely. In the standard analysis following Rogoff (1985), a conservative central banker places less weight on output gap variability relative to inflation variability than does society. Here, the weight refers to the balance between variability in the change in the gap relative to inflation variability. In the present case, λ^{cb} should be scaled by $\sigma^2_{\Delta x}/\sigma^2_x$ where $\Delta x_t=x_t-x_{t-1}$ to obtain the additional inflation variance the central bank following a speed limit policy would accept to reduce the variance of the gap by one unit. If e is serially uncorrelated, $\sigma^2_{\Delta x}/\sigma^2_x=2(1-a_x^{sl})$. Hence, the central bank is a liberal if $2(1-a_x^{sl})\lambda^{cb}>\lambda$. Using the definition of λ^{cb}, this becomes $2(1-a_x^{sl})/(1-\beta a_x^{sl})^2>1$ which holds for $\beta=0.99$ and all a_x^{sl}, $0<a_x^{sl}<0.99995$. Thus, λ^{cb} corresponds to a Rogoff-type liberal central banker. See Vestin (2000) who shows how the weight on output under a price level targeting policy relates to the degree of Rogoff-conservatism.

[11] Numerical calculations were carried using Söderlind's MATLAB programs.

Three unknown parameters appear in the model: β, κ, and λ. The discount factor, β, is set equal to 0.99, appropriate for interpreting the time interval as one quarter. A weight on output fluctuations of $\lambda = 0.25$ is used in the baseline simulations, although results using larger and smaller values are also reported. This value for λ is also employed by Jensen (2001) and McCallum and Nelson (2000). The parameter κ captures both the impact of a change in real marginal cost on inflation and the co-movement of real marginal cost and the output gap. McCallum and Nelson (2000) characterize the empirical evidence as consistent with a value of κ in the range [0.01, 0.05]. Roberts (1995) reports higher values; he estimates the coefficient on the output gap to be about 0.3. However, he measures inflation at an annual rate, so his estimated coefficient translates into a value for κ of 0.075. Jensen (2001) sets $\kappa = 0.1$. I set $\kappa = 0.05$ as the baseline value, but results are reported for values in the range $[0.01, 0.2]$.

Table 1 presents the asymptotic loss obtained under pure discretionary policy with the central bank minimizing the social loss function (PD) and the optimal discretionary policy under a speed limit policy (SL). Panels A and B of the table express the asymptotic loss under each policy relative to the outcome under the optimal precommitment policy. Results are reported for various values of the policy preference parameter λ and the output gap elasticity of inflation κ.

For the benchmark parameter values ($\beta = 0.99$, $\lambda = 0.25$, $\kappa = 0.05$), social loss is lower in a discretionary policy environment when the central bank follows a speed limit policy than when it acts to minimize social loss. While the loss is not reduced to what could be achieved under precommitment, shifting to a speed limit objective cuts the loss due to discretion by almost 30%. This gain arises from the persistence introduced by the change in the gap objective. Figure 1 shows the response of inflation to a positive cost shock under the timeless precommitment policy, pure discretion, and a speed limit policy. Under pure discretion, inflation returns to zero one period after the shock. In contrast, a speed limit policy induces a deflation beginning in period 2 that persists for several periods. The speed limit policy induces less persistence than the timeless precommitment policy. Figure 2 shows the behavior of the output gap. The speed limit policy, because it is a discretionary policy regime, lead to a worse trade-off than precommitment. The output gap falls much more than under the precommitment policy and returns to zero more rapidly.

A speed limit policy generates persistence in the face of a temporary cost shock, but the output gap is much more variable than under pure discretion. This suggests that the advantages of SL over PD will fall if society places greater weight on output gap stabilization (i.e., a larger λ). This is verified in Table 1, which shows that the relative performance of pure discretion improves, for given κ (the output gap elasticity of inflation), as λ increases. Only for very small values of κ or values of λ significantly above the baseline value, however, does pure discretion dominate discretion with a speed limit objective.

Table 1: Comparison of Pure Discretion and Speed Limit Policies (Percentage loss relative to precommitment)

A: Pure Discretion (PD):

	λ			
	0.1	0.25	0.5	1.0
$\kappa = 0.01$	2.14%	1.03%	0.49%	0.13%
$\kappa = 0.05$	13.20%	8.42%	5.81%	3.84%
$\kappa = 0.1$	23.49%	16.35%	11.87%	8.42%
$\kappa = 0.2$	32.15%	27.30%	21.67%	14.14%

B: Speed Limit Policy (SL)

	λ			
	0.1	0.25	0.5	1.0
$\kappa = 0.01$	4.73%	4.09%	3.57%	3.12%
$\kappa = 0.05$	6.29%	6.13%	5.81%	5.37%
$\kappa = 0.1$	6.16%	6.35%	6.24%	6.08%
$\kappa = 0.2$	5.76%	6.04%	6.19%	4.33%

One interesting implication of Table 1 is that under pure discretion the loss relative to optimal precommitment varies much more as the parameter κ varies than it does under a speed limit policy. The same is true of variations in the parameter λ. The SL policy appears more robust than pure discretion with respect to uncertainty about the slope of the short-run output–inflation trade off and uncertainty about the weight to place on output objectives.

Earlier, it was noted that the first order condition linking inflation and the change in the output gap under timeless precommitment could be expressed in terms of the price level and the level of the output gap. This suggested that a central bank given the task of minimizing the expected present discounted value of a loss function of the form $\Sigma\beta^i\left(p_{t+i}^2+\lambda x_{t+i}^2\right)$ might generate outcomes under discretion that are similar to those achieved under precommitment. For the range of values of λ and κ used to construct Table 1, a price level regime (PL) does yield a smaller asymptotic loss than either pure discretion or a speed limit policy for small values of λ and large values of κ. However, across the entire parameter space, the SL policy is always either best or second best in a three way comparison of PD, SL, and PL. Interestingly, both the PD and the PL policies often lead to very poor results. For example, when $\lambda = 0.1$ and $\kappa = 0.2$, the PL policy achieves a loss that is approximately equal to the value obtained under precommitment, the SL policy yields a loss that is approximately 6% higher, while the loss under PD is 32% higher. When $\lambda = 1.0$ and $\kappa = 0.01$, the PD policy achieves a loss that is approximately equal to the value obtained under precommitment, the SL policy yields a loss that is 3% higher, while the loss under PL is 20% higher. Thus, the SL policy appears more robust to uncertainty about the true values of these key parameters.[12]

3 Targeting regimes

So far, only one aspect of policy delegation has been considered – the definition of the variables in the central bank's loss function. Policy also depends on the relative weight assigned to the bank's inflation and output objectives, and this may differ from the value of λ that appears in the social loss. Alternative targeting regimes can be characterized by the objectives assigned to the central bank and the weights attached to each objective. Specifically, a *targeting regime* is defined by a) the variables in the central bank's loss function (the objectives), and b) the weights assigned to these objectives, with policy implemented under discretion to minimize the expected discounted value of the loss function.[13]

An inflation targeting regime, for instance, will be defined by the assignment of the loss

[12] The full results of these comparisons are available from the author.

[13] This definition of a targeting regimes is consistent with that of Svensson (1999c), who states "By a targeting rule, I mean, at the most general level, the assignment of a particular loss function to be minimize" (p. 617).

function $\pi_t^2 + \lambda_{IT} x_t^2$ to the central bank, where the weight λ_{IT} is chosen optimally to minimize the asymptotic social loss function. Similarly, a speed limit targeting regime is one in which the central bank's loss function is $\pi_t^2 + \lambda_{SLT} (x_t - x_{t-1})^2$ with λ_{SLT} chosen to minimize asymptotic social loss. The objective function under price level targeting is $p_t^2 + \lambda_{PLT} x_t^2$.

A total of five alternative targeting regimes are considered. All five regimes assume that the central bank operates with discretion. In addition to inflation targeting, speed limit targeting, and price level targeting, the two other regimes are forms of nominal income growth targeting. Jensen (2001) reports that nominal income growth targeting may be superior to inflation targeting or to pure discretion. The intuition for this result is that nominal income growth targeting imparts an inertia to policy that is absent under pure discretion, and this inertia allows a nominal income growth targeting regime to achieve outcomes that are closer to those achieved under precommitment. This is the same rationale behind the superior performance of a speed limit policy. Regime $NIT1$ parallels the definitions of inflation and speed limit targeting in that inflation variability appears together with a second objective, in this case nominal income growth. Regime $NIT2$ corresponds to Jensen's definition of nominal income growth targeting in which nominal income growth stabilization replaces inflation stabilization in the objective function. The single period loss functions for each targeting regime are given in Table 2.

Table 2: Alternative policy regimes

Regime name		**Loss function**
Inflation targeting	**IT**	$\pi_t^2 + \lambda_{IT} x_t^2$
Speed limit targeting	**SLT**	$\pi_t^2 + \lambda_{SLT} (x_t - x_{t-1})^2$
Price level targeting	**PLT**	$p_t^2 + \lambda_{PLT} x_t^2$
Nominal income growth targeting (1)	**NIT1**	$\pi_t^2 + \lambda_{NIT1} (\pi_t + y_t - y_{t-1})^2$
Nominal income growth targeting (2)	**NIT2**	$\lambda x_t^2 + \lambda_{NIT2} (\pi_t + y_t - y_{t-1})^2$

3.1 The extended model

In section 2, the basic framework could be kept quite simple since only the output gap and inflation were relevant and only cost shocks generated a policy trade off that posed interesting issues of policy design. Under nominal income growth targeting, however, shocks to potential output can affect nominal income and induce policy responses. Thus, to compare outcomes under different delegation schemes, the model needs to be enriched to incorporate other possible disturbances that may affect the economy differently under alternative policies.

The inflation adjustment equation is altered to incorporate endogenous persistence by including the lagged inflation rate in (1) and allowing the cost shock to be serially correlated. The purely forwarding looking inflation adjustment equation given by (1) has been criticized for failing to match the short-run dynamics exhibited by inflation (Arturo Estrella and Jeffrey Fuhrer 1998). Specifically, inflation seems to respond sluggishly and to display significant persistence in the face of shocks, while (1) allows current inflation to be a jump variable that can respond immediately to any disturbance. Most empirical studies of inflation have found significant effects of lagged inflation in addition to expectations of future inflation (Fuhrer 1997, Galí and Gertler 1999, Galí, Gertler, and J. David López-Salido 2001, and Glenn Rudebusch 2002).[14]

When the inflation adjustment incorporates a direct effect of lagged inflation on current inflation, equation (1) is replaced with

$$\pi_t = (1-\phi)\beta \mathrm{E}_t\pi_{t+1} + \phi\pi_{t-1} + \kappa x_t + e_t \tag{10}$$

where $\phi \in [0,1]$ measures the importance of backward looking inertia in the inflation process. The cost shock e_t follows the $AR(1)$ process

$$e_t = \gamma_e e_t + \varepsilon_t \tag{11}$$

and $0 \leq \gamma_e < 1$.

The choice of ϕ can be critical in assessing outcomes under alternative policies. In a backward looking model (i.e., $\phi = 1$), Laurence Ball (1999) found evidence that nominal income growth targeting could produce disastrous results. McCallum (1997), however, showed that this was no longer the case when expectations played a role. Rudebusch (2002) reached similar conclusions in his analysis of nominal income targeting, finding that it performed poorly for high values of ϕ. Rudebusch estimates an equation that takes the basic form of (10) and concludes

[14] Galí and Gertler (1999) argue that the poor empirical performance of equations such as (1) arises from the use of the output gap in place of the theoretically correct real marginal cost.

that, for the U.S., ϕ is about 0.7. That is, he finds that most weight is placed on the lagged inflation term. This is consistent with Fuhrer (1997) who reports estimates of ϕ close to 1. Galí and Gertler (1999) argue that the coefficient on lagged inflation rate is small when a measure of marginal cost is used in place of the output gap, however. Galí, Gertler, and López-Salido (2001) report a value of 0.3 for Europe. Much of the recent theoretical literature has adopted a value of $\phi = 0$, with only forward looking expectations entering. This was the form used in equation (1) and employed in the previous sections of this paper. Vestin (2000) sets $\phi = 0$ in his evaluation of price level targeting. Jensen (2001) sets $\phi = 0.3$ in his analysis of nominal income growth targeting, arguing that for policy evaluation it is appropriate to emphasize the role of forward looking expectations. McCallum and Nelson (2000) set $\phi = 0.5$. I follow McCallum and Nelson in adopting a value of 0.5 as a baseline.[15] However, I evaluate policies for values of ϕ ranging from zero to one.

Because nominal income growth targeting is based on the growth of nominal income and not on the output gap, it is necessary to specify the demand side of the model. The aggregate demand specification is derived from the representative household's Euler condition linking consumption at dates t and $t+1$, augmented with a backward looking element in the form of lagged output (see Estrela and Fuhrer 1998 Jensen 2001). This condition takes the form

$$y_t = (1-\theta)\mathrm{E}_t y_{t+1} + \theta y_{t-1} - \sigma\left(R_t - \mathrm{E}_t \pi_{t+1}\right) + u_t \tag{12}$$

where y is output, R is the nominal interest rate, and u is a stochastic disturbance. All variables are expressed as percent deviations around the steady-state. If output demand arises from

[15] The specifications in both Jensen and in McCallum and Nelson differ slightly from that used in equation (10). Jensen's inflation equation is (using my notation)

$$\pi_t = (1-\phi)\beta E_t \pi_{t+1} + \phi \pi_{t-1} + (1-\phi)\kappa x_t + e_t$$

while McCallum and Nelson assume

$$\pi_t = (1-\phi)\beta E_t \pi_{t+1} + \beta\phi \pi_{t-1} + \kappa x_t + e_t.$$

Jensen's specification can be written as

$$\pi_t = (1-\phi)\pi_t^* + \phi \pi_{t-1} + e_t$$

where $\pi_t^* = \beta E_t \pi_{t+1} + \kappa x_t$.

consumption and government purchases, then u_t includes $g_t - \mathrm{E}_t g_{t+1}$, where g is the percent deviation of government purchases around the steady-state. The demand shock u_t is assumed to be serially correlated and follows the $AR(1)$ process

$$u_t = \gamma_u u_{t-1} + \eta_t, \qquad 0 \leq \gamma_u < 1. \tag{13}$$

If the output gap variable x_t is defined as $y_t - \bar{y}_t$ where $\bar{y}_t$ is potential output, equation (12) can be written as

$$x_t = \theta x_{t-1} + (1-\theta)\mathrm{E}_t x_{t+1} - \sigma(R_t - \mathrm{E}_t \pi_{t+1}) + \mu_t \tag{14}$$

where $\mu_t = u_t - \bar{y}_t + \theta\bar{y}_{t-1} + (1-\theta)\mathrm{E}_t\bar{y}_{t+1}$. Finally, potential real output is assumed to follow an $AR(1)$ process:

$$\bar{y}_t = \bar{\gamma}\bar{y}_{t-1} + \xi_t, \qquad 0 \leq \bar{\gamma} < 1. \tag{15}$$

The innovations η_t and ξ_t are assumed to be white noise, zero mean processes that are mutually uncorrelated and uncorrelated with the cost shock innovation ε_t. The shock ξ_t represents a disturbance to potential output. The model now consists of equations (10), (11), (13), (14), and (15). This makes the model almost identical to the one employed by Jensen (2001). The central bank's policy instrument is the nominal interest rate R_t.

Noting that $\mathrm{E}_t\bar{y}_{t+1} = \bar{\gamma}\bar{y}_t$, μ_t can be written as $\mu_t = u_t - [1-(1-\theta)\bar{\gamma}]\,\bar{y}_t + \theta\bar{y}_{t-1}$. The state-space form of the entire model is then

$$\begin{bmatrix} u_{t+1} \\ \bar{y}_{t+1} \\ \bar{y}_t \\ e_{t+1} \\ x_t \\ \pi_t \\ \mathrm{E}_t x_{t+1} \\ \mathrm{E}_t \pi_{t+1} \end{bmatrix} = A \begin{bmatrix} u_t \\ \bar{y}_t \\ \bar{y}_{t-1} \\ e_t \\ x_{t-1} \\ \pi_{t-1} \\ x_t \\ \pi_t \end{bmatrix} + BR_t + \begin{bmatrix} \eta_{t+1} \\ \xi_{t+1} \\ 0 \\ \varepsilon_{t+1} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where

$$A = \begin{bmatrix} \gamma_u & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \bar{\gamma} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma_e & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -\frac{1}{1-\theta} & \frac{1-(1-\theta)\gamma_n}{1-\theta} & -\frac{\theta}{1-\theta} & \frac{\sigma}{\beta(1-\phi)(1-\theta)} & -\frac{\theta}{1-\theta} & \frac{\sigma\phi}{\beta(1-\phi)(1-\theta)} & \left(\frac{1}{1-\theta}\right)\left(1+\frac{\sigma\kappa}{\beta(1-\phi)}\right) & -\frac{\sigma}{\beta(1-\phi)(1-\theta)} \\ 0 & 0 & 0 & -\frac{1}{\beta(1-\phi)} & 0 & -\frac{\phi}{\beta(1-\phi)} & -\frac{\kappa}{\beta(1-\phi)} & \frac{1}{\beta(1-\phi)} \end{bmatrix}$$

and $B' = [0\ 0\ 0\ 0\ 0\ 0\ \frac{\sigma}{1-\theta}\ 0]'$. Define $X_{1t} = [u_t,\ \bar{y}_t,\ \bar{y}_{t-1},\ e_t,\ x_{t-1},\ \pi_{t-1}]'$, $X_{2t} = [x_t,\ \pi_t]'$, and $\chi_{t+1} = [\eta_{t+1},\ \xi_{t+1},\ 0,\ \varepsilon_{t+1},\ 0,\ 0,\ 0]'$. The system can be written compactly as

$$\mathrm{E}_t Z_{t+1} = AZ_t + BR_t + \chi_{t+1} \tag{16}$$

where

$$Z_t \equiv \begin{bmatrix} X_{1t} \\ X_{2t} \end{bmatrix}.$$

For each of the targeting regimes, the loss function takes the form $L_k = \mathrm{E}_t \sum \beta^i Z'_{t+i} Q_k Z_{t+i}$, where the specification of the Q_k matrix depends on the specific targeting regime. For example, for the speed limit targeting case,

$$Q_{SLT} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_{SLT} & 0 & -\lambda_{SLT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\lambda_{SLT} & 0 & \lambda_{SLT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

As in the previous subsection, the optimal discretionary policy is derived for each loss function. A gird search is conducted over values of λ_k to obtain the optimal weight to assign the central bank for its loss function. The equilibrium solutions for the output gap and inflation are then used to evaluate the asymptotic social loss.

When price level targeting is considered, the model must be rewritten in terms of p_t. For example, the inflation adjustment equation (10) becomes

$$p_t = \frac{(1-\phi)\beta \mathrm{E}_t p_{t+1} + (1+\phi)p_{t-1} - \phi p_{t-2} + \kappa x_t + e_t}{1+(1-\phi)\beta}.$$

In this case, both p_{t-1} and p_{t-2} are endogenous state variables.

The new parameters appearing in this extended model are the serially correlation coefficients γ_u and $\bar{\gamma}$, the weight on the lagged output gap in the expectational IS relationship, θ, and the variances of the innovations to demand and potential output. None of these parameters affects policy choice or social loss under the policies considered earlier. These policies, and the social loss function, involved only the output gap and inflation. The stochastic process followed by potential output did affect equilibrium output but not the output gap or inflation. This separation will no longer be true for the nominal income growth targeting regimes, so we now need to parameterize the complete model. Benchmark values for these parameters are taken from Jensen (2001) and are listed in Table 3, together with the parameters discussed earlier.

Table 3: Baseline parameter values for extended model

σ	λ	κ	ϕ	θ	β
1.5	0.25	0.05	0.5	0.5	0.99
σ_e	σ_u	σ_y	γ_e	γ_u	γ_y
0.015	0.015	0.005	0	0.3	0.97

3.2 Evaluation

Table 4 gives the asymptotic social loss under each regime for various parameter values. For comparison, the loss under the optimal precommitment policy (denoted PC) is also shown.

Table 4: Alternative policy regimes[16]

	(1) Baseline	(2) σ_y= 0.01	(3) κ = 0.01	(4) κ = 0.2	(5) γ_e= 0.3	(6) γ_e= 0.7
PC	9.937	9.937	24.650	3.356	25.850	169.251
IT	11.741	11.741	28.081	3.840	31.305	204.233
SLT	9.966	9.966	24.645	3.368	25.954	169.700
PLT	11.018	11.018	28.266	3.576	28.853	186.757
NIT1	11.980	12.022	49.930	3.457	30.483	185.441
NIT2	9.998	11.124	25.377	3.708	29.091	173.257

With the baseline parameter values, targeting the change in the output gap (speed limit targeting) yields the lowest social loss of any of the discretionary regimes. It comes within less than 1% of the precommitment loss (9.969 vs. 9.937). Jensen's form of nominal income growth targeting ($NIT2$) is second best, yielding a loss also less than 1% above precommitment. Price level targeting is slightly worse than either SLT or $NIT2$, but it is superior to inflation targeting and the $NIT1$ form of nominal income growth targeting.

Column 2 of Table 4 shows the impact of doubling the variance of shocks to potential output. The first three discretionary regimes depend only on inflation and the output gap, so none of these are affected by the increase in σ_y. However, policy regimes based on nominal income growth are affected. Greater variability in potential output reduces the desirability of the nominal income growth targeting regimes.

Alternative values of the output gap elasticity of inflation, κ, are considered next. For both smaller values of this elasticity (col. 3) and larger values (col. 4), the SLT policy continues to yield the lowest social loss among the discretionary targeting regimes. For the smaller value of κ, $NIT2$ remains the second best targeting regime. However, when κ is increased to 0.2, $NIT1$ is second, with PLT close behind. The $NIT2$ form of nominal income targeting still performs better than inflation targeting.

In columns 5 and 6, serially correlation in the cost shock process is introduced. Again, the speed limit policy yields the lowest loss among the discretionary regimes, with price level

[16] Loss times 100.

targeting second when $\gamma_e = 0.3$ and $NIT2$ second when $\gamma_e = 0.7$.

As we saw earlier, variations in the social weight λ on output gap stabilization can affect the relative performance of pure discretion and speed limit policies. Table 5 reports results for values of λ ranging from 0.1 to 1.0, and including the baseline value of 0.25. The speed limit targeting regime (SLT) continues to yield the lowest loss for both smaller and larger values of λ.

Table 5: Effect of Alternative Social Weights on Output Gap Variability [17]

	(1)	**(2)**	**(3)**	**(4)**
	$\boldsymbol{\lambda = 0.1}$	$\boldsymbol{\lambda = 0.25}$	$\boldsymbol{\lambda = 0.5}$	$\boldsymbol{\lambda = 1.0}$
PC	7.217	9.937	12.418	15.290
IT	8.491	11.741	14.665	17.982
SLT	7.243	9.966	12.446	15.313
PLT	7.906	11.018	13.885	17.232
NIT1	7.422	11.980	19.251	33.655
NIT2	7.631	9.998	12.729	16.213

Earlier work by Vestin (2000) found that price level targeting out performed inflation targeting, a result that holds for the parameter values used in Tables 4 and 5. Jensen (2001) found the $NIT2$ targeting regime out performs inflation targeting; this is also found in Tables 4 and 5. Both Vestin and Jensen employ models with less endogenous inflation persistence than the baseline value of $\phi = 0.5$ used here. When $\phi = \gamma_e = 0$, Vestin shows that price level targeting can replicate the timeless precommitment policy. Jensen sets $\phi = 0.3$ and $\gamma_e = 0$ for his baseline calibration. Rudebusch (2002) shows that the value of ϕ can be critical for the evaluation of alternative targeting regimes. To assess the relative performance of these targeting regimes for different values of ϕ, the optimal targeting weight is found for each regime and social loss evaluated for values of ϕ varying between 0 and 1. Figure 3 shows the relative performance of speed limit targeting, price level targeting, and the $NIT2$ version of nominal income growth

[17] Loss times 100.

targeting as a function of ϕ.[18] Asymptotic social loss under each targeting regime is expressed relative to the outcome under optimal inflation targeting.

When the inflation process is predominately backward-looking ($\phi \leq 0.35$), the price level targeting regime yields the best outcome. Optimal price level targeting does worse than optimal inflation targeting if ϕ is much above 0.5. Perhaps more interestingly, if the role of forward looking expectation is small (ϕ large), price level targeting performs much worse than the other targeting regimes. For values of ϕ greater than 0.35 and less than 0.7, optimal speed limit targeting does best, although the $NIT2$ form of nominal income growth targeting is only slightly worse.[19] Finally, for $\phi \geq 0.7$, optimal inflation targeting is the best regime. This last result is not surprising; the stabilization bias of discretion arose because of the presence of forward looking expectations. As these fall in importance, the difference between discretion and precommitment also falls. While $NIT2$ is never the best policy, PLT, SLT, and IT are each the best regime for about one-third of the range of values for ϕ. For the most empirically relevant range, the speed limit regime performs best.[20]

4 Conclusions

In this paper, I have assumed that the relevant monetary policy regime is one of discretion, and the problem faced in designing policy is to assign a loss function to the central bank. Virtually all the recent literature has assumed that a social loss function dependent on inflation and the output gap is the appropriate objective of policy, yet discretionary policy with such a social loss function imparts too little persistence to output and inflation. A policy aimed at stabilizing inflation and the change in the output gap (a speed limit policy) imparts inertia that can lead to improved stabilization relative to pure discretion or inflation targeting. Simulations suggested that a speed limit targeting policy dominates inflation targeting except when forward looking

[18] As $NIT1$ was always dominated by one of the other regimes, it is not shown.

[19] Since the nominal income growth regimes depend on the shocks to potential output, an increase in σ_y would reduce the gain from $NIT2$ while leaving unchanged the gain from SLT.

[20] After the first draft of this paper was circulated, Ulf Söderström (2001) added the output gap change objective to his evaluation of alternative targeting regimes. His regimes included money growth targeting, interest rate smoothing, nominal income targeting, and average inflation targeting. Except when inflation was predominately backward looking or the output elasticity of inflation was very large, output gap change targeting yielded the smallest asymptotic loss in his model, results consistent with those found here.

expectations are relatively unimportant. Policy regimes based on the change in the gap were also compared to alternative targeting regimes such as price level targeting and nominal income growth targeting. When inflation is affected by both expectations of future inflation and lagged inflation, a speed limit policy dominates price level targeting for empirical relevant parameter values. While earlier research suggested price level targeting might dominate inflation targeting, price level target leads to significantly poorer outcomes than either inflation targeting, nominal income growth targeting, or speed limit targeting if inflation is primarily backward looking.

Previous authors have considered the introduction of other objectives designed to induce inertia into policy. In Woodford's original discussion of interest rate inertia, he argued that empirical evidence of inertial interest rate behavior reflected the attempt by central banks to influence forward-looking expectations, and thereby improve the trade-off between inflation and output gap variability.[21] Nominal income growth targeting implicitly introduces the lagged value of real output into the state vector and generates some persistence even under a regime of pure discretion. This accounts for the good performance of nominal income growth targeting that Jensen finds. Speed limit policies also induce inertia. An avenue for future work is to investigate the impact of errors in measuring the output gap on the relative performance of different targeting regimes. If such errors are highly serially correlated, the case for a speed limit policy might be further strengthened.

A policy that responds to the change in the output gap incorporates a form of the derivative corrective factor analyzed by A. W. Phillips (1957).[22] In the models Phillips examined, he concluded that "it is usually necessary to include an element of derivative correction in a stabilization policy." That conclusion also seems to hold for New Keynesian models.

[21] Rudebusch (2001) argues that interest rate inertia may reflect responses to serially ocrrelated shocks rather than directly from a desire to smooth interest rates.

[22] I would like to thanks Ben Friedman for pointing out to me the similarity of a speed limit policy to Phillips's derivative corrective factor.

Appendix

A1. Model foundations

Equations (10) and (12) can be interpreted as governing the dynamic adjustment of the economy around the flexible-price equilibrium. In this appendix, the general equilibrium model structure that leads to these equations is specified. For simplicity, the model ignores the government sector.

Households

The preferences of the representative household are defined over a composite consumption good C_t, real money balances M_t/P_t, and leisure $1 - N_t$. Households maximize the expected present discounted value of utility:

$$\mathrm{E}_t \sum_{i=0}^{\infty} \beta^i \left[\frac{C_{t+i}^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} + \frac{\gamma}{1-b} \left(\frac{M_t}{P_t} \right)^{1-b} - \chi \frac{N_{t+i}^{1+\eta}}{1+\eta} \right]$$

The composite consumption good consists of differentiate products produced by monopolistically competitive final goods producers (firms). There are a continuum of such firms of measure 1. C_t is defined as

$$C_t = \left[\int_0^1 c_{jt}^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}} \qquad \theta > 0$$

Given prices p_{jt} for the final goods, this preference specification implies the household's demand for good j is

$$c_{jt} = \left(\frac{p_{jt}}{P_t} \right)^{-\theta} C_t$$

where the aggregate price index P_t is defined as

$$P_t = \left[\int_0^1 p_{jt}^{1-\theta} dj \right]^{\frac{1}{1-\theta}}$$

The budget constraint of the household is, in real terms,

$$C_t + \frac{M_t}{P_t} + \frac{B_t}{P_t} = \frac{W_t}{P_t} N_t + \frac{M_{t-1}}{P_t} + R_{t-1} \frac{B_{t-1}}{P_t} + \Pi_t$$

where M_t (B_t) is the household's nominal holdings of money (one period bonds). Bonds pay a gross nominal rate of interest given by R_t. Real profits received from firms are equal to Π_t.

In addition to the demand functions for the individual goods, the following first order conditions must hold in equilibrium:

$$C_t^{-\frac{1}{\sigma}} = \beta \mathrm{E}_t \left(\frac{R_t P_t}{P_{t+1}} \right) C_{t+1}^{-\frac{1}{\sigma}} \tag{17}$$

$$\frac{\left(\frac{M_t}{P_t}\right)^{-b}}{C_t^{-\frac{1}{\sigma}}} = \frac{R_t - 1}{R_t} \tag{18}$$

$$\frac{\chi N_t^{\eta}}{C_t^{-\frac{1}{\sigma}}} = \frac{W_t}{P_t} \tag{19}$$

Firms

Following the literature on staggered price setting, we adopt a Calvo specification in which the probability a firm adjusts its price each period is given by $1 - \omega$. If firm j sets its price at time t, it will do so to maximize expected profits, subject to the production technology

$$c_{jt} = N_{jt}^{a}$$

where N_{jt} is employment by firm j in period t.

Let φ_t denote the firm's real marginal cost (equal to $W_t/aP_tN_t^{a-1}$). The firm's decision problem then involves picking p_{jt} to maximize

$$\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \Delta_{i,t+i} \left[\left(\frac{p_{jt+i}}{P_{t+i}} \right)^{1-\theta} - \varphi_{t+i} \left(\frac{p_{jt}}{P_{t+i}} \right)^{-\theta} \right] C_{t+i}$$

where the discount factor $\Delta_{i,t+i}$ is given by $\beta^i (C_{t+i}/C_t)^{-\frac{1}{\sigma}}$. The first order condition is

$$\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \Delta_{i,t+i} \left[(1-\theta) \left(\frac{1}{p_{jt}} \right) \left(\frac{p_{jt}}{P_{t+i}} \right)^{1-\theta} + \theta \varphi_{t+i} \left(\frac{1}{p_{jt}} \right) \left(\frac{p_{jt}}{P_{t+i}} \right)^{-\theta} \right] C_{t+i} = 0$$

Since all firms adjusting in period t set the same price, let p_t^* be the optimally set price at time t. Then,

$$\left(\frac{p_t^*}{P_t}\right) = \left(\frac{\theta}{\theta - 1}\right) \frac{\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \Delta_{i,t+i} \left[\varphi_{t+i} \left(\frac{P_{t+i}}{P_t}\right)^{\theta} C_{t+i}\right]}{\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \Delta_{i,t+i} \left[\left(\frac{P_{t+i}}{P_t}\right)^{\theta-1} C_{t+i}\right]} \tag{20}$$

The aggregate price index is

$$P_t^{1-\theta} = (1-\omega)(p_t^*)^{1-\theta} + \omega P_{t-1}^{1-\theta} \tag{21}$$

Using the definition of $\Delta_{i,t+i}$, equation (20) becomes

$$\left(\frac{p_t^*}{P_t}\right) = \left(\frac{\theta}{\theta - 1}\right) \frac{\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \beta^i C_{t+i}^{1-\frac{1}{\sigma}} \varphi_{t+i} \left(\frac{P_{t+i}}{P_t}\right)^{\theta}}{\mathrm{E}_t \sum_{i=0}^{\infty} \omega^i \beta^i C_{t+i}^{1-\frac{1}{\sigma}} \left(\frac{P_{t+i}}{P_t}\right)^{\theta-1}}$$

Equilibrium and the approximation

Equilibrium paths for output, consumption and prices are given by equations (17) (20), and (21). Because the nominal interest rate is treated as the monetary policy instrument, equation (18) simply determines the nominal quantity of money in equilibrium.

Let $\hat{x}_t$ denote the percent deviation of X around its flex-price equilibrium. Equations (17) and (19) can be approximated as

$$\hat{c}_t = \mathrm{E}_t \hat{c}_{t+1} - \sigma \left(\hat{r}_t - \mathrm{E}_t \hat{\pi}_{t+1}\right) \tag{22}$$

$$\eta \hat{n}_t + \frac{1}{\sigma} \hat{c}_t = \hat{w}_t - \hat{p}_t$$

Real marginal costs is then

$$(1 - a + \eta)\hat{n}_t + \frac{1}{\sigma}\hat{c}_t = \left(\frac{1 - a + \eta}{a} + \frac{1}{\sigma}\right) \hat{c}_t \equiv \gamma \hat{c}_t$$

Finally, the price adjustment equation (20) can be approximated as

$$\hat{\pi}_t = \beta \mathrm{E}_t \hat{\pi}_{t+1} + \kappa \hat{c}_t \tag{23}$$

where

$$\kappa = \gamma \left(\frac{(1-\omega)\left[1-\omega\beta\right]}{\omega} \right)$$

Equations (22) and (23) are the basis for equations (12) and (1) of the text.

A2. The solution under precommitment and discretion

This appendix derives equations (7) and (8) of the text.

Precommitment

Under the optimal precommitment solution, inflation and the output gap are linked by the first order condition given by equation (5). Using this in the inflation adjustment equation (1) yields

$$x_t - x_{t-1} = \beta\left(\mathrm{E}_t x_{t+1} - x_t\right) - \left(\frac{\kappa^2}{\lambda}\right) x_t - \left(\frac{\kappa}{\lambda}\right) e_t \tag{24}$$

Using the proposed solution $x_t^c = a_x^c x_{t-1} + b_x^c e_t$ to express $\mathrm{E}_t x_{t+1} = \left(a_x^c\right)^2 x_{t-1} + a_x^c b_x^c e_t$, equation (24) becomes

$$\begin{aligned}(a_x^c - 1)x_{t-1} + b_x^c e_t &= \beta\left[a_x^c(a_x^c - 1)x_{t-1} + b_x^c(a_x^c - 1)e_t\right] \\ &\quad - \left(\frac{\kappa^2}{\lambda}\right)\left(a_x^c x_{t-1} + b_x^c e_t\right) - \left(\frac{\kappa}{\lambda}\right) e_t\end{aligned}$$

This implies a_x^c is a solution to

$$(a_x^c - 1) = \beta a_x^c(a_x^c - 1) - \left(\frac{\kappa^2}{\lambda}\right) a_x^c$$

or

$$(1 - \beta a_x^c)\left(\frac{1 - a_x^c}{a_x^c}\right) = \left(\frac{\kappa^2}{\lambda}\right)$$

which is equation (7) of the text.

When the cost shock is serially correlated, the function $c(a_x^c)$ and therefore the value of

a_x^c is unaffected. However, if $e_t = \gamma_e e_{t-1} + \varepsilon_t$, the value of b_x^c is given by[23]

$$b_x^c = -\frac{\kappa}{\lambda\left[1 - \beta\gamma_e + \beta(1 - a_x^c)\right] + \kappa^2}$$

Discretion with an output gap change objective

Under discretion, we can write the central bank's decision problem in terms of the value function $V(x_{t-1}, e_t)$:

$$V(x_{t-1}, e_t) = \min\left[\left(\frac{1}{2}\right)\pi_t^2 + \left(\frac{1}{2}\right)\lambda\left(x_t - x_{t-1}\right)^2 + \beta \mathrm{E}_t V(x_t, e_{t+1})\right]$$

where the minimization is subject to equation (1). Given the linear quadratic structure of the problem, the solutions for the output gap and inflation will take the form

$$x_t = a_x^{gc} x_{t-1} + b_x^{gc} e_t$$

and

$$\pi_t = a_\pi^{gc} x_{t-1} + b_\pi^{gc} e_t$$

From the second of these, it follows that $\mathrm{E}_t\pi_{t+1} = a_\pi^{gc} x_t$. The inflation adjustment equation can then be written as

$$\begin{aligned} \pi_t &= (\beta a_\pi^{gc} + \kappa)x_t + e_t \\ &= (\beta a_\pi^{gc} + \kappa)\left(a_x^{gc} x_{t-1} + b_x^{gc} e_t\right) + e_t \end{aligned}$$

Hence,

$$a_\pi^{gc} = (\beta a_\pi^{gc} + \kappa)a_x^{gc} = \frac{\kappa a_x^{gc}}{1 - \beta a_x^{gc}} = \bar{\kappa} a_x^{gc}$$

where $\bar{\kappa} \equiv \kappa/(1 - \beta a_x^{gc})$. Using this expression for a_π^{gc}, it will be useful to note that

$$\frac{\partial \pi_t}{\partial x_t} = \beta a_\pi^{gc} + \kappa = \frac{\kappa}{1 - \beta a_x^{gc}} = \bar{\kappa}$$

[23] Under pure discretion, the output gap depends only on the current value of the cost shock and $x_t = -\left[\kappa / \left(\lambda(1 - \beta\gamma_e) + \kappa^2\right)\right] e_t$.

The value of b_π^{gc} is given by

$$b_\pi^{gc} = (\beta a_\pi^{gc} + \kappa) b_x^{gc} + 1 = \bar{\kappa} b_x^{gc} + 1$$

Thus,

$$\pi_t = \bar{\kappa} x_t + \left(1 + \bar{\kappa} b_x^{gc}\right) e_t$$

The first order condition for the optimal choice of x_t is

$$\bar{\kappa}\pi_t + \lambda\left(x_t - x_{t-1}\right) + \beta \mathrm{E}_t V_x(x_t, e_{t+1}) = 0 \tag{25}$$

From the envelope theorem,

$$V_x(x_{t-1}, e_t) = -\lambda\left(x_t - x_{t-1}\right)$$

so the first order condition (25) becomes

$$\bar{\kappa}\pi_t + \lambda\left(x_t - x_{t-1}\right) - \beta\lambda\left(\mathrm{E}_t x_{t+1} - x_t\right) = 0$$

or

$$\begin{aligned} x_t - x_{t-1} &= \beta\left(\mathrm{E}_t x_{t+1} - x_t\right) - \left(\frac{\bar{\kappa}^2}{\lambda}\right) x_t \\ &\quad - \left(\frac{\bar{\kappa}}{\lambda}\right)\left(1 + \bar{\kappa} b_x^{gc}\right) e_t \end{aligned} \tag{26}$$

which should be compared to equation (24) under precommitment.

Using the proposed solution for x_t in (26), the coefficients a_x^{gc} and b_x^{gc}must satisfy

$$\begin{aligned} (a_x^{gc} - 1)x_{t-1} + b_x^{gc} e_t &= \beta\left[a_x^{gc}(a_x^{gc} - 1)x_{t-1} + b_x^{gc}(a_x^{gc} - 1)e_t\right] \\ &\quad - \left(\frac{\bar{\kappa}^2}{\lambda}\right)\left(a_x^{gc} x_{t-1} + b_x^{gc} e_t\right) \\ &\quad - \left(\frac{\bar{\kappa}}{\lambda}\right)\left(1 + \bar{\kappa} b_x^{gc}\right) e_t \end{aligned}$$

Hence,

$$(a_x^{gc} - 1) = \beta a_x^{gc}(a_x^{gc} - 1) - \left(\frac{\bar{\kappa}^2}{\lambda}\right) a_x^{gc}$$

Multiplying both sides by $(1 - \beta a_x^{gc})^2$ and recalling the definition of $\bar{\kappa}$ yields

$$(1 - \beta a_x^{gc})^3 \left(\frac{1 - a_x^{gc}}{a_x^{gc}}\right) = \left(\frac{\kappa^2}{\lambda}\right)$$

which yields equation (8) of the text.

When the cost shock is serially correlated, the function $gc(a_x^{gc})$ is unaffected. However, if $e_t = \gamma_e e_{t-1} + \varepsilon_t$, the value of b_x^{gc} is given by

$$b_x^{gc} = -\left(\frac{\bar{\kappa}}{\lambda(1 - \beta\gamma_e)\left[1 - \beta\gamma_e + \beta(1 - a_x^{gc})\right] + \bar{\kappa}^2}\right)$$

A3. The loss functions

For the model given by equation (**??**), the weighting matrices for the loss functions corresponding to pure discretion and an output gap growth objective are

$$Q_{PD} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{GC} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda & 0 & -\lambda & 0 \\ 0 & -\lambda & 0 & \lambda & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The policy weighting matrices for the model given by equation (16) are

$$Q_{PD} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{IT} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_{IT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{GC} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda & 0 & -\lambda & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\lambda & 0 & \lambda & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{GCT} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_{GCT} & 0 & -\lambda_{GCT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\lambda_{GCT} & 0 & \lambda_{GCT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{OGT} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{OGT} & -\lambda_{OGT} & 0 & -\lambda_{OGT} & 0 & \lambda_{OGT} & 0 \\ 0 & -\lambda_{OGT} & \lambda_{OGT} & 0 & \lambda_{OGT} & 0 & -\lambda_{OGT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\lambda_{OGT} & \lambda_{OGT} & 0 & \lambda_{OGT} & 0 & -\lambda_{OGT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{OGT} & -\lambda_{OGT} & 0 & -\lambda_{OGT} & 0 & \lambda_{OGT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q_{NIT} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{NIT} & -\lambda_{NIT} & 0 & -\lambda_{NIT} & 0 & \lambda_{NIT} & \lambda_{NIT} \\ 0 & -\lambda_{NIT} & \lambda_{NIT} & 0 & \lambda_{NIT} & 0 & -\lambda_{NIT} & -\lambda_{NIT} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\lambda_{NIT} & \lambda_{NIT} & 0 & \lambda_{NIT} & 0 & -\lambda_{NIT} & -\lambda_{NIT} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{NIT} & -\lambda_{NIT} & 0 & -\lambda_{NIT} & 0 & \lambda_{NIT} & \lambda_{NIT} \\ 0 & \lambda_{NIT} & -\lambda_{NIT} & 0 & -\lambda_{NIT} & 0 & \lambda_{NIT} & 1+\lambda_{NIT} \end{bmatrix}$$

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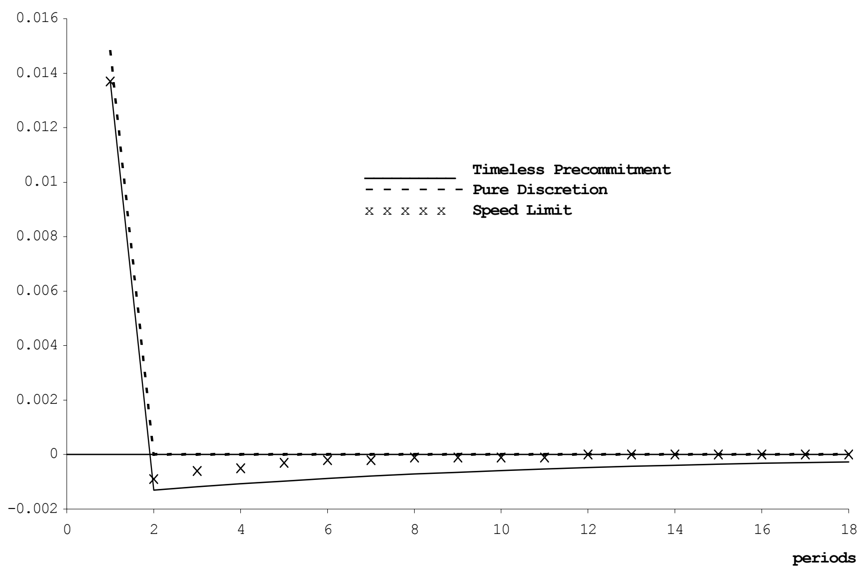

Figure 1: Response of inflation to a positive cost shock: timeless precommitment, pure discretion, and speed limit policies

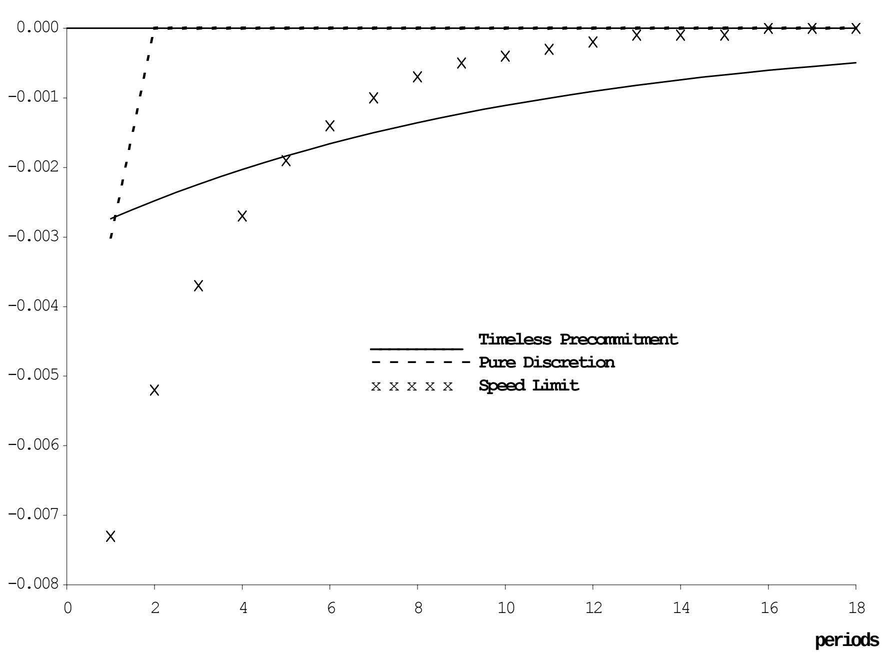

Figure 2: Response of output gap to positive cost shock: precommitment, pure discretion, and speed limit polices

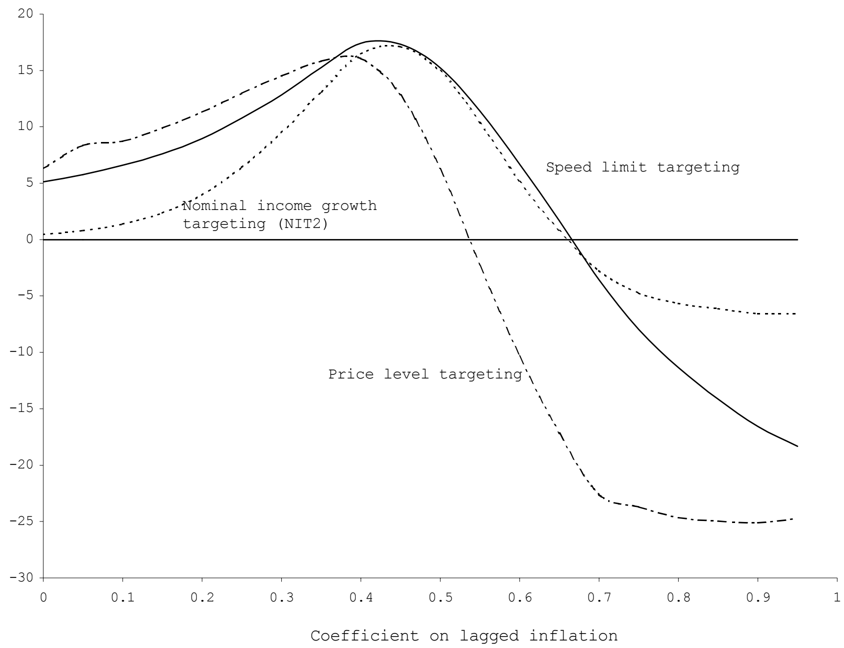

Figure 3: Alternative targeting regimes: gains relative to inflation targeting