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Monetary Policy with a Convex Phillips Curve and Asymmetric Loss

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Abstract

Recent theoretical and empirical work has cast doubt on the hypotheses of a linear Phillips curve and a symmetric quadratic loss function underlying traditional thinking on monetary policy. This paper analyzes the Barro-Gordon optimal monetary policy problem under alternative loss functions—including an asymmetric loss function corresponding to the “opportunistic approach” to disinflation—when the Phillips curve is convex. Numerical simulations are used to compare the implications of the alternative loss functions for equilibrium levels of inflation and unemployment. For parameter estimates relevant to the United States, the symmetric loss function dominates the asymmetric alternative.

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SUMMARY

Empirical monetary policy research suggests that the short-run Phillips curve in several developed countries may be moderately convex, reflecting a nonlinear tradeoff between inflation and unemployment. This has led to the question of whether economic performance is likely to be superior when policymakers minimize a symmetric loss function of the Barro-Gordon type or when policy is guided by an asymmetric loss function. This paper addresses this issue by assuming that the short-run Phillips curve is convex and examines the static and dynamic implications for the equilibrium levels of unemployment and inflation under alternative policymaker loss functions. Following recent arguments in support of an “opportunistic approach” to disinflation, we introduce an asymmetric loss function in which welfare is negatively related to the level of unemployment, as well as to the variances of unemployment and inflation, and contrast its equilibrium properties to those of the standard symmetric loss function.

There are three main results. First, it is shown that single-period optimization under the asymmetric loss function yields an “inaction range” of inflation shocks for which the optimal policy setting and equilibrium level of unemployment do not adjust. Second, numerical simulations of inflation and unemployment outcomes over a long horizon demonstrate that the symmetric and asymmetric loss functions both yield a positive expected inflation bias, that is, an expected inflation rate in excess of the target, and that bias is larger under the asymmetric specification. Third, the two loss function specifications are compared and contrasted using the simulated moments of the distributions of equilibrium levels of inflation and unemployment. For parameter values corresponding to the modest degree of convexity that may characterize the U.S. Phillips curve, we find that the symmetric loss function dominates the asymmetric alternative.

I. INTRODUCTION

Recent empirical contributions to the monetary policy literature have argued that the short-run Phillips curve in several developed countries is moderately convex, such that at any given point on the curve, the inflation increase associated with an incremental decline in the unemployment rate exceeds the inflation decline associated with an equal rise in the unemployment rate.¹ The principal difference between the linear and convex Phillips curves is that, under convexity, the short-run tradeoff facing policymakers is a function of the state of the economy: a one percentage point reduction in the unemployment rate leads to a smaller increase in inflation at high rates of unemployment than at low rates of unemployment. As a result, the nonaccelerating inflation rate of unemployment—the unemployment rate consistent with maintaining a stable average inflation rate over time—is not the same in a stochastic setting as it is in a deterministic setting. This reflects the fact that, in a stochastic economy with a convex Phillips curve, stable average inflation requires larger increases in unemployment when inflation is high than corresponding absolute declines in unemployment when inflation is low. Thus, the nonaccelerating inflation rate of unemployment in a stochastic setting is greater than its deterministic counterpart for any shock distribution. In contrast, under the linear model the nonaccelerating inflation rates of unemployment with and without shocks coincide. In order to emphasize this distinction we shall be referring to the nonaccelerating inflation rate in a stochastic setting as the *NAIRU*, while reserving the term *deterministic NAIRU*, or *DNAIRU*, for the nonaccelerating inflation rate of unemployment in the absence of shocks. Our NAIRU is thus consistent with the original Friedman (1968) definition of the natural rate of unemployment as the average unemployment rate in a stochastic setting.

Given convexity in the Phillips curve, the time series properties of inflation and unemployment are conditional on the specification of the loss function that the policymaker chooses to minimize. Recently, several anecdotal and theoretical arguments have been made in support of the “opportunistic approach” to disinflation.² The foundations of this approach lie in the perception that, in contrast to the traditional assumptions of Barro-Gordon type models, the welfare of the policymaker and society depends negatively on the *level* of the unemployment rate, as well as on the variances of unemployment and inflation. In line with this argument, we extend the standard quadratic loss function by including a term linearly increasing in unemployment when the latter is above the DNAIRU, and zero when

¹For research on the U.S. Phillips curve see Laxton, Meredith and Rose (1994), Turner (1995), Clark, Laxton and Rose (1996), and Macklem (1996). Studies involving other developed countries include Debelle and Laxton (1996) and Faruquee (1997). A prominent recent study arguing the case in favor of a linear Phillips curve is Gordon (1997).

²For two notable examples see Greenspan (1994) and Blinder (1997). A theoretical model of monetary policy with a linear Phillips curve rationalizing opportunistic disinflation strategies was introduced by Orphanides et al. (1996a, b).

unemployment is at, or below, the DN AIRU. This asymmetry is intended to capture an opportunistic monetary policy strategy in which the central bank is guarding against any incipient rise in inflation, but waits for the next favorable inflation shock to lower inflation toward the target, rather than seeking to actively lower inflation in a manner that pushes the unemployment rate higher. Thus, the time required to attain a given target decline in the inflation rate becomes a random variable.³

The analysis proceeds in the following stages. First, in a static, single-period equilibrium setting, we show that a convex and asymmetric specification of the Barro-Gordon problem with the standard stochastic inflation shocks gives rise to an “inaction range” of inflation shocks for which the optimal monetary policy setting does not adjust and the equilibrium level of unemployment is the DN AIRU. In contrast, under the alternative convex and symmetric specification, the equilibrium level of unemployment is generally different from the DN AIRU. We study the comparative static properties of the inaction range of shocks and their implications for the single-period tradeoff facing policymakers. It is shown that the effects of the asymmetry on the equilibrium levels of unemployment and inflation depend crucially on the inflation shock realization, and hence, implicitly, on its underlying distribution.

This leads to the second, dynamic part of the paper. Arguably, no metric and no discounting rule can be unambiguously specified for comparing the two loss functions. It may, nevertheless, be possible to rank them by evaluating their implications for the time series behavior of the target variables. The difficulties inherent in an analytical characterization of the optimization problem under convexity suggest employing numerical simulations in order to assess the properties of the equilibrium levels of inflation and unemployment. Using an iterative procedure based on a fixed point argument to derive model-consistent inflation expectations, we perform such simulations and find that the equilibrium inflation bias under both the symmetric and asymmetric loss functions is positive. Moreover, for plausible parameter values the bias is always larger in the convex and asymmetric specification. We then report the expectation, variance, skewness and kurtosis of the simulated distributions of the equilibrium levels of inflation and unemployment for three different parameterizations, based on the empirical methodology for the U.S. developed in Laxton, Rose and Tambakis (1997). It is found that, for both loss function specifications, there are significant departures from the normally distributed moments of the Barro-Gordon framework with a linear Phillips curve.

³This may be because unemployment deviations from target induce a greater social distortion than corresponding inflation deviations. For example, Blinder (1997) argues that unemployment at 2 percent above the natural rate implies that 2 percent of workers are fully unemployed, rather than all workers being 2 percent unemployed. Alternatively, a political economy rationale could be that the central bank’s vulnerability to political attack makes it more sensitive to positive than to negative deviations of unemployment from its natural rate, as positive deviations could threaten its independence.

Finally, we evaluate and compare expected welfare losses under the two alternative loss functions. Since in the equilibrium of a Barro-Gordon type model average unemployment is always at the natural rate, the comparative evaluation of Rogoff (1985, 1987) implies that a given loss function specification outperforms another in expectation if it yields lower average inflation and less variable inflation and output. Importantly, a comparison of actual losses based on evaluating the first two moments of the target variables is only sufficient if their underlying distributions are normal. Therefore, such a comparison is inappropriate under a convex Phillips curve, as the nonlinearity of the equilibrium first-order conditions implies that the third and fourth moments of inflation and unemployment are nonnormally distributed. However, an interesting result emerges from evaluating expected welfare under different combinations of the exogenous, “true” loss function perceived by society and the loss function used by the policymaker to guide the implementation of monetary policy. In particular, under either “true” social loss function, policymaking guided by the symmetric loss function specification does better in expectation than the asymmetric alternative. Conversely, the asymmetric specification does worse in expectation even if the policymaker implements monetary policy using an symmetric loss function. We tentatively conclude that when policy is guided by an “opportunistic” asymmetric loss function, the time series behavior of inflation and unemployment outcomes under a convex Phillips curve and an “opportunistic” asymmetric loss function is inferior to the outcomes when policy is guided by the symmetric loss function alternative.

The paper is arranged as follows. Section II reviews the properties of a standard model of the Barro-Gordon type, with a linear Phillips curve and symmetric quadratic loss function. Section III develops a model of monetary policy with a convex Phillips curve and an asymmetric loss function. In Section IV we analyze the static (single-period) equilibrium properties of this model, and compare them to those of a model with a symmetric loss function. We derive the quartic polynomial equations for the equilibrium first-order conditions for inflation and unemployment, and use them to show the existence of an “inaction range” of inflation shocks over which the optimal policy setting and equilibrium level of unemployment do not adjust. In Section V we present the results of numerical simulations on the distributional properties of the equilibrium levels of inflation and unemployment, and compare the expected performance of the symmetric and asymmetric specifications. Section VI concludes the paper.

II. A REVIEW OF THE LINEAR AND SYMMETRIC MODEL

The standard single-period symmetric loss function is quadratic in deviations of inflation and unemployment from their target values:

$$L_t^S = (U_t - U^*)^2 + \alpha(\pi_t - \bar{\pi})^2, \quad (1)$$

where the intermediate inflation target is $\bar{\pi} > 0$ ⁴ and the unemployment target is U^* , the nonaccelerating inflation rate of unemployment in a deterministic setting. The policymaker's preferences over inflation and unemployment stabilization are specified by the normalized fixed inflation aversion parameter $\alpha > 0$, assumed to coincide with society's preferences.⁵

The linear short-run Phillips curve is assumed to have constant slope $\gamma > 0$:

$$\pi_t = \pi_t^e + \gamma(U^* - U_t) + \epsilon_t, \quad (2)$$

where ϵ_t is an iid normally distributed supply shock with zero mean and constant variance σ_ϵ^2 . The shock realization occurs after expected inflation has been set.

The Barro-Gordon (1983) problem involves the determination of single-period optimal monetary policy by minimizing loss function (1) subject to the linear short-run Phillips curve constraint (2). The first-order condition for this problem clearly involves setting inflation and unemployment so that the sum of their respective marginal losses is zero. Following the tradition of the literature, it is assumed that the authorities directly choose the inflation rate. The equilibrium first-order condition then is:

$$L_U^s + L_\pi^s \frac{\partial \pi}{\partial U} = 0 \Rightarrow -L_\pi^s \frac{\partial \pi}{\partial U} = L_U^s \quad (3)$$

This may equivalently be expressed as a function of either inflation or unemployment. Solving for equilibrium expected inflation by substituting equation (2) in (3) and taking expectations yields:

$$E_{t-1} \pi_t = \bar{\pi} \quad (4)$$

Therefore, the linear model with $U=U^*$ implies that there is no equilibrium expected inflation bias. Meanwhile, substituting (4) into (2) and taking expectations yields the expected

⁴A dynamic specification could make the intermediate target a time-varying function of past inflation outcomes, e.g. $\bar{\pi}_t = \lambda \pi_{t-1}$.

⁵This assumption will be relaxed in Section V. In general, $U=U^*$ implies that there is no time-inconsistency and thus no expected inflation bias. Assuming that the target unemployment rate is less than U^* would simply yield the result of positive equilibrium inflation bias with no expected decline in unemployment. For a survey of relevant issues see Cukierman (1992).

unemployment rate to be U^* . Dropping the time subscripts, without loss of generality, the single-period equilibrium levels of inflation and unemployment are:

$$\begin{aligned}\pi &= \bar{\pi} + \frac{1}{1+\alpha\gamma^2} \epsilon \\ U &= U^* + \frac{\alpha\gamma}{1+\alpha\gamma^2} \epsilon\end{aligned}\tag{5}$$

Finally, substituting expressions (5) into (1) and taking expectations yields expected symmetric losses to be increasing in the variance of the supply shock:

$$EL^S = \frac{\alpha}{1+\alpha\gamma^2} \sigma_\epsilon^2\tag{6}$$

III. THE CONVEX AND ASYMMETRIC MODEL

A. Convex Phillips Curve

Convexity in the Phillips curve is introduced by means of a simple hyperbolic function similar to that adopted in Debelle and Laxton (1996), Clark, Laxton and Rose (1996) and Laxton, Rose and Tambakis (1997):⁶

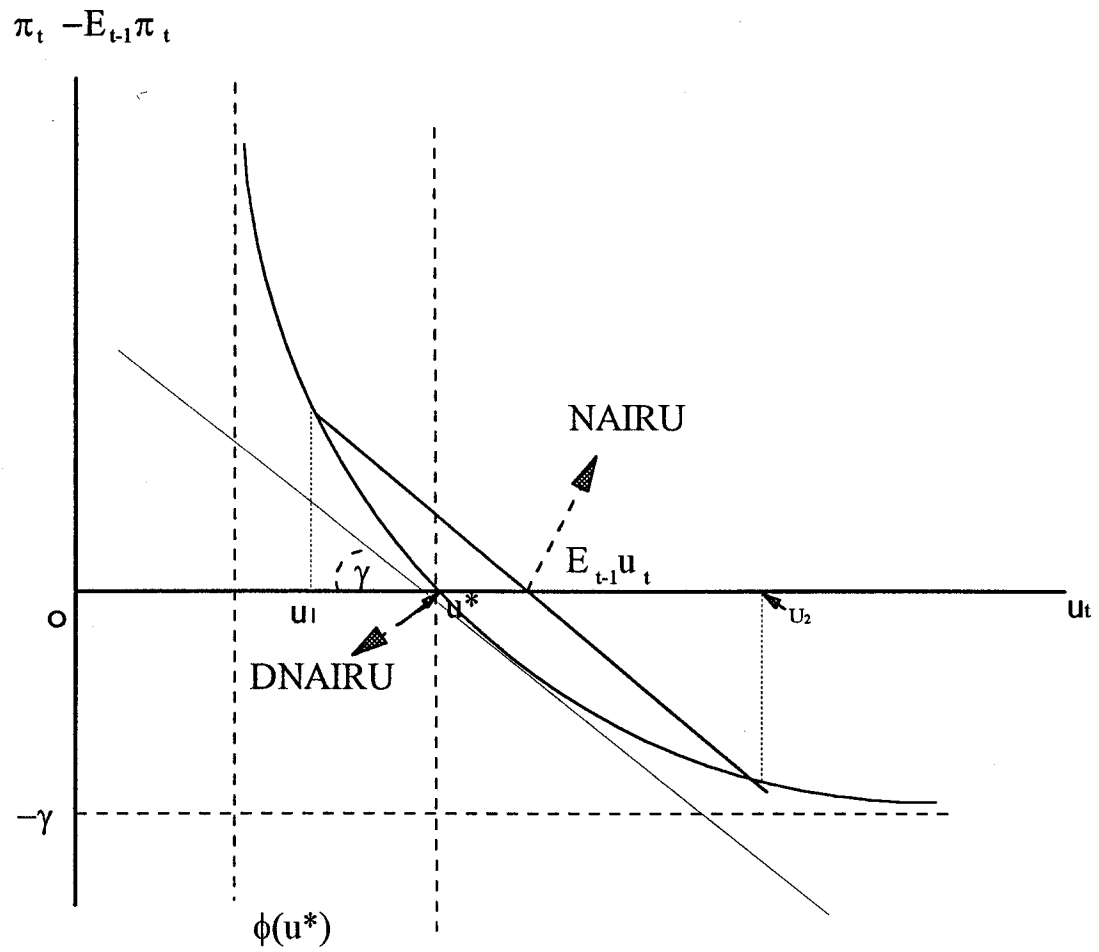
$$\pi = E\pi + \gamma \frac{U^* - U}{U - \phi(U^*)} + \epsilon, \quad 0 < \phi(U^*) < U^*\tag{7}$$

Note that our simple single-period specification does not include leads and lags in expected inflation. Figure 1 shows a general form of Phillips curve (7). The parameter $\phi(U^*)$ is assumed to be a vertical asymptote for the unemployment rate, capturing the fact that the lowest feasible unemployment rate is presumably bounded away from zero because of frictional and technological considerations.⁷ Although ϕ has to be less than U^* , it may be defined either as a fixed constant or as an increasing function in U^* . In the empirical section

⁶In referring to the Phillips curve, we employ the term *convex* rather than *nonlinear* as nonlinearity generally includes concave alternatives. For an example of the latter see Eisner (1996) and Stiglitz (1997). The term *asymmetric* is reserved for the loss function.

⁷There is also a notional horizontal asymptote corresponding to the value of unanticipated inflation in the limiting case $U=1$: $\pi - E\pi = \gamma(U^* - 1)/(1 - \phi) < 0$.

Figure 1. The Phillips Curve



we shall opt for the former. In the latter case, two plausible alternatives involve fixing the difference $U^* - \varphi(U^*)$ to be a constant, or defining $\varphi = \min\{U\}/2$ over the unemployment sample.

The nonlinear (convex) policy tradeoff implies that the slope of the Phillips curve is negative and continuously decreasing in U :

$$\frac{\partial \pi}{\partial U} = -\gamma \frac{U^* - \varphi(U^*)}{(U - \varphi(U^*))^2} < 0. \quad (8)$$

Evaluating equation (8) at $U=U^*$ yields:

$$\frac{\partial \pi}{\partial U}(U=U^*) = -\frac{\gamma}{U^* - \varphi(U^*)} \quad (9)$$

Therefore, unlike the linear case, the slope of the convex Phillips curve at U^* is jointly determined by coefficient γ and the levels of U^* and φ .

More generally, convexity of the Phillips curve implies that the average unemployment rate consistent with nonaccelerating inflation in a stochastic setting exceeds its deterministic counterpart U^* . This result follows from a simple application of Jensen's inequality. Referring to Figure 1, for any distribution of inflation shocks, the stochastic NAIRU is the linear combination of points on the Phillips curve yielding a zero mean inflation forecast error: $E(\pi - E\pi) = 0$. Without loss of generality, Figure 1 shows two points on the Phillips curve, $(U^1, \pi^1 - E\pi), (U^2, \pi^2 - E\pi)$, corresponding to a pair of inflation shocks $U^1 < U^*$ and $U^2 > U^*$ distributed symmetrically about U^* . Clearly, convexity in the Phillips curve implies that the intersection with the unemployment axis of the one-dimensional simplex of any two such points will always be to the right of U^* . Henceforth, we shall refer to EU , the average unemployment rate consistent with maintaining stable average inflation over time in a stochastic setting, as the *NAIRU*, and adopt the term *deterministic NAIRU (DNAIRU)* for U^* , the nonaccelerating inflation rate of unemployment in the absence of shocks.⁸

This property has important implications for stabilization policy. In particular, a policymaker who is more successful in stabilizing the business cycle will be inducing a lower average unemployment rate, as the gap between the NAIRU and the DNAIRU is increasing in the variance of the shock distribution, as well as in the degree of convexity of the Phillips

⁸This result is robust to both continuously differentiable and piecewise linear functional forms for the Phillips curve.

curve.⁹ Given a particular Phillips curve, the NAIRU rises as the inflation shock distribution becomes more skewed to the right, i.e. as inflation shocks are more positive. Conversely, the NAIRU will be closer to the DNAIRU if the inflation shock distribution is skewed to the left, as the economy is then more frequently in the expansion range ($U < U^*$).

B. An Asymmetric Loss Function

Following our discussion of opportunistic monetary policy strategies in Section I, we make the simplifying assumption that it is only when unemployment gets above the DNAIRU that the policymaker cares about the level, as well as the variance, of the unemployment rate. In contrast, when the unemployment rate is to the left of the DNAIRU, the symmetric quadratic loss function applies.¹⁰ A convenient way of incorporating the asymmetry into the policymaker's loss function is by introducing a breakpoint at U^* : we append a term linear in unemployment deviations from the DNAIRU, which is zero if the economy is in the expansion range ($U < U^*$), and positive if the economy is in the recession range ($U > U^*$). The loss function then is:

$$L_t^A = (U_t - U^*)^2 + \alpha(\pi_t - \bar{\pi})^2 + 2\psi \max(0, U_t - U^*), \quad \psi > 0 \quad (10)$$

The asymmetric loss function (10) thus captures the fact that welfare depends negatively on the level of unemployment, as well as its variance, when the unemployment rate gets above the NAIRU. In contrast, recall that, under the symmetric loss function (1), inflation (unemployment) aversion was constant in both regions of the unemployment domain.

IV. EQUILIBRIUM ANALYTICS

A. Equilibrium First-Order Conditions

Equation (3) specified that the equilibrium first-order condition for the linear model is at the intersection of the marginal loss schedules for inflation and unemployment. Reasoning analogously for the convex model, we apply the chain rule and express the first-order condition as a function of either target policy variable. Differentiating the loss function (10) and substituting in the Phillips curve (7) we get the first-order condition in terms of the inflation rate:

⁹For more details see Debelle and Laxton (1996).

¹⁰Put differently, unemployment rates above (below) the DNAIRU impose first-order (second-order) welfare costs to the policymaker.

$$-L_U^A(\pi) \frac{\partial U}{\partial \pi} = L_\pi^A \quad (11)$$

The asymmetry in the loss function implies that the first-order condition consists of two segments, each corresponding to the expansion and recession regions of the economy. Manipulating equation (11) then implies that the single-period equilibrium level of inflation is the solution(s) to the following quartic polynomial equations in π :

$$U < U^*: \alpha(\pi - \bar{\pi})(\pi - E\pi - \epsilon + \gamma)^3 - \gamma^2(U^* - \phi)^2 + \gamma(U^* - \phi)^2(\pi - E\pi - \epsilon + \gamma) = 0 \quad (12)$$

$$U > U^*: \alpha(\pi - \bar{\pi})(\pi - E\pi - \epsilon + \gamma)^3 - \gamma^2(U^* - \phi)^2 + \gamma(U^* - \phi)(U^* - \phi - \psi)(\pi - E\pi - \epsilon + \gamma) = 0$$

The first polynomial in (12) corresponds to the expansion region to the left of the DNAIRU. Clearly, as the asymmetric term is zero, this is also the first-order condition for the equilibrium inflation rate of a symmetric loss function under a convex Phillips curve. Taking expectations, notice that the second and third terms always sum to zero regardless of the magnitude of expected inflation. However, the higher order moments in the first term imply that imposing zero inflation bias ($E\pi = \bar{\pi}$) on the expression does not necessarily satisfy the first-order condition. Therefore, we cannot *a priori* rule out a nonzero equilibrium inflation bias in expected minimization of a symmetric loss function under a convex Phillips curve.

The second polynomial in (12) corresponds to the economy's recession region to the right of the DNAIRU, where welfare is negatively related to the level as well as the variance of the unemployment rate. Taking expectations, the sum of the second and third terms is strictly negative because $\psi > 0$. Therefore, the first term has to be strictly positive. Thus, compared to the first (symmetric) segment, a larger equilibrium inflation bias ($E\pi > \bar{\pi}$) may be required. Intuitively, this may be interpreted as the inflationary cost of maintaining a lower average unemployment rate.

As the variance of inflation is clearly different in the two segments, ranking the average performance of the two loss function specifications requires simulated estimates of the sample moments of the inflation process. Before turning to numerical simulations, we also derive the equilibrium first-order condition as a function of the unemployment rate. Equation (11) may be equivalently written as:

$$-L_\pi(U) \frac{\partial \pi}{\partial U} = L_U \quad (13)$$

Manipulating the derivative term implies that the single-period equilibrium level of unemployment is the solution(s) to the following quartic polynomial equations in U :

$$\begin{aligned} U < U^*: \quad & \frac{\alpha\gamma^2(U^* - \phi)^2}{(U - \phi)^3} + \frac{\alpha\gamma(U^* - \phi)}{(U - \phi)^2}(E\pi - \bar{\pi} - \gamma + \epsilon) = U - U^* \\ U > U^*: \quad & \frac{\alpha\gamma^2(U^* - \phi)^2}{(U - \phi)^3} + \frac{\alpha\gamma(U^* - \phi)}{(U - \phi)^2}(E\pi - \bar{\pi} - \gamma + \epsilon) = U - U^* + \psi \end{aligned} \quad (14)$$

As in the previous case, the asymmetry in the loss function implies that there are two segments to the equilibrium first-order condition, corresponding to the expansion and the recession regions of the unemployment domain. The difference between the two segments is now in the right-hand side of (14), representing the asymmetric marginal loss function of unemployment (L_U^A). This is linear with unit slope and discontinuous and nondifferentiable at $U = U^*$ because of the asymmetry.

Meanwhile, the left-hand side of first-order condition (14), representing the marginal loss function of inflation as a function of the unemployment rate (L_π^A), is clearly identical in both segments. L_π^A may be expressed in the following form:

$$-L_\pi^A \frac{\partial \pi}{\partial U} = \frac{A_1}{(U - \phi)^3} + \frac{A_2}{(U - \phi)^2}, \quad (15)$$

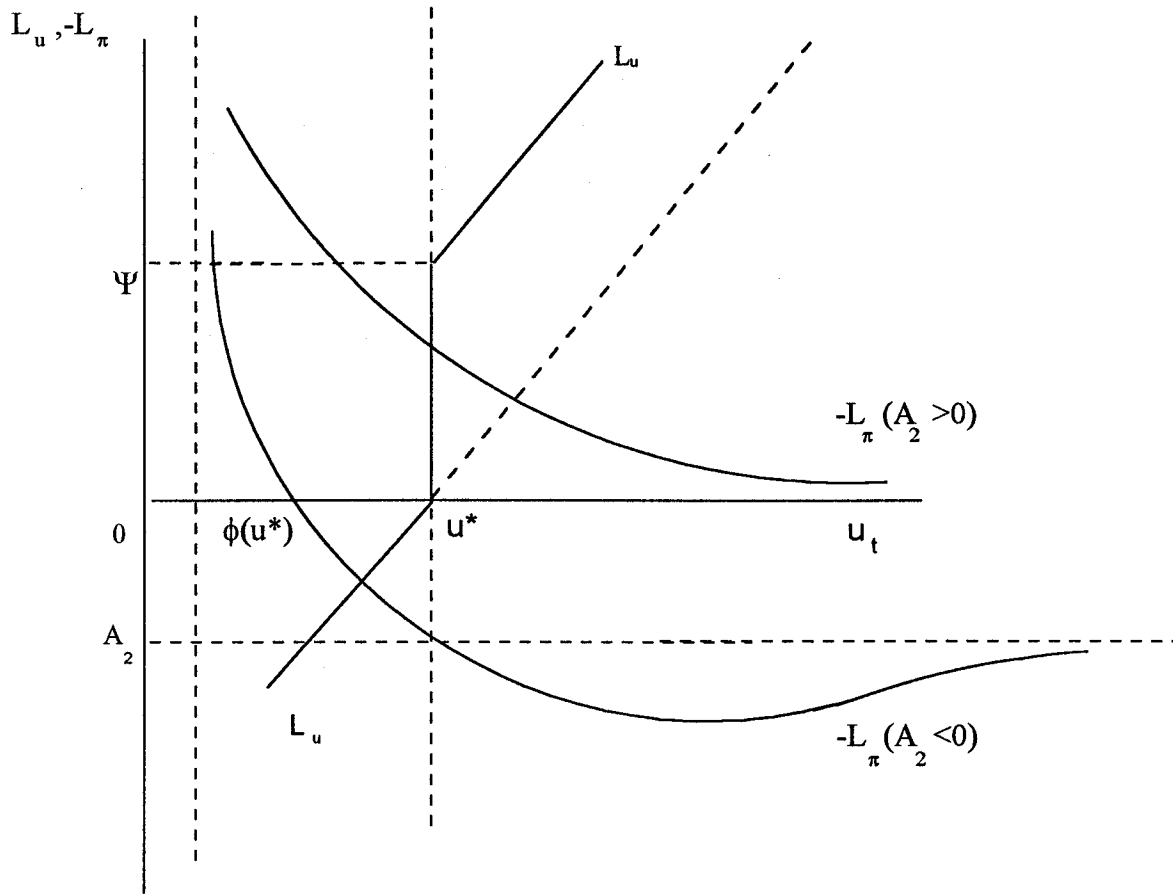
where the coefficients A_1 and A_2 are given by:

$$\begin{aligned} A_1 &= \alpha\gamma^2(U^* - \phi)^2 \\ A_2 &= \alpha\gamma(U^* - \phi)(E\pi - \bar{\pi} - \gamma + \epsilon) \end{aligned} \quad (16)$$

Note that, whereas coefficient A_1 is always positive, the sign of A_2 is ambiguous, as it is a function of expected inflation, the inflation target, the Phillips curve slope coefficient and the realization of the shock. Consequently, requiring that A_1 be positive is neither a necessary nor a sufficient condition for expression (15) to be positive.

Figure 2 graphs the functions $-L_\pi^A(\partial\pi/\partial U)$ and L_U^A as a function of the unemployment rate. The effective range of $-L_\pi^A(\partial\pi/\partial U)$ corresponds to the feasible values $(\phi, 1)$ for the unemployment rate. Note that there are only two possible solutions to the equation $-L_\pi^A(\partial\pi/\partial U) = 0$ depending on the sign of coefficient A_2 : it either has no real root, in which case it has a general hyperbolic shape, or it has one real positive root and a pair of complex

Figure 2. Loss Functions



conjugate roots, in which case it has one stationary point and one inflexion point.¹¹ The following section utilizes the geometrical intuition of Figure 2 to motivate an important equilibrium property.

B. Deriving the Inflation Shock Inaction Range

First-order conditions (12) or (14) define the single-period equilibrium levels of inflation and unemployment at the intersection of the inflation and unemployment marginal loss schedules. The equilibrium is a function of the shock realization ϵ , conditional upon the values of $E\pi$ and the fixed parameters of the model. Henceforth we shall analyze expression (14) in terms of the unemployment rate, without loss of generality.

Although complex-valued solutions are guaranteed, it is clear, both analytically and from referring to Figure 2, that a real-valued solution is not, due to the discontinuity of the L_U^A schedule at U^* . The two possible forms of the inflation marginal loss function suggest that the existence of a real intersection depends on the value of L_π^A at the DNAIRU, $L_\pi^A(U^*)$. In particular, existence of an intersection requires that this fall outside the range of discontinuity $(0, \psi)$ of the marginal loss function for unemployment. Substituting coefficients (16) into (15) yields the value of the inflation marginal loss schedule at $U=U^*$:

$$-L_\pi \frac{\partial \pi}{\partial U}(U^*) = \frac{\alpha \gamma}{U^* - \varphi} (E\pi - \bar{\pi} + \epsilon) \quad (17)$$

It follows that there are three possibilities for the equilibrium unemployment rate as a function of the value of the inflation marginal loss schedule at U^* :

(i) If the value of (17) is positive and greater than ψ , implying $E\pi - \bar{\pi} + \epsilon > \frac{\psi(U^* - \varphi)}{\alpha \gamma}$, then the inflation marginal loss schedule intersects the segment of L_U^A to the right of the DNAIRU, i.e. in the economy's recession range. Such an intersection reflects, for example, a large positive inflation shock realization, other things equal. The equilibrium level of unemployment is clearly above U^* , and is given by the (real positive) root of the first quartic polynomial equation in (14). Intuitively, a large positive shock realization induces tighter monetary policy, so the one-period equilibrium unemployment rate exceeds the DNAIRU.

(ii) If expression (17) is negative ($E\pi - \bar{\pi} + \epsilon < 0$), then the inflation marginal loss schedule intersects the segment of L_U^A to the left of U^* , i.e. in the economy's expansion range. The equilibrium level of unemployment then lies below U^* , and is given by the (real positive) root of the second quartic polynomial in (14). The intuition is analogous to the

¹¹The proof is tedious but straightforward. Details may be provided for the interested reader.

previous case: a large negative inflation shock realization induces looser monetary policy, hence the single-period optimal unemployment rate is less than the DNAIRU.

(iii) Finally, if the value of $-L^A_{\pi}(\partial\pi/\partial U)$ at U^* is positive and within the range $[0, \psi]$, the two marginal loss schedules do not intersect. Equation (17) implies that the relevant range of inflation shocks for this to occur is:

$$0 \leq \frac{\alpha\gamma^2}{U^* - \phi} + \frac{\alpha\gamma}{U^* - \phi}(E\pi - \bar{\pi} + \epsilon - \gamma) \leq \psi, \quad (18)$$

which can be written as:

$$\begin{aligned} 0 &\leq E\pi - \bar{\pi} + \epsilon \leq \frac{\psi(U^* - \phi)}{\alpha\gamma} \\ \Rightarrow \bar{\pi} - E\pi &\leq \epsilon \leq \frac{\psi(U^* - \phi)}{\alpha\gamma} + \bar{\pi} - E\pi \end{aligned} \quad (19)$$

The asymmetric loss function (10) then implies that the single-period equilibrium level of unemployment is U^* . Therefore, inequalities (19) define an *inaction range* of inflation shocks over which the optimal policy setting and equilibrium unemployment do not adjust. Importantly, this is the case for either a linear or a convex Phillips curve: it is the asymmetry in the loss function and not the nonlinearity in the Phillips curve which generates the nonintersection of the marginal loss schedules.

The comparative static properties of the inaction range are as follows:

(I) A larger ψ widens the inaction range, as unemployment rates above U^* become relatively more costly.

(ii) A larger inflation aversion coefficient (α), and/or a larger Phillips curve slope coefficient (γ), induces a narrower inaction range. The intuition for α is that a more inflation averse policymaker pursues a tighter monetary policy, hence is more likely to disinflate in any given period, other things equal. In the case of a larger γ , a steeper Phillips curve implies that, other things equal, a one percent decline in the inflation rate involves smaller unemployment costs, i.e. the sacrifice ratio is smaller, other things equal. This creates a higher incentive to disinflate, so the range of inflation shocks for which U^* is the equilibrium level of unemployment is narrower.

(iii) An exogenous increase in U^* widens the inaction range. The intuition centers on the value of the slope of the Phillips curve at U^* , which equals $-\gamma/(U^* - \phi(U^*))$ from equation (9). Provided that $\partial\phi/\partial U^* < 1$, a higher U^* implies a (locally) flatter Phillips curve, hence higher

unemployment costs for a one percent inflation decline. Thus, as the sacrifice ratio increases, there is a wider range of inflation shocks for which U^* is the equilibrium unemployment rate. This property is in stark contrast to the linear Phillips curve framework, in which the size of the inaction range is invariant to changes in U^* . Therefore, an asymmetric loss function implies the DNAIRU has an effect on the inaction range only under a convex Phillips curve. Whereas asymmetric policymaker preferences are necessary for the existence of the inaction range, it is convexity in the Phillips curve which underlies the result of the positive effect of changes in U^* on the inaction range. Each of the two conditions on its own is necessary, but not sufficient for this result.

V. EQUILIBRIUM SIMULATIONS

A. Valuating the Equilibrium Expected Inflation Bias

Following the empirical methodology of Laxton, Rose and Tambakis (1997), we assume that the vertical asymptote $\varphi(U^*)$ of the Phillips curve is fixed at 1 percent. Thus a change in the DNAIRU estimate from 5 percent to 10 percent for the United States does not affect the value of φ . The inflation target is set at 2 percent. The value of γ corresponding to these parameter values for the U.S. is 4.7, estimated using nonlinear least squares on quarterly data for 1955–96. Finally, we set the inflation aversion parameter at $\alpha=1$ and the initial value of the asymmetric coefficient at $\psi=1$.

Recall that the nonlinearity of first-order conditions (12) or (14) does not allow us to substitute $E\pi=\bar{\pi}$ for the equilibrium expected inflation rate, as we would do in the linear model. Indeed, as the nonlinearity is a property of the Phillips curve, this consideration is independent of the particular loss function under consideration. From our earlier discussion, we know that drawing a large number of inflation shocks and solving first-order condition (12) by substituting the inflation target for expected inflation would yield an average inflation rate different from $\bar{\pi}$. We would thus have a contradiction, and our choice of expected inflation would not be model-consistent.

In order to overcome this problem, we adopt an iterative numerical procedure whose convergence employs a simple fixed point argument. First, we specify an arbitrary initial estimate for the value of the expected inflation bias, call it $\beta_0=E\pi-\bar{\pi}>0$. Given this value, we solve for the single-period equilibrium level of inflation for a large number of shocks and compute the resulting sample mean: $\hat{\pi}(\beta_0)$. This yields an associated expected inflation bias corresponding to the particular choice of β_0 : $b_0=\hat{\pi}(\beta_0)-\bar{\pi}$. We then compare β_0 against b_0 . If the latter does not confirm our choice of β_0 , i.e. $b_0\neq\beta_0$, then the exercise is repeated using $\beta_1=b_0$ as the iterated estimate of the expected inflation bias. Eventually, repeated iteration and substitution on the choice of inflation bias will converge to a particular value β^* such that $\hat{\pi}(\beta^*)-\bar{\pi}=\beta^*$. Thus, for the particular shock distribution under consideration, β^* is self-

sustaining as a fixed point of the expected inflation bias.¹² Therefore, β^* is a model-consistent expectation, and can be used in first-order conditions (12) or (14) to derive the one-period equilibrium levels of inflation and unemployment.

B. Distributional Properties of (π, U) Under Alternative Loss Functions

We analyze the alternative loss function specifications in two stages. First, based on the results of numerical simulations of first-order conditions (12) and (14) for a large number of shocks, Tables 1-3 present convergent values of the first four moments of the distributions of single-period optimal inflation and unemployment rates. The tables correspond to three different levels for the variance of the inflation shock distribution, and each reports the results of numerical simulations for one benchmark set of parameter values and two alternatives. Overall, therefore, we examine nine parameterizations. In each case, the values of the moments of the nonnormal inflation and unemployment distributions are obtained for both the symmetric and the asymmetric loss function. In the second stage, these results are used to evaluate the expected performance of the two loss function specifications.

Table 1 reports the values of the four moments of the equilibrium inflation and unemployment distributions when the underlying shock distribution is standard normal. The simulation results correspond to the following parameterizations: (I) a benchmark case in which $U^*=0.05$, $\bar{\pi}=0.02$ and $\varphi=1$, (ii) an alternative in which the asymmetry in the loss function is reduced to $\psi=0.2$, indicating relatively less losses compared to the benchmark when unemployment is in the recession region, and (iii) an alternative where the DNAIRU is doubled to $U^*=0.10$. Note, first, that the symmetric outcomes in cases (I) and (ii) are identical, as they are not affected by changing the asymmetry in the loss function. Second, the values of expected inflation used in the first-order conditions were derived using the fixed-point iterative procedure described earlier. The procedure stops when the choice of expected inflation comes arbitrarily close to the inflation sample mean.

We now discuss the behavior of each of the four moments across parameterizations. We make two observations on the behavior of expectations. First, in all three cases, the difference between the mean unemployment rate and the DNAIRU is very small. This suggests that the convexity in the Phillips curve is not felt for relatively small shock variances such as the standard normal. Second, in each case there is positive expected inflation bias, and it is always larger for the asymmetric loss function specification than for the symmetric alternative. In particular, under the symmetric loss function it is at most 0.2 percent, whereas under the asymmetric loss function it reaches 0.7 percent when $U^*=0.10$.

¹²It is implicitly assumed that the inflation distribution is ergodic, so that convergence occurs for finite sample sizes after a finite number of iterations.

Concerning the behavior of the second moment, the variance of inflation is always greater than the variance of unemployment under the asymmetric loss function, and *vice versa* when the loss function is symmetric. This appears to be an intuitive implication of the asymmetric welfare costs of an increase in unemployment on either side of U^* . The symmetric specification penalizes unemployment deviations from target relatively less than the asymmetric alternative. Consequently, the equilibrium level of the variance of unemployment (inflation) is relatively larger (smaller) under the symmetric (asymmetric) loss function.

Regarding the behavior of the third and fourth moments of the inflation and unemployment distributions, both skewness and kurtosis rarely approach 0 and 3, their respective values for a normal distribution. In particular, the skewness of the unemployment distribution is almost always negative regardless of the loss function specification. This suggests that its lower tail is thicker than a normal distribution's, or equivalently that the mean unemployment rate exceeds the median. This finding is consistent with the fact that the NAIRU exceeds the DNAIRU ($EU > U^*$) under convexity. Conversely, the skewness of the inflation distribution is mostly positive, reflecting an upper tail which is thicker than that of a normal distribution, or equivalently a median unemployment rate which exceeds the mean.

The kurtosis of the unemployment distribution is always greater when the loss function is asymmetric than when it is symmetric. Conversely, the kurtosis of the inflation distribution is always greater under a symmetric than under an asymmetric loss function. This property seems consistent with the relation between the variances of unemployment and inflation, discussed above. Intuitively, the fact that the unemployment (inflation) distribution has less (more) variance under the asymmetric loss function specification implies that it has relatively more (less) probability mass in the tails, so it tends to be more (less) leptokurtic than the respective distribution under a symmetric loss function, other things equal.

Tables 2 and 3 report the numerical simulations for the four moments of the inflation and unemployment distributions for moderate and large shock variances, $\sigma_\epsilon^2=9$ and $\sigma_\epsilon^2=36$, respectively. In each case, the benchmark and alternative parameterizations are the same as in Table 1. Note that the qualitative features of the results are the same as in the case of the standard normal variance. Moreover, the difference between the NAIRU and the DNAIRU increases as the variance of the shock distribution grows. However, the difference does not exceed 0.7 percentage points (Table 3, the symmetric case in (I), and both symmetric and asymmetric cases in (ii)). Therefore, it does not seem, for our parameter range at least, that more volatility induces a marked increase in the NAIRU. Finally, note that the variance of inflation and unemployment rises substantially with the variance of the shock across the three parameterizations, whereas the characteristics of skewness and kurtosis in Table 1 are broadly preserved.

C. A Comparative Evaluation of Expected Welfare Losses

Having established the distributional characteristics of the equilibrium levels of inflation and unemployment, we turn to evaluate the expected welfare implications of the symmetric and asymmetric loss functions. For this purpose we consider four cases, corresponding to two alternative assumptions about the exogenous “true” social loss function, each paired with two choices of the loss function to use for guiding monetary policy.

The expected losses are derived from equations (1) and (10), respectively. Denoting means by μ and variances by σ^2 , the expression for expected symmetric welfare losses only involves the first two moments of the target variables:

$$EL^S = \sigma_U^2 + \alpha\sigma_\pi^2 + \mu_U(\mu_U - 2U^*) + \alpha(\mu_\pi - \bar{\pi})^2 + U^{*2} \quad (20)$$

Analogously, expression (10) yields expected asymmetric welfare losses to be:

$$EL^A = EL^S + 2\psi E [\max(0, U - U^*)] \Rightarrow \quad (21)$$

$$EL^A = \sigma_U^2 + \alpha\sigma_\pi^2 + \mu_U(\mu_U - 2U^*) + \alpha(\mu_\pi - \bar{\pi})^2 + U^{*2} + 2\psi E [\max(0, U - U^*)]$$

Substituting in equations (20) and (21) the expectations and variances from Tables 1-3 yields an expected welfare comparison for each combination of parameter values.¹³

The results are in Table 4. For each parameterization, we report four expected evaluations, reflecting the fact that the policymaker and society (or representative agent) may not share the same loss function. If they do, that loss function is used both by the policymaker, for guiding monetary policy, and by society, for evaluating the expected (and actual) macroeconomic outcome. The two relevant cases may be referred to as the consistent scenarios. However, it may be that, over a certain time period, society is characterized by an asymmetric loss function while the policymaker implements monetary policy using a symmetric loss function, and vice versa. In the first case, the policy loss function is symmetric, but society evaluates the expected macroeconomic outcome using an asymmetric loss function./ Conversely, in the second case the policy loss function is asymmetric, but society evaluates the expected macroeconomic outcome using a symmetric loss function. The two relevant combinations may be referred to as the inconsistent scenarios, in reference to the fact that an equilibrium with two different loss functions is unlikely to be sustainable in the long

¹³Note that computing the last term in (21) involves averaging only those draws whose equilibrium unemployment rates are above U^* .

term if only for political economy reasons. However, for our purposes, comparing expected welfare across the two consistent and the two inconsistent scenarios is an important robustness test of the alternative loss functions' expected performance.

Overall, Table 4 shows that the symmetric social loss function specification yields lower expected welfare losses than the asymmetric specification. There are two exceptions involving the benchmark parameterization with an asymmetric "true" social loss function and a symmetric policy loss function (an inconsistent scenario) when the shock variance is small, and when the shock variance is large. Also, in the case of a large shock variance, the benchmark parameterization with a symmetric social loss function and an asymmetric policy loss function performs marginally better than when the policy loss function is symmetric (a consistent scenario). Comparing the results across the consistent and inconsistent scenarios seems to reinforce the case in favor of the symmetric "true" social loss function specification. Almost all parameterizations under the symmetric social loss function do strictly better than—and, in one case, as well as—the parameterizations under the asymmetric social loss function. In other words, expected social welfare losses are lower under the symmetric specification regardless of the policy loss function under consideration.

In interpreting these results, it is clear that the modest degree of convexity implicit in the parameterizations induces a disproportionately higher inflation bias under the asymmetric specification, which contributes to worsening its expected performance. Moreover, the difference between the expected losses under the two specifications becomes relatively smaller as the shock variance increases. More generally, the above results should be treated with caution, as the unambiguously better expected performance of the symmetric loss function is conditional on the parameter values. For example, we have used $\alpha=1$ throughout for the inflation aversion coefficient, thus penalizing to the same extent quadratic deviations of inflation and unemployment from their respective targets. However, it may be that a specification with a smaller value of α , i.e. a higher weight on unemployment deviations, yields an improvement in the expected performance of the asymmetric loss function. The intuition is that the higher expected inflation bias under the asymmetric loss function is then valued less: the term in α in equations (20) and (21) becomes smaller.

VI. CONCLUSION

This paper analyzed the single-period Barro-Gordon optimal monetary policy problem when the Phillips curve is convex and the policymaker's loss function is asymmetric, and examined the static and dynamic implications for the equilibrium levels of inflation and unemployment. Following recent arguments favoring an "opportunistic approach" to disinflation, we introduced an asymmetric loss function specifying that, at high unemployment rates, the welfare of the policymaker and society depends negatively on the level of unemployment, as well as on the variances of unemployment and inflation. It was shown, first, that the convex and asymmetric specification gives rise to an "inaction region" of inflation shocks for which the optimal policy setting and equilibrium unemployment do not adjust.

Second, numerical simulations were used to study the moments of the equilibrium inflation and unemployment distributions. It was found that, in contrast to the results under the linear Phillips curve, the symmetric and asymmetric loss functions under convexity both yield a positive expected inflation bias—that is, an expected inflation rate in excess of the target—and that bias is larger under the asymmetric specification. Third, for plausible parameter values for U.S. post-war data, policymaking based on the symmetric loss function specification was shown to dominate policy based on the asymmetric alternative in expectation. This result was found to be robust to a variety of informational assumptions, taking into account the possibility that the loss function on which the policymaker relies may differ from the "true" social loss function.

Table 1. Simulated Inflation and Unemployment Distributions: $\sigma_\epsilon^2=1$

1. **Benchmark:** $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	2.18	2.50	5.09	4.98
Variance	0.22	0.39	0.22	0.09
Skewness	1.17	0.29	-0.03	-0.67
Kurtosis	4.92	2.16	2.91	5.14

2. **Small asymmetry:** $\psi=0.2$, $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	2.18	2.20	5.09	5.02
Variance	0.22	0.25	0.22	0.20
Skewness	1.17	0.91	-0.03	-0.10
Kurtosis	4.92	3.95	2.91	3.04

3. **Large DNAIRU:** $U^*=0.10$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	2.14	2.69	10.04	9.95
Variance	0.58	0.86	0.16	0.03
Skewness	0.21	0.16	-0.40	-2.12
Kurtosis	2.98	2.50	3.55	10.72

Table 2. Simulated Inflation and Unemployment Distributions: $\sigma_\varepsilon^2=9$

1. **Benchmark:** $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	3.06	3.56	5.39	5.30
Variance	2.77	3.49	1.41	0.97
Skewness	1.27	0.85	-0.20	-0.25
Kurtosis	4.24	3.28	2.24	2.64

2. **Small asymmetry:** $\psi=0.2$, $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	3.06	3.14	5.39	5.39
Variance	2.77	2.61	1.41	1.22
Skewness	1.27	1.21	-0.20	-0.32
Kurtosis	4.24	4.45	2.24	2.51

3. **Large DNAIRU:** $U^*=0.10$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	3.98	4.72	10.55	10.33
Variance	5.66	6.15	1.29	0.72
Skewness	0.50	0.20	-0.82	-1.11
Kurtosis	2.80	2.44	4.03	7.64

Table 3. Simulated Inflation and Unemployment Distributions: $\sigma_\varepsilon^2=36$

1. **Benchmark:** $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	4.41	4.54	5.73	5.44
Variance	13.55	13.93	3.63	2.93
Skewness	1.30	1.17	-0.15	-0.23
Kurtosis	4.29	3.82	1.80	2.20

2. **Small asymmetry:** $\psi=0.2$, $U^*=0.05$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	4.41	4.37	5.73	5.67
Variance	13.55	13.39	3.63	3.31
Skewness	1.30	1.31	-0.15	-0.19
Kurtosis	4.29	4.30	1.80	1.97

3. **Large DNAIRU:** $U^*=0.10$, $\bar{\pi}=0.02$, $\alpha=1$, $\gamma=4.7$, $\phi=1$, $\psi=1$.

	Inflation		Unemployment	
	Symmetric	Asymmetric	Symmetric	Asymmetric
Mean	7.49	8.05	11.37	11.04
Variance	23.03	26.10	3.50	2.63
Skewness	0.50	0.46	-1.32	-1.06
Kurtosis	2.69	2.75	5.31	4.95

Table 4. Expected Loss Evaluation

Small shock variance ($\sigma_\epsilon^2=1$):

Social loss function	Symmetric		Asymmetric	
Policy loss function	Symmetric	Asymmetric	Symmetric	Asymmetric
1. Benchmark	0.48	0.73	1.21	1.29
2. Small asymmetry	0.40	0.49	0.63	0.54
3. Large DNAIRU	0.76	1.37	1.68	1.37

Moderate shock variance ($\sigma_\epsilon^2=9$):

Social loss function	Symmetric		Asymmetric	
Policy loss function	Symmetric	Asymmetric	Symmetric	Asymmetric
1. Benchmark	5.45	6.98	8.79	7.75
2. Small asymmetry	4.93	5.28	5.71	5.37
3. Large DNAIRU	11.17	14.38	16.00	13.36

Large shock variance ($\sigma_\epsilon^2=36$):

Social loss function	Symmetric		Asymmetric	
Policy loss function	Symmetric	Asymmetric	Symmetric	Asymmetric
1. Benchmark	23.52	23.51	26.75	27.42
2. Small asymmetry	22.05	22.76	23.50	22.81
3. Large DNAIRU	58.55	66.41	69.90	62.67

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