Monetary Policy When Potential Output Is Uncertain: Understanding the Growth Gamble of the 1990s

YURIY GORODNICHENKO

University of Michigan

MATTHEW D. SHAPIRO

University of Michigan and NBER

December 1, 2004

Monetary Policy When Potential Output Is Uncertain:
A Tale of Two Alans

ABSTRACT

The Fed kept interest rates low and essentially unchanged during the late 1990s despite a booming economy and record-low unemployment. These interest rates were accommodative by historical standards. Nonetheless, inflation remained low. How did the Fed succeed in sustaining rapid economic growth without fueling inflation and inflationary expectations? In retrospect, it is evident that the productive capacity of the economy increased. Yet as events unfolded, there was uncertainty about the expansion of the capacity of the economy and therefore about the sustainability of the Fed's policy.

This paper provides an explanation for the success of the Fed in accommodating noninflationary growth in the late 1990s. It shows that if the Fed is committed to reverse policy errors it makes because of unwarranted optimism, inflation can remain in check even if the Fed keeps interest rates low because of this optimism. In particular, a price level target—either strict or partial— can serve to anchor inflation even if the public believes the Fed is overly optimistic about shifts in potential output. The paper shows that price level targeting is superior to inflation targeting in a wide range of situations. The paper also provides econometric evidence that, in contrast to earlier periods, the Fed has recently has put substantial weight on the price level in setting interest rates.

Yuriy Gorodnichenko
Department of Economics
University of Michigan
Ann Arbor MI 49109-1220
tel. 734-615-4433
ygorodni@umich.edu

Matthew D. Shapiro
Department of Economics
University of Michigan
Ann Arbor MI 48109-1220
 and NBER
tel. 734 764-5419
shapiro@umich.edu

1. Introduction

The performance of the U.S. economy during the second half of the 1990s was outstanding. Rapid GDP and productivity growth were coupled with a very low unemployment rate and low-and-falling inflation. The sources of this performance are the focus of much of recent research (e.g., Krueger and Solow 2001). Of course, many factors—including a possible decline in the equilibrium rate of unemployment (Staiger, Stock and Watson 2001), changes in the structure of the labor force (Blank and Shapiro 2001), acceleration in technological progress (Jorgenson and Stiroh 2000, Oliner and Sichel 2000, Basu, Fernald and Shapiro 2001), and pure luck (Mankiw 2002)—likely contributed to the success of the late 1990s.

Nonetheless, few question that the Fed's policies were very important in supporting economic growth and sustaining low and stable inflation. Since output was above its historical trend and unemployment was near a historical low, based on its history of past policy actions one might have expected the Fed to raise interest rates. Even though inflation was not increasing, a preemptive tightening of monetary policy such as the Fed undertook in 1994 seemed likely. Yet the Fed held interest rates essentially unchanged in the face of output's spurt without an increase in inflation. Indeed, the rate of inflation has trended down since the mid-1990s. Alan Greenspan (2004, p. 35) agrees that monetary policy was expansionary relative to historical standards: "…from 1995 forward, we at the Fed were able to be much more accommodative to the rise in economic growth than our past experiences would have deemed prudent."

The aim of this paper is to explain why accommodative monetary policy in this period did not increase inflation or inflationary expectations. One possibility is that the expansion of the economy's capacity in the late 1990s was apparent at the time so that monetary policy merely

accommodated an increase in productive capacity. In retrospect, this explanation has some appeal. But as the 1990s unfolded, it was much less clear that the economy experienced an increase in capacity. As Greenspan (2004, p. 34) notes, "The rise in structural productivity growth was not obvious in the official data… until later in the decade but precursors had emerged earlier." Though it is now clearly established that a burst of productivity occurred in the late 1990s, there was a sequence of positive surprises as events unfolded. In the context of these very substantial favorable surprises, the Fed pursued what at the time appeared to be a very expansionary policy.

We argue that the Fed was effectively committed to a stable price level. We do not claim that the Fed was following a price level rule *per se*, but rather that price stability was an important ingredient in its policy actions. We show that a policy rule that takes into account the price level performs better than a rule that targets only inflation, especially when potential output is not observable. In an economy with forward-looking agents, having the price level as an objective serves to anchor inflationary expectations. Put differently, a commitment to price level stability is a commitment to reverse errors. Making this commitment can help keep inflation in check even if the central bank is pursuing what looks momentarily like a very expansionary policy.

We provide evidence that this model fits the late 1990s experience. When the Fed in the late 1990s took the gamble that economic growth had increased, inflation and inflationary expectations remained in check because the public believed that the Fed would quickly counter inflation if the projected rapid growth in productive capacity did not materialize. We show that an inflation targeter, who would not reverse errors, would have had much more difficulty keeping inflation under control during the 1990s than a central banker who puts some weight on price stability when setting interest rates.

2

The organization of this paper is as follows. Section 2 discusses the economic events in the 1990s and how they relate to policy. These facts motivate the analysis. Section 3 lays out a standard model that allows us to study policymaking when potential output is not observed. In this section, we draw general lessons about the performance of policy reaction functions when potential output is uncertain. Our results show that having the price level in the interest rate rule has significant benefits. This finding contrasts with the standard view that inflation targeting is the first-best option. We do not argue that previous results showing the desirable features of inflation targeting are wrong. Rather, we show that they do not apply to the situation where potential output is uncertain.

In Section 4, we present empirical evidence suggesting that the price level was a part of the Fed's decision rule during the Greenspan era. This econometric evidence suggests that the Fed was indeed pursing the type of policy that our theoretical model shows would perform well against the shocks of the late 1990s. Hence, the theoretical and empirical results of the paper present a consistent explanation of the good economic performance during the period when the Fed took its growth gamble. In section 5, we present conclusions.

2. Monetary Policy in the Late 1990s

This section provides some evidence that monetary policy in the late 1990s was, by historical standards, unusually accommodative. First, we document Alan Greenspan's views about the new economy. Second, we look at inflation forecasts, based on both backward looking Phillips curves and professional forecasts. Third, we report what a standard Taylor rule would have predicted given current conditions.

Consider first the evolving views of the Fed Chairman. In December, 1996, Alan Greenspan gave his famous "irrational exuberance" speech, which was widely regarded as

skepticism concerning the heights that the stock market had reached.[1] There was, however, a shift

in Greenspan's thinking. For example, in a speech at the Berkeley Business School in September,

1998, he took note of the increase in productivity and investment and implied that the market was

at least in part responding to it. Significantly, he linked this performance to the surprising lack of

inflation despite the booming economy:

> The question posed for this lecture of whether there is a new economy reaches
> beyond the obvious: Our economy, of course, is changing everyday, and in that
> sense it is always "new." The deeper question is whether there has been a
> profound and fundamental alteration in the way our economy works that creates
> discontinuity from the past and promises a significantly higher path of growth
> than we have experienced in recent decades.
>
> The question has arisen because the economic performance of the United States in
> the past five years has in certain respects been unprecedented. Contrary to
> conventional wisdom and the detailed historic economic modeling on which it is
> based, it is most unusual for inflation to be falling this far into a business
> expansion.[2]

Hence, in the space of two years, Greenspan's assessment of the boom of the 1990s moved from

skepticism to seriously considering the possibility of a structural shift.

The assessment of the real economy and its prospects for inflation need not be inferred

from speeches. Mechanical projections of inflation based on historical relationships with real

variables indicated that inflation should have increased substantially. Yet, the Fed was cutting

interest rates in the fall of 1998 even though the unemployment rate was the lowest it had been in

decades. Figure 1 shows actual and forecast inflation for the U.S. based on a conventional Phillips

curve (e.g., Staiger, Stock, and Watson 1997, 2001) where equilibrium unemployment is

recalculated using data through 1995. The forecasts take into account the best estimate of the

---

[1] The text of the speech refers to balance sheet effects of the stock market and does not confront directly the question
of whether there was sufficient economic growth to sustain the stock market values. See
http://www.federalreserve.gov/boarddocs/speeches/1996/19961205.htm.
[2] See http://www.federalreserve.gov/boarddocs/speeches/1998/19980904.htm.

NAIRU as of the beginning of the period of the productivity acceleration.[3] The figure shows

forecasts over 12-quarter horizons for 1996:4, 1997:4, and 1998:4.[4] Looking ahead from the ends

of 1996 and 1997, one would have expected much more inflation based on this historical

relationship than was realized.

In a similar vein, professional forecasters overestimated inflation and underestimated GDP

growth.[5] In Table 1, we show the forecast errors for GDP growth and inflation for the Blue Chip

consensus and the Survey of Professional Forecasters.   (Krane 2003 show identical figures for

output.) Throughout the period, the forecasters consistently underestimated economic growth.

The story with inflation is slightly more subtle. Through 1998, the forecasters systematically

overestimated inflation; thereafter, the forecast errors were positive but much smaller. Similar

conclusions apply to the regression-based forecasts from Figure 1. The pattern whereby the

professional forecasters underestimate growth yet have inflation expectations that fall substantially

is consistent with our story: the forecasters remained unconvinced that the economy could grow

faster, yet were confident that the Fed would keep inflation down.

Finally, the Taylor rule predicted significant increases in the federal funds rate, the major

policy instrument of the Fed. Using quarterly data for the Greenspan chairmanship, we estimate

the conventional Taylor rule for the federal funds rate using current inflation, the unemployment

rate and two lags of the federal funds rate as regressors. Following Clarida, Gali and Gertler

(2000), we estimate the rule by GMM using four lags of the federal funds rate, the inflation rate,

the unemployment rate and an index of commodity prices as instruments. To construct projections

---

[3] We compute the NAIRU as the trend component from a two-sided low-pass filter. Frequencies with period of 40 and more quarters are filtered out. Truncation is at 16 lead/lag quarters.
[4] Updating the estimate of the NAIRU for each successive year has only a modest effect on the forecasts. The decomposition of inflation surprises into NAIRU surprises and other surprises needs to be investigated further.
[5] Yet there is no documented evidence of inflationary pressure (Mankiw 2002). The index of inflationary expectations was fairly flat over the period, and inflation was in the range of a modest 2–3%.

for the federal funds rate, we estimate the rule up to the date in which we start the forecast and feed

the actual inflation rate and unemployment rate and the dynamically forecasted federal funds rates

into the estimated rule. Figure 2 shows these 1- to 12-quarter ahead forecasts of the federal funds

rate starting at the fourth quarter of 1995, 1996, 1997, and 1998. We find that the actual federal

funds rate was well below the rate that would have prevailed if the Fed had continued its previous

practice. Ball and Tchaidze (2002) present a similar finding.

Hence, in the second half of the 1990s, the strong performance of output and employment

implied that, based on historical patterns, inflation should have increased and monetary policy

should have tightened. These forecasts proved to be persistently wrong. In the next section, we

present a model and simulations that provide an explanation of these facts.

3. Model

3.1.   Setup

To analyze price level and inflation targeting in a unified framework, we suggest a modest but very

useful generalization that allows for partial price level targeting—i.e., that allows for some

revision of the price level target. To simplify notation, define the price level gap $\tilde{p}_t$ and the

inflation gap $\tilde{\pi}_t$ as:

$$\tilde{p}_t \equiv p_t - p_t^*, \tag{1}$$

$$\tilde{\pi}_t \equiv \pi_t - \pi_t^*, \tag{2}$$

where p is the (log) price level, π is the inflation rate, and stars indicate "desired" magnitudes.

We define *inflation targeting* (IT) as $\tilde{p}_t = \tilde{\pi}_t$ and *strict price level targeting* (strict PLT) as

$\tilde{p}_t = \tilde{p}_{t-1} + \tilde{\pi}_t$. To nest these two regimes, we define *partial price level targeting* (partial PLT)

with the law of motion for the price level target,

$$p_t^* = p_{t-1}^* + (1-\delta)\left(p_{t-1} - p_{t-1}^*\right) + \pi_t^* .$$

Equivalently, using the identity $p_t = p_{t-1} + \pi_t$, under partial PLT the price level gap evolves according to

$$\tilde{p}_t = \delta \tilde{p}_{t-1} + \tilde{\pi}_t , \qquad (3)$$

where $\delta \in [0,1]$ is the adjustment factor measuring how the desired price level responds to deviations from past targets.

The parameter value $\delta = 0$ corresponds to IT. Under IT, past failures to hit the target inflation rate do not affect current decisions—"bygones are bygones"—and the target for the price level is fully revised each period. In contrast, the parameter value $\delta = 1$ corresponds to strict PLT. Under strict PLT, there is no revision of the price level target.

Note that PLT is typically interpreted as *strict* price level targeting. For $0 < \delta < 1$ we have a continuum of cases between IT and strict PLT. By iterating (3) backward, one can find that

$$\tilde{p}_t = \sum_{s=0}^{\infty} \delta^s \tilde{\pi}_{t-s} . \qquad (4)$$

Hence, δ can also be interpreted as the discount factor for past deviations of the actual inflation rate from the desired inflation rate. Alternatively, partial PLT resembles IT when the target for inflation is set over a long horizon.[6]

We embed our nested specification of IT and PLT in a very standard aggregate model. We assume that the economy evolves according to the system of equations:

$$p_t = p_{t-1} + \pi_t , \qquad (5)$$
$$\tilde{p}_t = \delta \tilde{p}_{t-1} + \pi_t , \qquad (6)$$
$$y_t = \theta_1 E_t y_{t+1} + (1-\theta_1) y_{t-1} - \sigma^{-1}\left(i_t - E_t \pi_{t+1}\right) + g_t , \qquad (7)$$

---

[6] For example, if an inflation target is set for two years then inflation overshooting in the first period must be matched with undershooting in the second.

$$\pi_t = \theta_2 \Delta E_t \pi_{t+1} + (1 - \theta_2) \pi_{t-1} + \Lambda (y_t - y_t^*) + u_t, \tag{8}$$

$$y_t^* = y_{t-1}^* + \varepsilon_t, \tag{9}$$

$$i_t = \alpha \tilde{p}_t + \beta \pi_t + \gamma (y_t - y_t^*) + \rho i_{t-1}, \tag{10}$$

where y_t is output, y_t^* is potential output, π_t is inflation, p_t is the price level, $\tilde{p}_t$ is the price level gap, and i_t is the interest rate. The variables u_t, g_t, and ε_t are exogenous, zero mean shocks with variances σ_T^2, σ_g^2, and σ_P^2, respectively. E_t denotes expectations conditional on the information set available at time t. We suppress constants. In particular, we normalize π_t^* to 0, so $\pi_t = \tilde{\pi}_t$ in (6) and (10).

The interpretation of the model is as follows. Equation (5) is the identity describing the evolution of the price level. Equation (6) is the law of motion for the price level gap. Equation (7) is the log-linearized Euler equation (or the IS schedule; see Clarida, Gali and Gertler 1999, p. 1691). Equation (8) is the Phillips curve derived from Calvo-type price setting (see Woodford 2003). The parameters θ_1 and θ_2 measure the fractions of forward-looking agents in the IS and Phillips curves.[7] In the standard New Keynesian model, $\theta_1 = \theta_2 = 1$. By assumption, potential output is a random walk (equation (9)).

The last equation (10) is the generalized Taylor rule for interest rates. We choose the Taylor rule to close the model because this rule is empirically plausible (Taylor, 1993) and it performs relatively well in various setups (e.g., Levin and Williams 2003, Levin, Wieland and Williams 1999, 2003). Our generalized rule nests IT ($\alpha = 0, \beta > 0, \delta = 0$), strict PLT

---

[7] Ball, Mankiw and Reis (2003), in contrast, have an alternative formulation of the Phillips curve where PLT is the best option. We choose a baseline model that favors IT.

($\alpha > 0, \beta = 0, \delta = 1$) and intermediate cases ($\alpha > 0, \beta > 0, 0 < \delta < 1$).[8] The parameter ρ captures

interest rate smoothing. We assume that the central banker is fully credible and the Taylor rule

embodies all his commitments.

Our use of the Taylor rule to determine the central bank's policy is an alternative to the

approach of specifying an objective function for the central bank and deriving its behavior based

on dynamic optimization.[9] Svensson and Woodford (2003) study the question of uncertain and

symmetric information on the part of the central bank using the optimization approach. They

derive an interest rate rule that includes the price level and excludes inflation (see their equation

(75)).[10] Our approach allows us to systematically nest the IT and PLT policies and consider a

convex combination of them. Since the structure of the models is so similar, the merits of one

approach versus another in this context are mainly expositional. Below, when we want to evaluate

the merits of different rules, we specify an objective function.

It is worth noting that price level targeting has two, subtly different meanings in the

optimization versus rules formulations. In the optimization formulation, PLT refers to assigning a

positive weight to the price level in the objective function of the central banker. In the rules

formulation, PLT refers to having the price level in the policy reaction function—e.g., the Taylor

rule. Owing to the results of Svensson and Woodford, these two formulations can be

observationally equivalent in certain circumstances.

The baseline New Keynesian setup we describe above is built on the presumption that

agents are rational and all variables are perfectly observable. On the other hand, the literature on

measuring potential output and related concepts like the NAIRU (e.g., Staiger, Stock, and Watson

---

[8] If β=0 and α>0, the Taylor rule becomes, in Woodford's terminology, quasi-Wicksellian in the sense that the policymaker responds to the output gap and deviations of price level from the target. If, in addition, γ=0 and δ=1, the Taylor rule is Wicksellian.
[9] See Walsh (2003) for an evaluation of these approaches for closing models such as ours.
[10] Woodford (2003) derives a similar rule for the case when all variables are perfectly observable.

1997, 2001) documents that measurement or estimation of these economic indicators is notoriously imprecise. Moreover, output itself is subject to numerous revisions.[11] Because of these considerations, we modify the standard model to make potential output an unobservable quantity. Specifically, we assume that variables y_t^* and u_t are not necessarily observed separately in the Phillips curve. In some specifications, we assume that the public and the central banker observe only $e_t \equiv -\Lambda y_t^* + u_t$ and they use filtering techniques to infer the potential output, y_t^*, from the sequence of e_t. Alternatively, we consider the possibility that the central banker might have a superior estimate of the potential output. We use this possibility to evaluate the experience of the late 1990s when, as discussed in section 2, the Fed appeared to have revised its estimate of potential before professional forecasters.

Since the observed shock e_t has random walk (y_t^*) and white noise (u_t) components, we follow Muth (1960) and find weights $\{v_i\}_{i=0}^{\infty}$ that minimize the mean squared error forecast of potential output

$$\hat{y}_t^* = a_1 \sum_{i=0}^{\infty} v_i e_{t-i}, \tag{11}$$

where $\sum_i v_i = 1$ and a_1 is a scaling constant. The optimal parameters are $v_k = (1-\lambda)\lambda^k$ and $a_1 = \frac{1}{\Lambda}$ where $\lambda \in (0,1]$ is a function of $\left(\sigma_P^2/\sigma_T^2\right)$. See Appendix A for details. Estimates of potential output evolve as

$$\hat{y}_t^* = \hat{y}_{t-1}^* - \left[\frac{1-\lambda}{\Lambda}\right]\tilde{e}_t, \tag{12}$$

where $\tilde{e}_t = e_t - E\left(e_t \mid e_{t-1}, e_{t-2}, \ldots\right)$ is the innovation in e_t. Hence, equation (8) becomes

---

$$\pi_t = \theta_2 \Delta E_t \pi_{t+1} + (1-\theta_2)\pi_{t-1} + \Lambda\left(y_t - \hat{y}_t^*\right) + \lambda\tilde{e}_t. \tag{13}$$

The parameter λ is of central importance. It shows the fraction of the observed shock attributed to the temporary shock u_t. Note that rationality is preserved under this learning mechanism in the sense that the true potential output is eventually learned and the precision (MSE) of the forecast cannot be improved. Filtering, however, implies that ex post errors in the estimates can be serially correlated.

We allow the central banker and the public to have different beliefs. One possibility is that they have different beliefs about λ. Another possibility is that one of the parties knows potential output while the other does not. In this situation, the party that does not observe y_t^* can learn potential output not only from e_t but also from the actions of the other party which can observe potential output. One possible explanation of the 1990s is that the Fed knew more about potential output or that it was more optimistic (smaller λ) than the public.

We assume that the central banker's estimate of potential output is in the public's information set.[12] Hence when the central banker's belief deviates from that of the public, the public is aware of what the central banker believes. We assume that the public is guided by its own estimate of potential output (based on the statistically objective Muth filtering) so it forms its own estimate independent from the beliefs of the central banker. The public, however, rationally takes into account consequences of the central banker's actions— that is, the public takes into account that the central banker has a different estimate of potential output.

To provide a framework to evaluate policy rules, we consider the loss function

---

[12] Alternatively the central banker can keep his knowledge secret and surprise the public every period with his choice of interest rates. Simulations show that this behavior is not optimal as it destabilizes the economy. Alan Blinder (1998) also argues that in a world with rational agents, monetary policy should be transparent.

$$\mathcal{L} \equiv \sum_{t=0}^{\infty} \Delta^{t} \left(\omega_{x} \left(y_{t} - y_{t}^{*} \right)^{2} + \pi_{t}^{2} \right) \equiv \omega_{x} \mathcal{L}_{x} + \mathcal{L}_{\pi} . \tag{14}$$

To be clear, we use this function only to evaluate policies, not to derive them. Woodford (2003) shows that (14) approximates welfare loss when the Phillips curve is as in (8) with $\theta_{2} = 1$. We put a zero weight on the price level gap so as to give no direct benefit to PLT.[13]

Our model is similar to those used in other studies that model output uncertainty (e.g., Cukierman and Lippi 2002, Svensson and Woodford 2003, Aoki 2003). The components of these models are essentially identical to ours: a quadratic loss function, a New Keynesian Phillips curve, an IS schedule or other linear constraints, and a signal extraction problem.[14] In contrast to other studies, we assume informational asymmetry where the central banker has either an informational advantage or subjective pessimism or optimism.[15] Inflation targeting is the backbone of the rules analyzed in the literature, yet it is unclear to what extent the conclusions can be extended to other types of rules and other environments. Specifically, little is known about relative (dis)advantages of price level targeting over inflation targeting in uncertain environments, even in the class of interest rate rules. We explore this gray area by augmenting the Taylor rule with an element of PLT.

Since analytical derivations become complicated even in fairly simple models, most studies focus on numerical simulations and report optimal response surfaces for various calibrations. We proceed in the same vein and calibrate the model in the following section.

---

[13] Note that the loss function does not penalize for volatile interest rates. See Levin and Williams (2003) for a good discussion of calibrating the objective function and the interest rate smoothing parameter in particular.

[14] The Kalman filter in various incarnations plays a prominent role in these exercises. A conceptually different approach is to apply a game theoretic approach to model uncertainty (e.g., Caplin and Leahy 1996). Alternatively, some studies consider design rules that depend only on observable quantities. For example, Orphanides and Williams (2002) suggest a difference rule—use $\left(y_{t} - y_{t-1} \right)$ instead of $\left(y_{t} - y_{t}^{*} \right)$—to make policy robust to unknown natural rates.

[15] A typical assumption in the literature is informational symmetry or informational asymmetry where the public observes potential output and the central banker does not (e.g., Ehrmann and Smets 2003)

3.2.   Calibration

Following Roberts (1995) and Clarida, Gali and Gertler (2000), we set the slope of the Phillips curve to be $\Lambda = 0.35$. Like Clarida, Gali and Gertler (1999), we assume that the intertemporal elasticity of substitution (inverse of the slope of the IS schedule) is $\sigma = 1$. The quarterly discount factor Δ is set to 0.98. The fraction of forward-looking agents (θ) substantially differs across studies. We vary this parameter to observe how sensitive optimal policy is to changes in the share of forward-looking agents. Our baseline calibration is $\theta_1 = \theta_2 = 1$ so that all agents are forward-looking.

The central banker is not optimizing each period. He sticks to a rule and the social loss function is used to evaluate the chosen rule. The weight on output in the social objective function can be determined from microeconomic foundations. Woodford (2003) estimates $\omega_x = 0.05$. In a slightly different setting, Erceg and Levin (2002) obtain a much larger $\omega_x = 1$. Because price level targeting generally reduces the volatility of inflation and increases the volatility of output, we set $\omega_x = 1$ to bias the findings against PLT. We vary the PLT adjustment factor, δ, which is a policy choice, to examine the consequences of alternative values for price level targeting.

Estimates of the Taylor rule for the Greenspan period typically suggest that the response of the interest rate to the output gap is close to unity and the response to inflation is approximately two. Hence, we assume that $\gamma = 1$ and $\alpha + \beta = 2$ with $\alpha, \beta \geq 0$ so that determinacy conditions are satisfied. Note that because the social loss function has zero weight on interest rate volatility, there is no closed-form solution for an optimal interest rate rule. Specifically, infinitely large interest rate responses to output and inflation can be optimal. The constraints on the parameters of the Taylor rule make the problem well-defined.

The interest rate smoothing parameter ρ is often found to be close to unity. Rudebusch (2002) shows, however, that much of the observed interest rate smoothing is a consequence of serially correlated policy errors. We demonstrate below that PLT produces a large estimate of ρ even when there is no interest rate smoothing objective. Our baseline calibration has $\rho = 0$.

Next we need to calibrate σ_T^2 and σ_P^2, the variances of temporary shock u_t and permanent shock ε_t. Because the model is linear and the loss function is quadratic, it is only the ratio σ_P^2 / σ_T^2 that matters. To get an idea of σ_P^2, we use the variance of the growth rate of potential output as estimated by the Congressional Budget Office (CBO). Note that this estimate probably understates real-time uncertainty associated with unobserved potential output because the CBO's estimate is based on final estimates of GDP. We find that $\sigma_P = 0.57$ for 1954-2003 period. To calibrate variances of u_t and g_t, we estimated the Phillips curve (8) and the IS schedule (7) using GMM over the same period. The variance of the residual from the Phillips curve is $\sigma_T = 0.33$ and the variance of the residual from the IS schedule (7) is $\sigma_g = 0.54$. We set $\sigma_P = 1$, $\sigma_T = 0.33/0.57 = 0.34$, and $\sigma_g = 0.54/0.57 = 0.89$ in our baseline specification. The autocorrelation of demand shocks g_t is set to 0.9.

3.3.   Simulation Results: Policy Rules and Growth Gambles

In this section, we show the results of simulations and relate them to the experience of the late 1990s. Our results suggest that PLT, either strict or partial, could account for the performance of output and inflation when Alan Greenspan shifted to an optimistic outlook for long-run growth. Specifically, we consider three policy rules: 1) inflation targeting (IT: $\beta = 2, \alpha = 0, \delta = 0$), 2) partial price level targeting (partial PLT: $\beta = 1, \alpha = 1, \delta = 0.9$), and 3) strict price level targeting

(PLT: $\beta = 0, \alpha = 2, \delta = 1$). These rules allow us to contrast the behavior of the economy when the central bank would, at least, partially offset the impact of adverse shocks to the price level versus policies where the central bank lets "bygones-be-bygones."

Figure 3 presents impulse responses to a permanent shock to potential output under our baseline calibration. In this simulation actual potential output increases by one percent. The central banker perceives this increase while the public does not. The public, however, does know that the central banker believes potential has increased.[16] Price level targeting clearly dominates inflation targeting. A central banker pursuing IT would have to increase interest rates and would still experience higher inflation. In contrast, a central banker pursuing a price level target could keep the interest rate unchanged or even decrease it without igniting inflation. Moreover, under IT output achieves its new steady state level more slowly than under PLT.

Under PLT, the public knows that any inflation now must be matched with a deflation later to bring the current price level to its starting point. Hence, agents who can reset their prices immediately after the shock would set a lower price than they would under IT. Likewise, agents who are not able to revise their prices on impact do not need to revise them later as significantly as they would under IT. Thus, PLT effectively anchors inflationary and deflationary expectations.

Note that the public attributes only a portion of the observed innovation in the Phillips curve equation to a shock to potential output. Given anchored expectations about the future path of inflation, a policymaker can afford expansionary policy by cutting real interest rate. Via the IS schedule, this change in real interest rates raises output. Therefore, output converges faster to its new steady state after a permanent shock to potential output. If the shock turns out to be

---

[16] Note that a perfectly observable innovation to potential output would result in an instantaneous jump in output to its new potential with no change in all other variables.

15

transitory, the central banker does not need to significantly raise interest rate to correct the policy instrument in the next period because inflation is kept in check by the PLT.

The findings for the baseline specification survive a number of modifications discussed in what follows (and also shown in Appendix B). Adding backward-looking agents ($\theta_1 = \theta_2 = 0.5$), which makes output and inflation more persistent, does not qualitatively change the ranking of the regimes (Figure 4). Note that the shape of the inflation response now has a hump-shape. In addition, PLT regimes predict that the central banker should reduce interest rates. The response of output is similar across regimes. As the share of backward-looking agents increases, the advantage of PLT diminishes and responses (under PLT) become oscillatory. Likewise, interest rate smoothing ($\rho = 0.9$) decreases the gap between PLT and IT (Appendix B: Figure A1), but the ranking of the regimes is preserved.

Overall, the impulse responses under PLT for the baseline calibration appear to be consistent with the experience of the late 1990s: relatively stable interest rates, soaring output, and low inflation. In contrast, IT would have led to higher inflation, higher interest rates and lower output in response to the same shocks.

Can one generalize the superior performance of PLT to models that include combinations of demand and supply shocks? To address this question, we randomly draw shocks in the IS and Phillips curves, compute dynamics of the variables for each targeting regime, calculate the social loss, and average the results over 500 replications. The resulting isoloss map for our baseline calibration is presented in Figure 5. The vertical axis of the figure plots the parameter α in the generalized Taylor rule $i_t = \alpha \tilde{p}_t + \beta \pi_t + \gamma \left(y_t - y_t^* \right) + \rho i_{t-1}$ with $\beta = 2 - \alpha$. The horizontal axis plots the PLT adjustment factor δ. The point $\alpha = 0$ and $\delta = 0$ corresponds to IT (no weight on the price level gap). The right edge of the figure with $\delta = 1$ corresponds to regimes with strict

PLT. The point $\delta = 1$ and $\alpha = 2$ is strict PLT with no weight on the inflation gap. The points with δ between zero and one correspond to partial PLT.

Relative to IT, PLT (partial or strict) always reduces the volatility of inflation. Under the baseline calibration, PLT can cut the social loss by 66% and the volatility of inflation by more than 87%. Importantly, the volatility of the output gap is also reduced by 30%. Strict PLT minimizes the social loss function.[17]

If the share of backward-looking agents is 50%, strict PLT remains the first-best option (Figure 6). The volatility of the output gap is now increasing in the adjustment factor (δ) and the response of the interest rate to the price level gap (α). In addition, the volatility of inflation rises for all possible policy regimes. As the share of backward-looking agents rises, PLT continues to minimize the volatility of inflation—the isoloss map $\mathcal{L}_\pi$ continues shifting up—and the isoloss map $\mathcal{L}_x$ becomes increasingly steeper. If sufficiently many agents are backward-looking (i.e., θ_1 and θ_2 are low), the increased volatility of the output gap outweighs gains in reducing the volatility of inflation so that IT begins to dominate PLT.

Adding interest rate smoothing shifts the isoloss maps $\mathcal{L}_\pi$ and $\mathcal{L}_x$ down and makes them flatter. Generally, the larger is ρ, the flatter and lower are isoloss maps $\mathcal{L}_\pi$ and $\mathcal{L}_x$ (see Figure 7).

To complete the picture, we present isoloss maps for cases when potential output y^* is perfectly observed by the public and the central banker (Figure 8) and when y^* is not observed by either of the parties (Figure 9). With full information about potential output and symmetric information, PLT still dominates IT. In the former case there is a trade-off between inflation

---

[17] PLT does not achieve these results by increasing the volatility of the interest rate. The volatility of the interest rate, as measured by the present value of the squared deviations of the interest rate from its steady state level, is also minimized by strict PLT.

volatility and output volatility, with PLT increasing the volatility of output.[18] Hence, in contrast to

the baseline case, IT may dominate if there are different weights in the loss function. When the

central banker does not enjoy an informational advantage (Figure 9), partial PLT minimizes the

variance of output. Further sensitivity analysis indicates that qualitative conclusions are insensitive

to changes in the parameters $\sigma, \Lambda, \sigma_P^2 / \sigma_T^2$ (Figures A2-A4 in Appendix B).[19,20]

In sum, we conclude that PLT can not only match the stylized facts of the late 1990s, but

also that undoing past policy mistakes as under PLT is generally a better policy regime than letting

bygones be bygones as under IT.

3.4.   Discussion

The key ingredient in PLT dominating IT is the expectations about the future path of the policy

instrument. According to Woodford (2003, p. 587)

> … in the presence of forward-looking private-sector behavior, the central bank mainly
> affects the economy though changes in expectations about the future path of its instrument;
> a predictable adjustment of interest rates later, once the disturbances substantially affect
> inflation and output, should be just as effective in restraining private-sector spending and
> pricing decisions as an immediate preemptive increase in overnight interest rates.

Our findings are consistent with Woodford's observation. Although the impact response of

interest rates is stimulating output, the subsequent response is to slow down output growth. The

larger the share of backward-looking agents, the less attractive PLT is. Once forward-looking

---

[18] Note that temporary i.i.d. shocks to the Phillips curve exogenously increase inflation and the adjustment to
permanent shocks is instantaneous. Hence, the volatility of output is higher under PLT because PLT has to generate
deflation to bring the price level back to target after exogenous shocks to the Phillips curve. In contrast, under IT, i.i.d.
shocks to the Phillips curve have only contemporaneous effects and do not propagate to other periods.

[19] We do not report the cases when the public has an informational advantage. If the public is more optimistic about
potential output than the central banker, there is substantial downward pressure on inflation because the public expects
future monetary ease as the central banker learns about the improvement in productive capacity. Under IT, the decline
in inflation is so large that the interest rate sharply falls despite the central banker's skepticism about a shift in
potential output. In contrast, under PLT, the decline in interest rates is attenuated because the public sets current
prices higher in anticipation of future accommodative policy.

[20] We also consider an alternative specification where the growth rate rather than the level is subject to shocks. These
results (not reported) have the same qualitative features as those highlighted in this paper.

behavior of agents is turned off ($\theta \approx 0$), PLT is not better than IT. Backward-looking expectations cannot be anchored by promising a future path of interest rates. Because PLT requires returning prices to a starting level through unpleasant deflations following any inflation above target, PLT thus destabilizes the economy. In contrast, IT simply "forgets" about missed inflation targets in the past.

A more technical channel of PLT's dominance is the magnitude of the long run responses to the output gap and inflation. Provided that ρ and δ less than one, our generalized Taylor rule in (10) implies that the long run response of the nominal interest rate to inflation is $\left(\frac{\beta}{1-\rho} + \frac{\alpha}{(1-\rho)(1-\delta)} \right)$, while the long run response to the output gap is $\frac{\gamma}{1-\rho}$. Hence, interest rate smoothing and PLT make long run responses more aggressive. This finding is consistent with previous studies (e.g., Ehrman and Smets 2003), who show if potential output is not observed perfectly there should be a more aggressive response to inflation gaps under inflation targeting. The literature, however, has focused only on increasing β or ρ in the Taylor rule. We identify PLT as another, potentially superior, policy for reducing the volatility of inflation and, in some cases, the output gap. Note that under IT ($\alpha = 0, \delta = 0$), the ratio of short run to long run responses to the output gap and inflation is fixed at $(1-\rho)^{-1}$. Combined with interest rate smoothing, PLT has more degrees of freedom thus relaxing this constraint and improving social welfare.

Additionally, Woodford (2003) argues that history dependence embodied in interest rate smoothing is critical for the optimality of interest rate rules. Here, even if there is no interest rate

smoothing, a Taylor-type rule with PLT is history dependent. As we will see in Section 4, interest

rate smoothing and PLT look very similar in an econometric specification.[21]

The gain from PLT can be substantial even when agents care about inflation, not the price

level.[22] Some economists (e.g., Tobin 1984, Friedman and Kuttner 1996, Friedman 1999) discard

PLT (in favor of IT) as an implausible, non-credible and even detrimental policy design to

implement price stability. They argue that PLT leads to a higher volatility of economic activity as

past misfortunes in sustaining a stable price level must be corrected at some point, thus

destabilizing the economy. Our findings, however, undermine this critique of PLT because output

and interest rates are not destabilized relative to IT.[23]

A final critique of PLT is that it is not feasible for central banks to make the very tough

decision to pull down the price level following adverse shocks. This critique does not apply to the

situation we have analyzed. PLT keeps inflation in check even when it turns out that the

policymaker was overly-optimistic about potential output. Hence, policy errors do not have

serious consequences that require very contractionary policy and it should be feasible for the

central bank to maintain the credibility that our analysis presumes.

4. Testing for Price Level Targeting

The paper has presented some models and simulations showing that PLT has desirable properties.

The foregoing analysis shows that PLT could have contributed to the low inflation and high

growth seen in the late 1990s, but does not prove that the Fed was following this policy. In this

---

[21] Note that the generalized Taylor rule that we consider combines proportional (response to the current output gap), derivative (response to current inflation gap) and integral (response to the price level gap) stabilization components. This is an example of PID (proportional-integral-derivative) controllers extensively used in engineering to improve efficiency and stability of feedback controls in dynamic systems (see Lewis's (2003) textbook for examples and discussion). Works by Phillips (1954, 1957) are early applications of PID controllers in economics.

[22] Recall that our setup biases against PLT, since 1) social loss function does not penalize for deviating from the price level target, 2) social loss function has a high weight on volatility of the output gap, 3) this is a sticky price, not sticky information, model, 4) the central banker is fully credible.

[23] Surprisingly, Shiller (1997, p. 28) reports that approximately 70% of the general public favor PLT while more than 90% of economists favor IT.

section we discuss several pieces of evidence that suggest that the Fed was indeed behaving consistently with PLT in recent years.

In testing PLT, we focus on two falsifiable implications of PLT. First, if the central banker sticks to PLT, discrepancies between the actual price level and the desired (target) price level are transitory. Hence the (log) actual price level is trend stationary where the trend is some target price level. In contrast, IT implies that the price level has a unit root (see Walsh 2003). So whether or not the price level has a unit root helps distinguish between the two policies. Second, we consider estimates of a generalized Taylor rule that allows the Fed to respond to the price level along the lines of the model in the previous section. Of course, Alan Greenspan has never been an advocate of monetary rules. He acknowledges, however, that a rule may serve as a useful benchmark for policy actions (Greenspan 2004). Our estimates of a Taylor rule may capture key elements of a much more complex reaction function.

4.1. Unit Root Tests

In practice, it is hard to test the unit root implications of PLT. First, twenty years (e.g., 1982:01–2003:03) is a fairly short horizon to decisively discriminate trend stationarity from difference stationarity. Second, the desired price level may indeed be trend stationary but the trend can have breaks. When the dates and the number of breaks are unknown the power of unit root tests is quite weak (e.g., Zivot and Andrews 1992). These factors limit the power of unit root tests. Nonetheless, these univariate procedures are a sensible starting point for testing for PLT.

Not surprisingly, the unit root tests are not decisive. Simple unit root tests reject trend stationarity (Kwiatkovski-Phillips-Schmidt-Shin) or cannot reject a unit root (Augmented Dickey-Fuller, GLS detrended Dickey-Fuller, Perron-Phillips); see Table 2. For example, the augmented Dickey-Fuller statistic for the GDP deflator is -0.75 while the 5% critical value is -3.46; thus, we

cannot reject the null hypothesis of a unit root in the series. This result holds for all key price index series: the GDP deflator, the Consumer price index (CPI), the CPI less energy and food, the Producer price index (PPI) less energy and food, and the CPI research series (less energy and food). The largest autoregressive root for each price level series is unity. Other studies (e.g., Cecchetti and Kim 2003) report similar results.

A different picture emerges if we allow for a break in the trend of the price level. If we assume the break date to be known at the second quarter of 1991, we can reject a unit root null hypothesis at 5% for most price indices except for the GDP deflator which is a borderline case at the 10% significance level (column (8) in Table 2). Using the sup-t test, which allows for an unknown trend break (see Zivot and Andrews 1992), we again find that a unit root is rejected at 5% for most series except for the GDP deflator, which again is a borderline case at the 10% significance level (column (6)–(7) in Table 2). The largest autoregressive roots decrease from unity to the 0.8–0.9 range. In sum, if we allow for a break in the trend, the unit root tests might suggest PLT since 1982. Moreover, the largest autoregressive root in the price level is substantially lower than in the earlier period once a break is allowed for. We examine more closely the stability of these parameters in the next section.

4.2. Taylor rule: PLT or IT?

Starting with Taylor (1993), many studies document that the Taylor rule in various incarnations describes U.S. monetary policy fairly well. It is very tempting to take this as evidence for IT. We show that such a conclusion would be premature. Our parameter estimates suggest that there is a substantial weight on the price level in the Taylor rule in the Greenspan period, but not earlier.

Suppose the central banker uses the generalized Taylor rule with a price level target as well as inflation target,

$$i_t = \alpha \tilde{p}_{t-1} + \beta \pi_t + \gamma x_t + \rho i_{t-1} + \varepsilon_t, \tag{15}$$

where $x_t = y_t - y_t^*$ is the output gap and ε_t is an exogenous innovation to monetary policy. Using

(6), we quasi-difference (15) to eliminate the unobserved $\alpha \tilde{p}_{t-1}$ term,

$$i_t = \beta \pi_t + (\alpha - \beta \delta) \pi_{t-1} + \gamma x_t - \gamma \delta x_{t-1} + (\rho + \delta) i_{t-1} - \delta \rho i_{t-2} + \varepsilon_t - \delta \varepsilon_{t-1}. \tag{16}$$

In contrast, a typical specification in the context of IT (e.g., Clarida, Gali and Gertler 2000) is

$$i_t = a_1 \pi_t + a_2 x_t + \rho_1 i_{t-1} + \rho_2 i_{t-2} + v_t. \tag{17}$$

Specifications (16) and (17) are quite similar. The PLT specification (16) provides clear falsifiable

implications about signs and restrictions on the coefficients. In particular, PLT specification (16)

predicts:

1. A negative coefficient on the lagged output gap
2. A large positive (possibly close to unity) coefficient on the lagged interest rate and a small negative coefficient on the second lag of the interest rate
3. A large negative MA root
4. An overidentifying restriction on the parameters (six coefficients and five parameters)

Note that absent the price-level term in (10), the lagged terms in (16) involving δ would be

irrelevant. That is, without a price level objective, δ is not identified.

To make analysis concrete, consider estimates of the unrestricted version of specification

(16):

$$i_t = a_1 \pi_t + a_2 \pi_{t-1} + a_3 x_t + a_4 x_{t-1} + \rho_1 i_{t-1} + \rho_2 i_{t-2} + \varepsilon_t + \theta \varepsilon_t. \tag{18}$$

We estimate (18) for two subsamples: 1955–1979 (pre-Greenspan) and 1982–2003 (late Volker

and Greenspan era).[24] The output gap x is measured as a residual after HP filtering log real

chained 1996 GDP. The price level is measured with the GDP deflator and, consequently,

inflation π is the growth rate of the GDP deflator. The federal funds rate is our i. Following

---

[24] We exclude 1979-1981 because the Fed used a different operating target (e.g., Bernanke and Mihov 1998).

Clarida, Gali and Gertler (2000), we use GMM to estimate the interest rate rules. The set of instruments includes four lags of the output gap, inflation, log commodity price index, and the federal funds rate. Data are quarterly.

The results (Table 3) indicate that for 1982–2003 sample the estimated MA root is not statistically different from zero. It is not clear, however, that one should rely heavily on MA coefficients to test theories.[25] First, time aggregation considerably attenuates the magnitude of the MA root (Working 1960). Second, learning and filtering typically introduces positively serially correlated errors, especially when the analyzed data are from final releases (Orphanides and van Norden 2002). This can reverse the sign of the estimated MA root. Third, we do not observe desired output and inflation. If the data generating process for any of these has a positive MA root with sufficiently large variance, we would again have a positive estimate for the MA root in the reduced or restricted specification. In sum, the estimates of the MA root may be too fragile to be decisive in this analysis.

In light of this problem, we base our analysis on testing the restrictions imposed on the coefficients by specification (16). Given our inability to estimate the true MA term, we will not impose the error structure as in (16) and instead estimate[26]

$$i_t = \beta\pi_t + \left(\alpha - \beta\delta\right)\pi_{t-1} + \gamma x_t - \gamma\delta x_{t-1} + \left(\rho + \delta\right)i_{t-1} - \delta\rho i_{t-2} + e_t. \tag{19}$$

The unrestricted specification is

$$i_t = a_1\pi_t + a_2\pi_{t-1} + a_3 x_t + a_4 x_{t-1} + \rho_1 i_{t-1} + \rho_2 i_{t-2} + e_t. \tag{20}$$

Table 4 presents the estimates of the restricted specification (19) for the 1955–1979 and 1982–2003 samples. The p-values for the test of the restrictions are 0.27 and 0.12, respectively.

---

[25] The problem is similar to finding positive MA roots in Mankiw's (1982) model of consumption of durable goods.
[26] Aoki (2003) derives a similar rule in a setup where the data are revised. Hence, PLT can be observationally equivalent to other models, e.g., models with a noisy signal (Aoki 2003). Although the interpretation of coefficients is different, the ultimate outcome is the same. Put differently, pursuing a goal other than PLT can be effectively a PLT.

The parameter δ controls the rate at which past errors affect the price level target. For the pre-Greenspan sample, the point estimate is 0.364. For the Greenspan sample, it is 0.814. Hence, neither period has strict PLT, but the Greenspan era is characterized by much less discounting of past errors, i.e., is much closer to strict PLT than the earlier period. The differences are statistically and economically significant. IT targeting causes the new price level trend to shift by the entire amount of inflation error. With a δ of 0.364, after four quarters the new trend is within 2 percent ($0.364^4 = .02$) of the IT level; with a δ of 0.814, the new trend is only 43 percent ($0.814^4 = 0.43$) of it. On the other hand, the estimated δ of 0.814 is much less hawkish than strict PLT. Finally, note that a δ of 0.8 is close to the optimal level that we find in our simulations.

Note that the interest rate smoothing motive is much stronger in the pre-Greenspan period than in the Greenspan period, as the estimate of ρ falls from 0.74 to 0.17. In addition, $(\rho + \delta) =$ 0.17+0.81=0.98 is a value that is often found in reduced from specifications. As we show above, interest rate smoothing and PLT have very similar implications for the Taylor rule. Hence, our approach provides an alternative explanation for why the lagged interest rate is so important in explaining the variance of the federal funds rate and why the coefficient is so close to unity.

This point can be made clear by considering the unrestricted estimates in Table 5. Columns (2) and (3) give the unrestricted estimates for the two sample periods. Columns (5) and (6) give the reduced form estimates implied by the restricted estimates in Table 4. Finally, for comparison, we include the specification of Clarida, Gali and Gertler (2000) that includes no lags of inflation and the output gap. Table 5 shows that the presence of lagged interest rates in the Taylor rule can arise from PLT even if there is no interest rate smoothing objective.

The short run response of the federal funds rate to the output gap is significantly larger for the Greenspan period than for the pre-Greenspan period. The long run response of federal funds

rate to the output gap ($\frac{\gamma}{1-\rho}$) is roughly unchanged: 0.95 for the Greenspan period and 1.11 for the pre-Greenspan period. Importantly, the estimate of the coefficient on the lagged output gap in the unrestricted model (20) has a negative sign, which is consistent with PLT. Moreover, the coefficients for the current and lagged output gap are of comparable absolute magnitudes as predicted by PLT.

Finally and most importantly, we observe a tremendous change in α and β reflecting the relative import of PLT and IT, respectively. The marginal short run effect of inflation on the interest rate, β, is economically identical for both subsamples. In contrast, point estimates of response to the price level gap, α, increases ninefold from 0.04 to 0.37. In sum, the long run response of the federal funds rate to inflation, $\frac{1}{1-\rho}\left(\frac{\delta}{1-\delta}\alpha + \beta\right)$, increases from 0.66 in the 1955–1979 sample to 2.66 in the 1982–2003 sample. These estimates, together with the change in the estimate of δ from 0.364 to 0.814 (see Table 4), suggest that a combination of toughness about inflation and taking into account passed inflation errors—i.e., partial PLT—characterize monetary policy under Greenspan.

We confirm the results of Clarida, Gali and Gertler (2000): the Fed responded to inflation in 1982–2003 much more aggressively than in 1955–1979. However, we give a different interpretation of why we observe a more aggressive response to inflation. Clarida, Gali and Gertler put all weight on short run response propagated by interest rate smoothing while our estimates suggest that most of the response to inflation goes through PLT.[27,28]

---

[27] The results with respect to the output gap are slightly different because we use the HP filter while Clarida, Gali and Gertler (2000) use a quadratic trend.

[28] We run a number of robustness checks. The qualitative conclusions are insensitive to changes in the definition of price index (e.g., CPI or PPI instead of GDP deflator), slack capacity (unemployment rate instead of the output gap) and the time span of the Greenspan era. All these perturbations to the baseline specification lead to the same results: the importance of PLT significantly increased during the Greenspan chairmanship.

5. Conclusions

In the late 1990s, Alan Greenspan and the Federal Open Market Committee took a gamble. They kept interest rates low and essentially steady in the face of extraordinarily strong output growth and record-low unemployment rates. If the Fed had followed its historical reaction to economic conditions, it would have raised interest rates to keep inflation under control. Instead the Fed kept interest rates low because it believed that the productive capacity of the economy had expanded. Though it is now clear that there was such a shift, at the time the evidence for it was quite limited. Why did the gamble pay off? Even though the Fed turned out to be correct about potential output growth, why did inflation not increase as private agents took into account the risk that the Fed was being too stimulative when they set their price and inflation expectations?

This paper provides an explanation for the success of the Fed in accommodating noninflationary growth in the late 1990s. A commitment of the Fed to reverse policy errors had it been too optimistic about the capacity of the economy can explain why inflation remained in check despite historically loose monetary policy. In particular, the paper shows that a price level target, either strict or partial, can serve to anchor inflation even if the public believes the Fed is overly optimistic about potential growth. The expectation that policy errors will be reversed leads to very favorable outcomes. The Fed is able to gamble on its belief that capacity has increased without the public raising inflationary expectations because the public knows that the Fed would reverse itself in the event the gamble does not pay off. The costs of reversing itself in this case are also low because the price level target keeps inflation low even in bad realizations. So the disinflation needed to reverse policy errors is modest.

The paper shows that price level targeting is superior to inflation targeting in a wide range of situations. The analysis does not depend on strict price level targeting. In particular, our formulation nests inflation targeting and strict price level targeting within a specification that

allows for partial adjustment of the price level target to past inflation. For price level targeting to have these favorable properties, sufficiently many agents must be forward-looking. If not, then there is no value to the commitment to reverse errors.

The paper also provides econometric evidence that the Fed, in contrast to earlier periods, has recently put substantial weight on the price level in setting interest rates. A generalized Taylor rule puts weight on the price level gap as well as the inflation gap in the Greenspan era. In the pre-Greenspan period, there is no evidence of price level targeting. Moreover, the presence of the price level gap in the Taylor rule provides an explanation that does not rely on interest-rate smoothing or serially correlated policy errors for the significance of lagged interest rates in standard Taylor rules. Price level targeting induces error correction that resembles serial correlation of interest rate decisions in specifications that do not control for the price level gap.

Our analysis does not ascribe strict adherence to a price level target, or indeed any other rule, to Alan Greenspan or the Fed. Rather, it shows that there is both theoretical and empirical support for the contention that correcting past errors has been a part of Federal Reserve decision making in recent years.

References

AOKI, KOSHE. 2003. "On optimal monetary policy response to noisy indicators," *Journal of Monetary Economics* 50(3), 501-23.

BALL, LAURENCE AND ROBERT R. TCHAIDZE. 2002. "Monetary Policy Rules in Practice," *American Economic Review* 92(2), 108-114.

BALL, LAWRENCE, N. GREGORY MANKIW, AND RICARDO REIS. 2003. "Monetary Policy for Inattentive Economies", *NBER Working Paper* #9491.

BASU, SUSANTO, JOHN G. FERNALD, AND MATTHEW D. SHAPIRO. 2001. "Productivity Growth in the 1990s: Technology, Utilization, or Adjustment?" *Carnegie-Rochester Conference Series on Public Policy* 55(0), 117-65

BERNANKE, BEN S. AND ILIAN MIHOV. 1998. "Measuring Monetary Policy," *Quarterly Journal of Economics* 113(3), 869-902.

BLANK, REBECCA AND MATTHEW D. SHAPIRO. 2001. "Labor and the Sustainability of Output and Productivity Growth," in *The Roaring Nineties*, Alan Kruger and Robert M. Solow, eds., New York: Russell Sage Foundation.

BLINDER, ALAN. 1998. *Central Banking in Theory and Practice*. Cambridge: MIT Press.

CAPLIN, ANDREW AND JOHN LEAHY. 1996 "Monetary Policy as a Process of Search," *American Economic Review* 86(4), 689-702.

CECCHETTI, STEPHEN G. AND JUNHAN KIM, 2003. "Inflation Targeting, Price-Path Targeting and Output Variability," *NBER Working Paper* #9672

CLARIDA, RICHARD, JORDI GALI, AND MARK GERTLER. 1999. "The Science of Monetary Policy: A New Keynesian Perspective," *Journal of Economic Literature* 37(4), 1661-1707.

CLARIDA, RICHARD, JORDI GALI, AND MARK GERTLER. 2000. "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory," *Quarterly Journal of Economics* 115(1), 147-80.

CUKIERMAN, ALEX, AND FRANCESCO LIPPI. 2002. "Endogenous Monetary Policy with Unobserved Potential Output." working paper.

EHRMANN, MICHAEL, AND FRANK SMETS. 2003. "Uncertain potential output: Implications for Monetary policy" *Journal of Economic Dynamics and Control* 27(9), 1611-1638.

ELLIOTT, GRAHAM, THOMAS J. ROTHENBERG AND JAMES H. STOCK (1996). "Efficient Tests for an Autoregressive Unit Root," *Econometrica* 64(4), 813-836.

ERCEG, C.J., AND LEVIN, A.T., 2002. "Optimal monetary policy with durable and non-durable goods," *European Central Bank Working Paper* 179.

FRIEDMAN, BENJAMIN M. 1999. "Comment", in *Monetary Policy Rules*, John B. Taylor, ed., Chicago: University of Chicago Press.

FRIEDMAN, BENJAMIN M. AND KENNETH N. KUTTNER. 1996. "A Price Target for U.S. Monetary Policy? Lessons from the Experience with Money Growth Targets," *Brookings Papers on Economic Activity* 1, 77-146.

GREENSPAN, ALAN. 2004. "Risk and Uncertainty in Monetary Policy," *American Economic Review* 94(2), 33-40.

JORGENSON, DALE W., AND KEVIN J. STIROH. 2000. "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers of Economic Activity* 0(1), 125-211.

KRANE, SPENCER. 2003. "An Evaluation of Real GDP Forecast: 1996-2001," *Economic Perspectives*, Federal Reserve Bank of Chicago, Issue 1, 2-21

KRUEGER, ALAN B. AND ROBERT. M. SOLOW. 2001. *The Roaring Nineties: Can Full Employment Be Sustained?* New York: Russell Sage Foundation.

KWIATKOWSKI, DENIS, PETER C. B. PHILLIPS, PETER SCHMIDT AND YONGCHEOL Shin (1992). "Testing the Null Hypothesis of Stationary against the Alternative of a Unit Root," *Journal of Econometrics* 54(1-3), 159-178.

LEVIN, ANDREW T. AND JOHN C. WILLIAMS. 2003. "Robust Monetary Policy with Competing Reference Models," *Journal of Monetary Economics* 50(5), 945-975.

LEVIN, ANDREW, VOLKER WIELAND, AND JOHN C. WILLIAMS. 1999. "Robustness of Simple Monetary Policy Rules under Model Uncertainty," in *Monetary Policy Rules*, John B. Taylor, ed., Chicago: University of Chicago Press.

LEVIN, ANDREW, VOLKER WIELAND, AND JOHN C. WILLIAMS. 2003. "Performance of Forecast-Based Monetary Policy Rules Under Model Uncertainty," *American Economics Review* 93(3), 622-645.

LEWIS, ANDREW D. 2003. *A Mathematical Approach to Classical Control*. Preprint.

MANKIW, N. GREGORY, AND MATTHEW D. SHAPIRO. 1986. "News or Noise: An Analysis of GNP Revisions," *Survey of Current Business* 66(5), 20-25.

MANKIW, N. GREGORY. 1982. "Hall's Consumption Hypothesis and Durable Goods," *Journal of Monetary Economics* 10(3), 417-425.

MANKIW, N. GREGORY. 2002. "U.S. Monetary Policy During the 1990s." *NBER Working Paper* #8471.

MUTH, JOHN F. 1960. "Optimal Properties of Exponentially Weighted Forecasts," *Journal of the American Statistical Association* 55(290), 299-306.

OLINER, STEPHEN D., AND DANIEL E. SICHEL. 2000. "The Resurgence of Growth in the late 1990s: Is Information Technology the Story?" *Journal of Economic Perspectives* 14(4), 3-22.

ORPHANIDES, ATHANASIOS AND JOHN WILLIAMS. 2002. "Robust Monetary Policy Rules with Unknown Natural Rates," *Brookings Papers on Economic Activity* 0(2), 63-118.

ORPHANIDES, ATHANASIOS AND SIMON VAN NORDEN. 2002. "The Unreliability of Output-Gap Estimates in Real Time," *Review of Economics and Statistics* 84(4), 569-583.

PHILLIPS, A.W. 1954. "Stabilization Policy in a Closed Economy," *Economic Journal* 64(254), 290-323

PHILLIPS, A.W. 1957. "Stabilization Policy and the Time-Forms of Lagged Responses," *Economic Journal* 67(266), 265-277.

ROBERTS, JOHN M. 1995. "New Keynesian Economics and the Phillips Curve," *Journal of Money, Credit and Banking* 27(4), 975-984.

RUDEBUSCH, GLENN. 2002. "Term Structure Evidence on Interest Rate Smoothing and Monetary Policy Inertia," *Journal of Monetary Economics* 49(6), 1161-1187.

SHILLER, ROBERT J. 1997. "Why Do People Dislike Inflation?" in *Reducing Inflation*, Romer C.D. and Romer D., eds., Chicago: University of Chicago Press.

STAIGER, DOUGLAS, JAMES H. STOCK AND MARK W. WATSON. 1997. "The NAIRU, Unemployment, and Monetary Policy," *Journal of Economic Perspectives* 11(1), 33-49.

STAIGER, DOUGLAS, JAMES H. STOCK AND MARK W. WATSON. 2001. "Prices, Wages, and the U.S. NAIRU in the 1990s," in *The Roaring Nineties*, Alan Kruger and Robert M. Solow, eds., New York: Russell Sage Foundation.

SVENSSON, LARS O.E. AND MICHAEL WOODFORD. 2003. "Indicator Variables for Optimal Policy," *Journal of Monetary Economics* 50, 691-720.

TAYLOR, JOHN B. 1993. "Discretion versus policy rules in practice," *Carnegie-Rochester conference Series on Public Policy* 39(0), 195-214.

TOBIN, JAMES. 1984. "Overview," paper prepared for Symposium on "New challenges for monetary policy" sponsored by the Federal Reserve Bank of Kansas city at Jackson Hole, Wyoming, 27 August 1982.

WALSH, CARL. 2003. *Monetary Theory and Policy*. Cambridge: The MIT Press.

WOODFORD, MICHAEL. 2003. *Interest and Prices*. Princeton: Princeton University Press.

WORKING, HOLBROOK. 1960. "Note on the Correlation pf First Differences of Averages in a Random Chain," *Econometrica* 28(4), 916-918.

ZIVOT, ERIC, AND DONALD ANDREWS. 1992. "Further Evidence on the Great Crass, the Oil-Price Shock, and the Unit-Root Hypothesis," *Journal of Business and Economic Statistics* 10(3), 251-270.

Appendix A: The Muth Problem

Statistical (objective) learning

Suppose that

$$y_t = y_t^* + x_t \tag{A.1}$$

where

$$x_t \sim nid\left(0, \sigma_T^2\right) \text{ (can be interpreted as the output gap)} \tag{A.2}$$

$$y_t^* = y_{t-1}^* + \varepsilon_t = \sum_{i=0}^{\infty} \varepsilon_{t-i} \text{ (can be interpreted as potential output)} \tag{A.3}$$

$$\varepsilon_t \sim nid\left(0, \sigma_P^2\right) \tag{A.4}$$

We are interested in finding a sequence of weights $\{v_i\}_{i=0}^{\infty}$ such that

$$\{v_i\}_{i=0}^{\infty} = \arg\min\left\{V \equiv E\left(y_t^* - \hat{y}_t^*\right)^2 : \hat{y}_t^* = \sum_{i=0}^{\infty} v_i y_{t-i}\right\} \tag{A.5}$$

This problem is in the spirit of Muth (1960).

Solution

Expand (A.5) and use (A.2)-(A.4) to find:

$$V = \sigma_T^2 \sum_{j=0}^{\infty} v_j^2 + \sigma_P^2 \sum_{j=0}^{\infty}\left(1 - \sum_{i=0}^{j} v_i\right)^2. \tag{A.6}$$

The first order condition with respect to $\{v_i\}_{i=0}^{\infty}$ is

$$\frac{\partial V}{\partial v_k} = 2\sigma_T^2 v_k - 2\sigma_P^2 \sum_{j=k}^{\infty}\left(1 - \sum_{i=0}^{j} v_i\right) = 0 \qquad k = 0, 1, \ldots. \tag{A.7}$$

Difference (A.7) twice:

First difference: $\sigma_T^2\left(v_k - v_{k+1}\right) - \sigma_P^2\left(1 - \sum_{i=0}^{k} v_i\right) = 0 \tag{A.8}$

Second difference: $\sigma_T^2 v_k - \left(2\sigma_T^2 + \sigma_P^2\right) v_{k+1} + \sigma_T^2 v_{k+2} = 0 \tag{A.9}$

The general solution to (A.9) is

$$v_k = c\lambda^k \text{ where}$$

$$\lambda = \frac{z - \sqrt{z^2 - 4}}{2} \text{ (the stable eigenroot of (A.9))} \tag{A.10}$$

$$z = 2 + \frac{\sigma_P^2}{\sigma_T^2} \tag{A.11}$$

$$\lim_{\sigma_P^2/\sigma_T^2 \to \infty} \lambda = 0, \lim_{\sigma_P^2/\sigma_T^2 \to 0} \lambda = 1$$

Constant c is found from (A.8): $c = \left(1 - \lambda\right)$

Hence

$$v_k = (1-\lambda)\lambda^k \qquad (A.12)$$

and the updating process can be written in recursive form:

$$\hat{y}_t^* = \lambda\hat{y}_{t-1}^* + (1-\lambda)y_t = \hat{y}_t^* + (1-\lambda)\left(y_t - E\left(y_t^* \mid y_t, y_{t-1}, \ldots\right)\right) \qquad (A.13)$$

which is a form of adaptive (and fully rational) expectations.

To apply this result to our model, note that if we multiply (A.3) by $-\Lambda$ and set $y_t \equiv e_t$, we would get our shocks to the Phillips curve:

$$e_t = -\Lambda y_t^* + u_t.$$

Accordingly, the variance of the permanent component is $\Lambda^2\sigma_P^2$, not σ_P^2. Also, to compute expected y_t^*, we need to multiply $\hat{e}_t$ by $-\frac{1}{\Lambda}$. Hence,

$$\hat{y}_t^* = \lambda\hat{y}_{t-1}^* - \frac{(1-\lambda)}{\Lambda}e_t \ .$$

Table 1.   GDP Growth and Inflation Rates: Forecast Errors

(Percent change, fourth quarter to fourth quarter)

	1996	1997	1998	1999	2000
GDP growth rate					
Blue Chip	1.1	1.8	2.2	1.8	0.2
Survey of Professional Forecasters	1.1	1.4	2.1	1.7	0.3
Inflation rate					
Blue Chip	-0.7	-0.7	-1.1	-0.1	0.6
Survey of Professional Forecasters	-0.7	-0.7	-1.2	0.1	0.5
Simple Phillips curve	-0.8	-0.6	-1.3	-0.1	-0.1

Notes: Forecast errors are computed as actual minus forecasted value of the variable for the year indicated. The forecasts are produced at the beginning of the year.   Inflation rate is computed for the GDP deflator. Source: Blue Chip Economic Indicators, Survey of Professional Forecasters, and authors' calculations. The specification of the Phillips curve is described in the text.

Table 2. Price Level: Unit Root Tests

Series	ADF	PP	DFGLS	KPSS	ADF sup-t (unknown break)		ADF (known break at 1991:2)	Largest autoregressive root		
					statistic	break date		1955:1-1978:4	1982:1-2002:4	1982:1-2002:4 break at 1991:2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
GDP deflator	-0.75	-0.99	-0.62	0.29	-4.01	1993:2	-3.40	1.001	0.997	0.931
CPI	-0.63	-0.84	-1.10	0.27	-4.44	1990:4	-4.26	1.004	0.989	0.866
CPI less food and energy	-0.63	-0.84	-1.10	0.27	-4.98	1991:2	-4.87		1.003	0.908
PPI less energy and food	-0.07	-0.25	-0.57	0.28	-4.75	1991:4	-4.64		1.004	0.875
CPI research series (less food and energy)	-1.16	-2.34	-0.58	0.30	-4.32	1991:2	-4.20		0.994	0.875
Critical values 1%	-4.07	-4.07	-3.65	0.22	-4.93		-4.55			
5%	-3.46	-3.46	-3.09	0.15	-4.42		-3.94			
10%	-3.16	-3.16	-2.80	0.12	-4.11		-3.66			

Notes: Columns (2)-(6) and (8) report test statistics for unit root tests. Sample is 1982:1-2003:1 unless otherwise noted. Critical values for column (4) are from Elliot, Rothenberg and Stock (1996), Table 1. Critical values for column (5) are from Kwiatkowski et al (1992). Critical values for column (6) are from Zivot and Andrews (1992, p. 256), Table 3. ADF is the augmented Dickey-Fuller test. PP is the Perron-Phillips test. DFGLS is the GLS detrended Dickey-Fuller test; see Elliot, Rothenberg and Stock (1996). KPSS is the Kwiatkowski-Phillips-Schmidt-Shin test; see Kwiatkowski et al (1992). The null hypothesis for ADF, PP, and DFGLS test is presence of unit root in the series. The hull hypothesis for KPSS is trend stationarity in the series.

Table 3. Generalized Taylor rule: Restricted specification

| Parameter | Unrestricted specification with MA(1) term, eq. (18) | |
	1955–1979	1982–2003
(1)	(2)	(3)
Current inflation, π_t	0.324	0.118
	(0.103)	(0.200)
Lagged inflation, π_{t-1}	-0.254	0.270
	(0.089)	(0.096)
Current output gap, x_t	0.582	1.090
	(0.173)	(0.342)
Lagged output gap, x_{t-1}	-0.402	-0.778
	(0.120)	(0.250)
1st lag of federal funds rate, i_{t-1}	1.100	0.764
	(0.240)	(0.378)
2nd lag of federal funds rate, i_{t-2}	-0.180	0.099
	(0.224)	(0.351)
MA(1)	-0.394	0.180
	(0.219)	(0.320)
R^2	0.916	0.942
Durbin-Watson	1.891	1.825
S.E.E.	0.765	0.663

Notes: Dependent variable is quarterly average annualized federal funds rate. Columns (2) and (3) are estimated by 2SLS. Instruments include four lags of the output gap, inflation, federal funds rate, and log commodity price index. HAC standard errors are in parentheses.

Table 4. Generalized Taylor Rule: Restricted Specification

Parameter	1955–1979	1982–2003
(1)	(2)	(3)
Price level gap, α	0.043	0.369
	(0.043)	(0.072)
Inflation, β	0.135	0.185
	(0.109)	(0.097)
Output gap, γ	0.294	0.778
	(0.070)	(0.204)
Adjustment factor, δ	0.364	0.814
	(0.124)	(0.027)
Interest rate smoothing, ρ	0.736	0.177
	(0.102)	(0.105)
R^2	0.937	0.948
Durbin-Watson	1.986	1.546
S.E.E.	0.652	0.621
P-value for restriction	0.270	0.117

Notes: Dependent variable is quarterly average annualized federal funds rate. Estimates are from two-step GMM. Instruments include four lags of the output gap, inflation, federal funds rate, and log commodity price index. HAC standard errors are in parentheses. P-value is for the test of the restriction on coefficients in equation (19).

Table 5. Estimates of the Taylor Rules: Restricted versus Unrestricted Specifications

Parameter	Unrestricted specification, eq. (20)		Restricted specification, eq. (19)			Clarida, Gali and Gertler (2000), eq. (17)	
	1955–1979	1982–2003	Constraint	1955–1979	1982–2003	1955–1979	1982–2003
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
current inflation, π_t	0.004	0.051	β	0.135	0.185	0.169	0.209
	(0.058)	(0.107)		(0.109)	(0.097)	(0.055)	(0.079)
lagged inflation, π_{t-1}	0.046	0.176	$\alpha - \beta\delta$	-0.006	0.218		
	(0.040)	(0.061)		(0.066)	(0.106)		
Current output gap, x_t	0.407	0.760	γ	0.294	0.778	0.219	0.121
	(0.114)	(0.185)		(0.070)	(0.204)	(0.051)	(0.051)
Lagged output gap, x_{t-1}	-0.258	-0.559	$-\gamma\delta$	-0.107	-0.633		
	(0.087)	(0.148)		(0.118)	(0.029)		
1st lag of federal funds	1.196	0.948	$\delta + \rho$	1.100	0.991	0.969	1.167
	(0.083)	(0.106)		(0.145)	(0.108)	(0.103)	(0.096)
2nd lag of federal funds	-0.230	0.010	$-\delta\rho$	-0.268	-0.144	-0.180	-0.241
	(0.080)	(0.108)		(0.092)	(0.085)	(0.073)	(0.097)
R^2	0.929	0.948		0.937	0.948	0.936	0.947
Durbin-Watson	2.053	1.479		1.986	1.546	1.779	1.500
S.E.E.	0.697	0.627		0.652	0.621	0.655	0.622

Note: Dependent variable is quarterly average annualized federal funds rate. Columns (2)-(8) are estimated by two-step GMM.
Instruments include four lags of the output gap, inflation, federal funds rate, and log commodity price index. HAC standard errors are in
parentheses. Standard errors in columns (5) and (6) are computed by delta method. Overidentifying restriction test cannot reject validity
of instruments at any reasonable significance level.

Figure 1. Inflation Rate: Actual and Forecasted
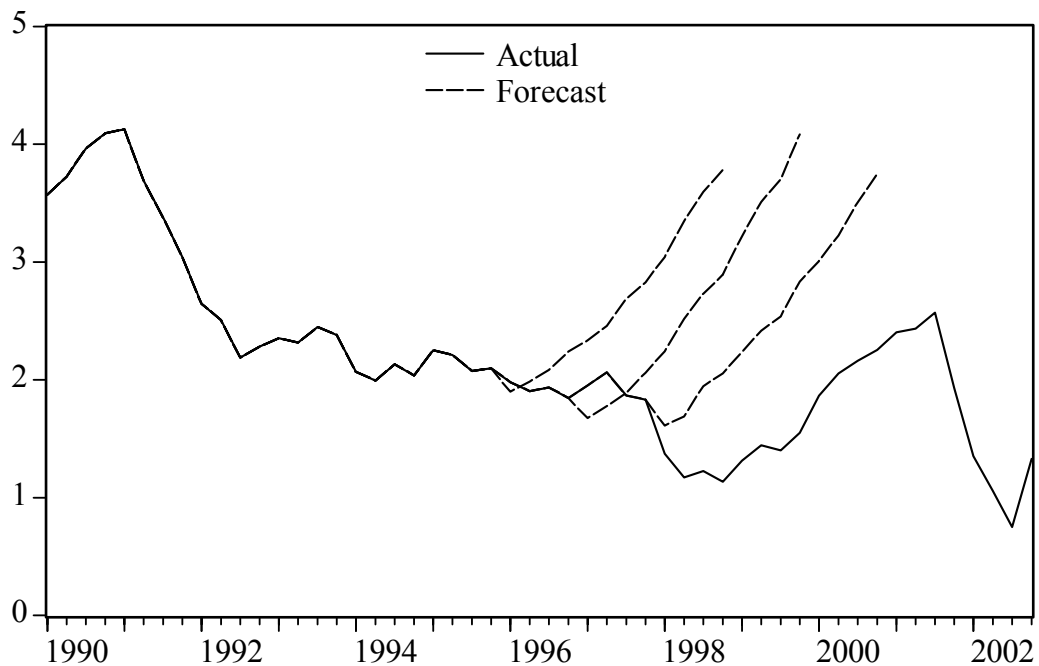
Notes: Solid line is the actual inflation rate (four quarter percent change in GDP deflator), dashed

line is its forecast based on a backward looking Phillips curve. The Phillips curve includes four

lags of inflation rate and deviation of unemployment rate (quarterly average) from real-time

estimate of NAIRU. Inflation rate is forecasted dynamically. The forecasts use real-time

deviation of unemployment rate from NAIRU.

Figure 2. Federal Funds Rate: Actual and Forecasted by the Taylor Rule
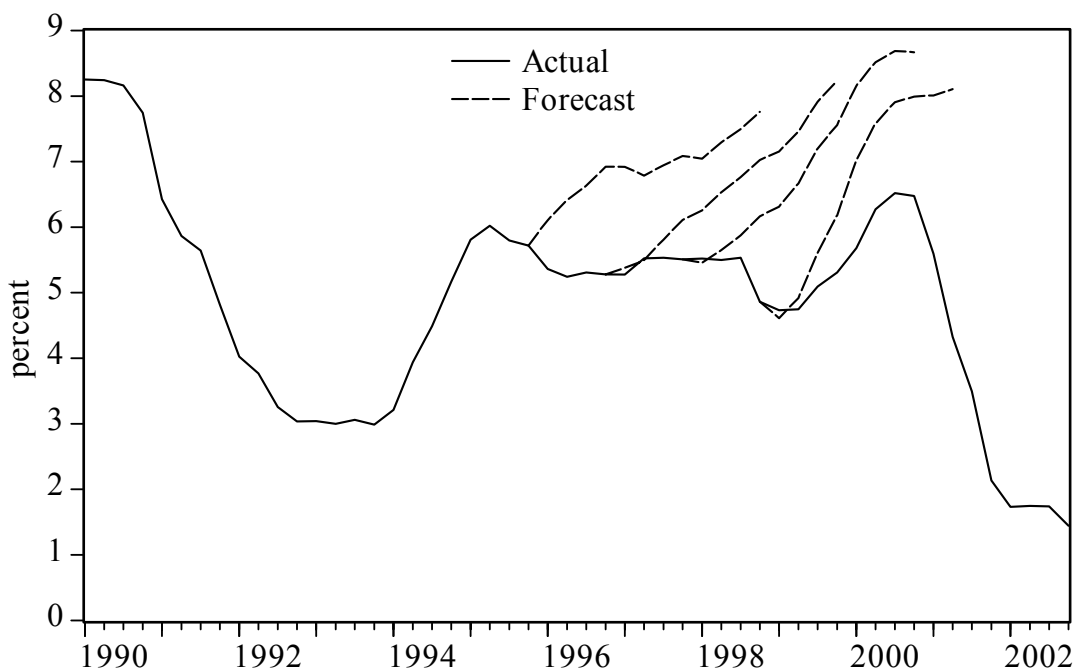
Notes: Solid line is the actual quarterly average annualized federal funds rate, dashed line is the predicted value. Dependent variable in the Taylor rule is quarterly average annualized federal funds rate. Taylor rule includes current unemployment rate, GDP deflator inflation rate and two lags of federal funds rate. Predictions are as of 1995:Q4, 1996:Q4, 1997:Q4, and 1998:Q4. These predictions use actual inflation and unemployment rates and the dynamic forecast of the federal funds rate based on the Taylor rule. Taylor rule is estimated by two-step GMM. Instruments are four lags of GDP deflator inflation rate, unemployment rate, federal funds rate, and log commodity price index.

Figure 3. Impulse Responses to a Permanent Innovation to Potential Output
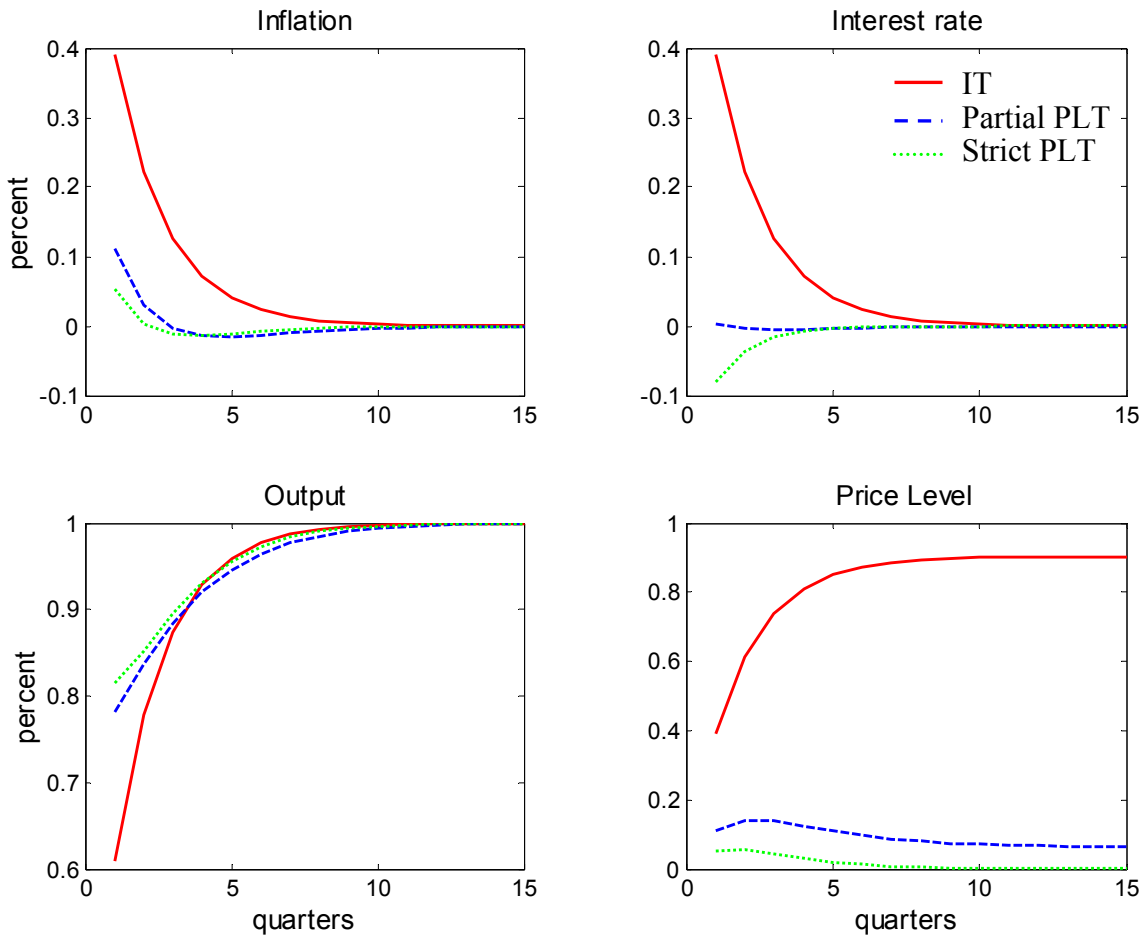
Notes: The figure shows percent deviations from steady state. Baseline calibration. The central banker observes potential output while the public does not. Shock to potential output is one percentage point. Solid line is inflation targeting (IT), dashed line is partial price level targeting (partial PLT), and dotted line is strict price level targeting (strict PLT). See text for details of parameter values.

Figure 4. Impulse Responses to a Permanent Innovation to Potential Output when a Fraction of Agents is Backward-Looking
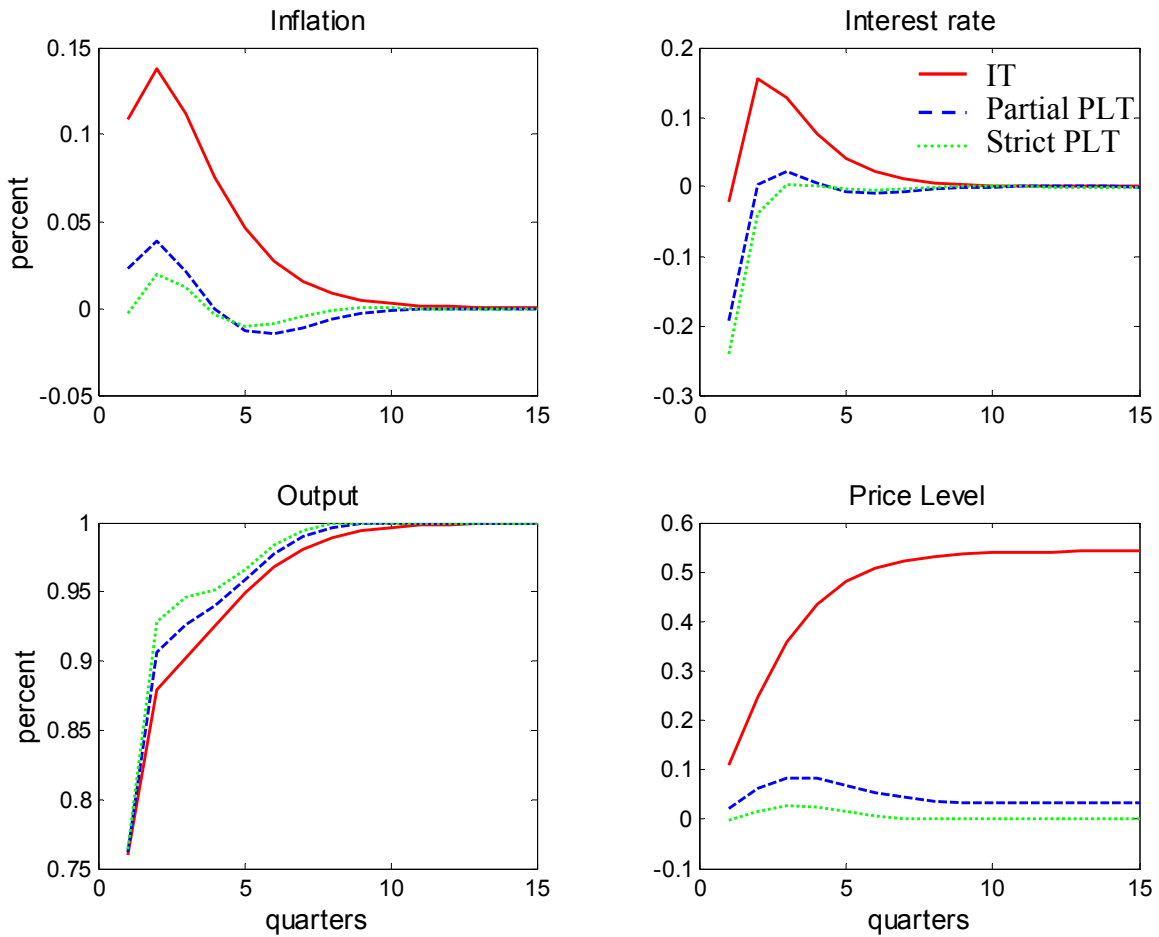
Notes: The figure shows percent deviations from steady state. The share of backward-looking agents is $\theta_1 = \theta_2 = 50\%$. Otherwise baseline calibration. The central banker observes potential output while the public does not. Shock to potential output is one percentage point. Solid line is inflation targeting (IT), dashed line is partial price level targeting (partial PLT), and dotted line is strict price level targeting (strict PLT). See text for details of parameter values.

Figure 5. Isoloss Maps: Forward-Looking Agents
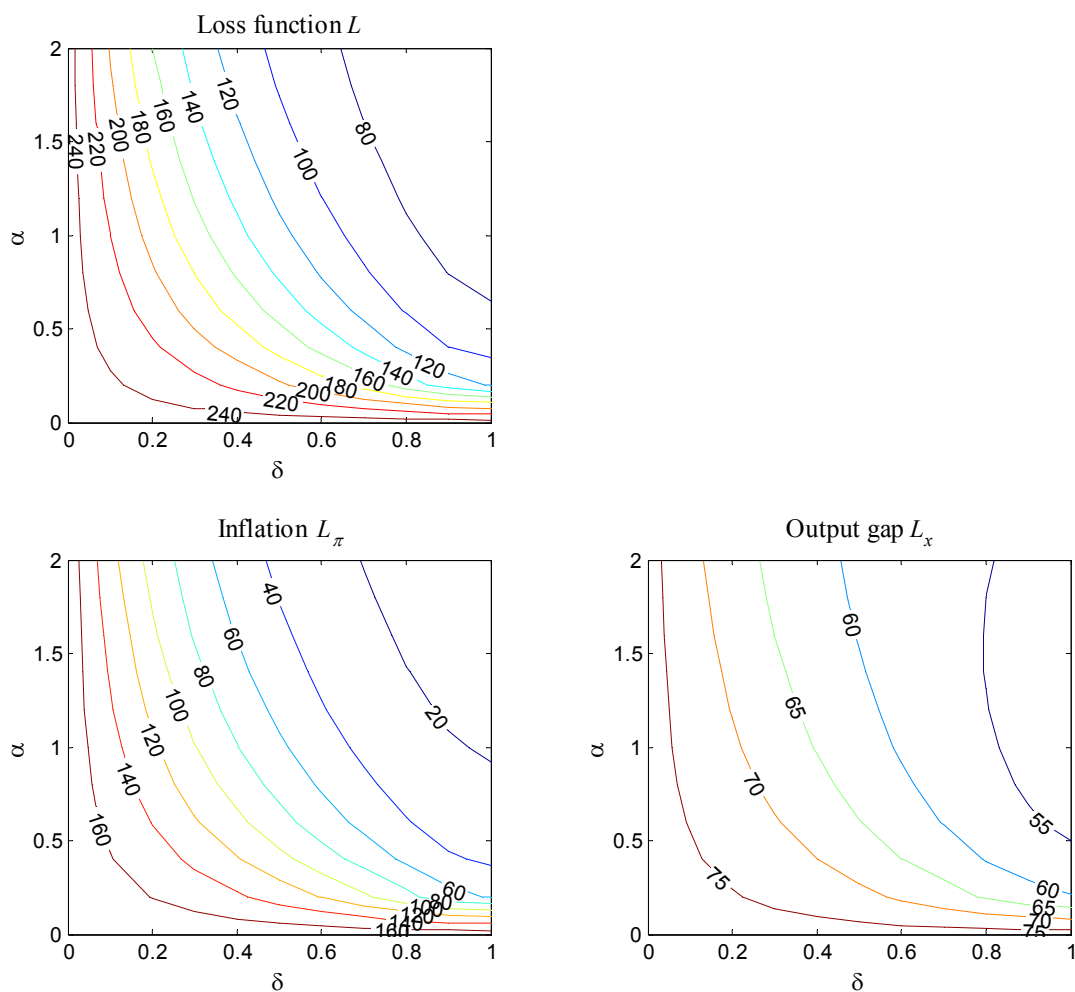
Note: The central banker observes potential output while the public does not. Baseline calibration:

$\gamma = 1,\ \omega_x = 1,\ \theta_1 = \theta_2 = 1,\ \lambda = 0.57,\ \Delta = 0.98,\ \rho = 0,\ \sigma = 1,\ \Lambda = 0.35$.

Figure 6. Isoloss Maps: Partially Backward-Looking Agents
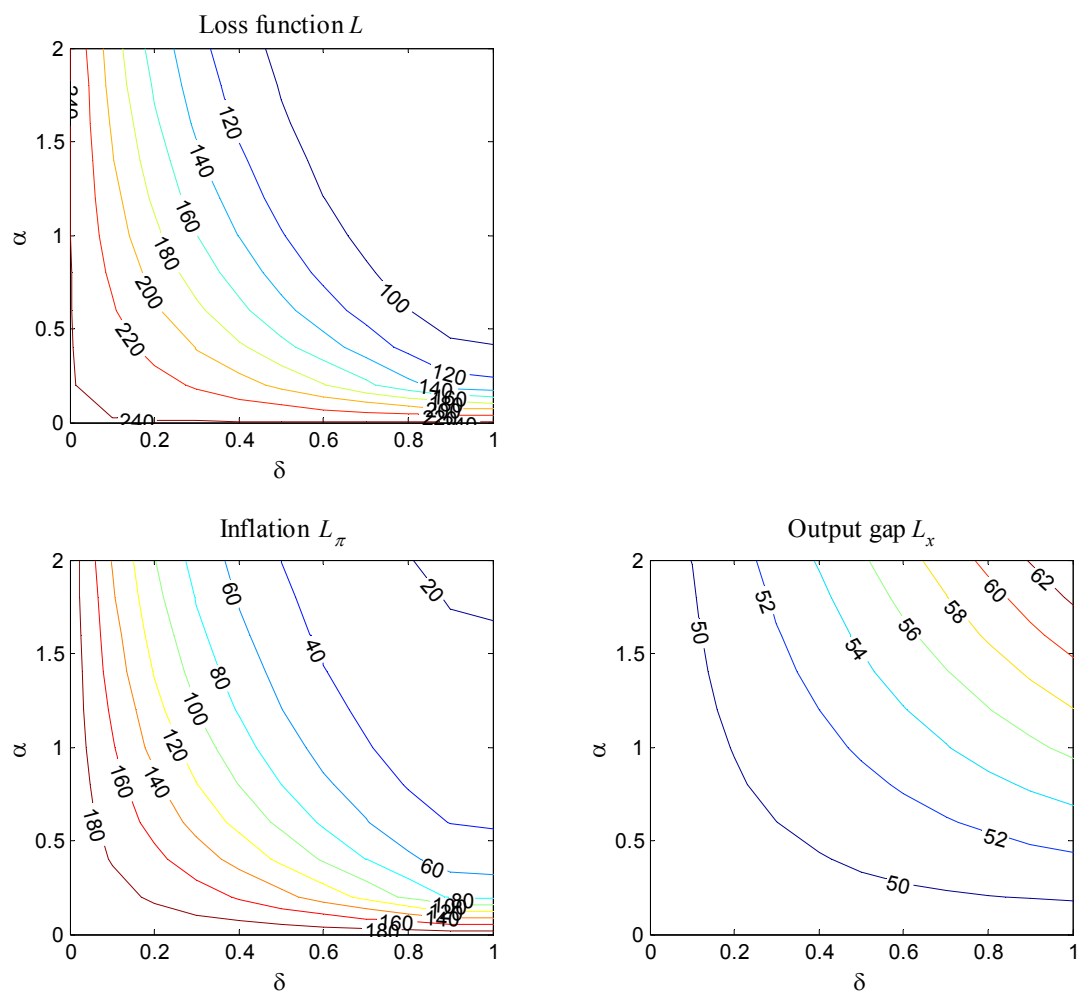
Note: The central banker observes potential output while the public does not. The share of backward-looking agents is 50%. Calibration: $\gamma = 1$, $\omega_x = 1$, $\theta_1 = \theta_2 = 0.5$, $\lambda = 0.57$, $\Delta = 0.98$, $\rho = 0$, $\sigma = 1$, $\Lambda = 0.35$.

Figure 7. Isoloss Maps: Interest Rate Smoothing
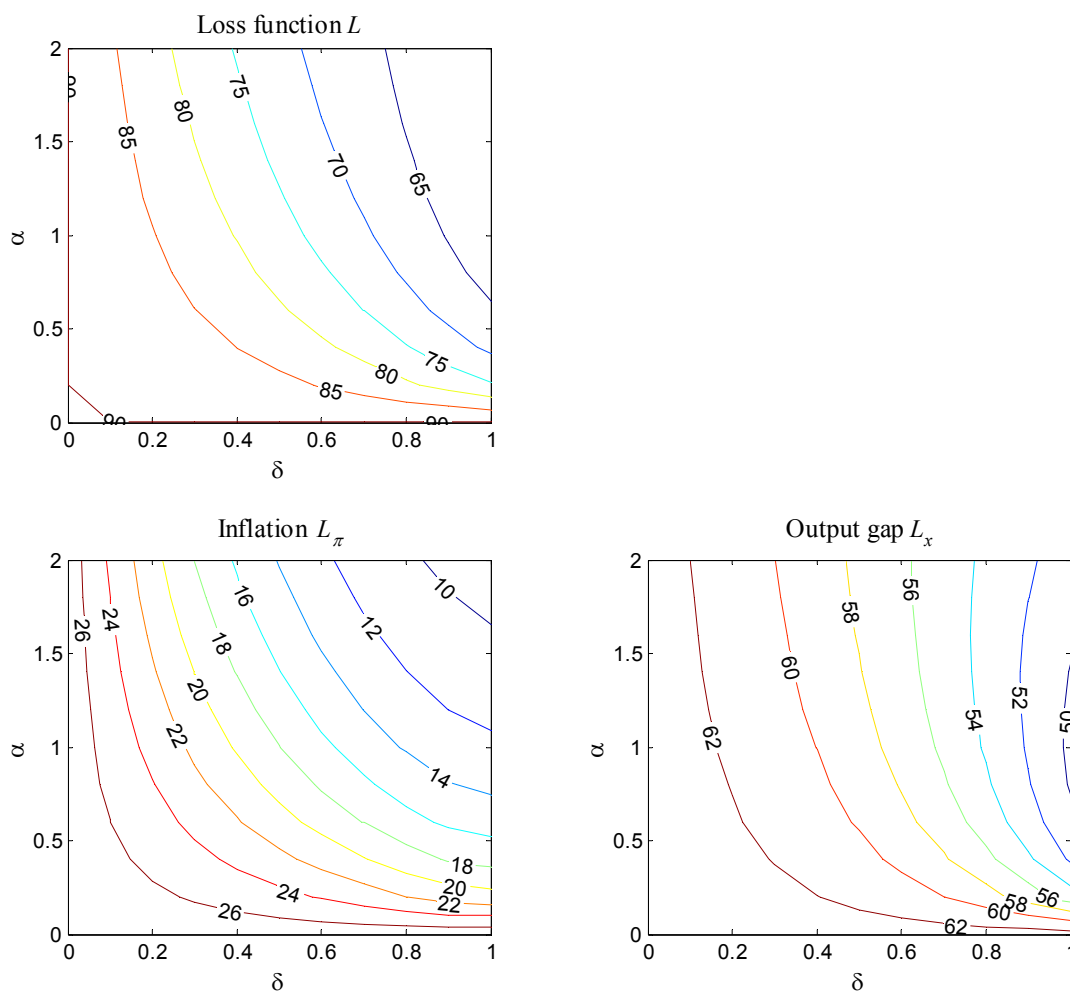
Note: The central banker observes potential output while the public does not. The interest rate smoothing parameter is $\rho = 0.9$. Calibration: $\gamma = 1,\ \omega_x = 1,\ \theta_1 = \theta_2 = 1,\ \lambda = 0.57,\ \Delta = 0.98,$ $\rho = 0.9,\ \sigma = 1,\ \Lambda = 0.35$.

Figure 8. Isoloss Maps: Potential Output is Perfectly Observable by All
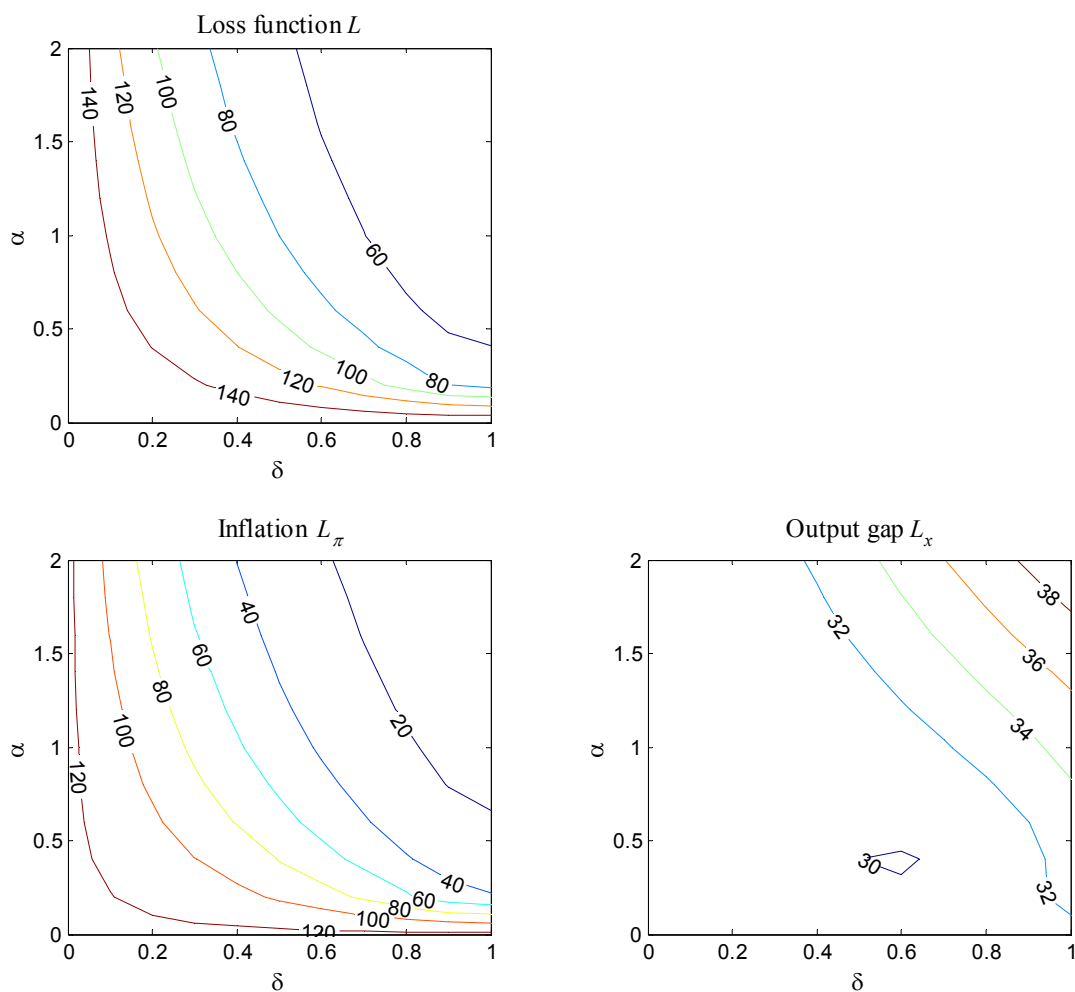
Note: The central banker and the public observe potential output. Baseline calibration:

$$\gamma = 1, \ \omega_x = 1, \ \theta_1 = \theta_2 = 1, \ \lambda = 0.57, \ \Delta = 0.98, \ \rho = 0, \ \sigma = 1, \ \Lambda = 0.35.$$

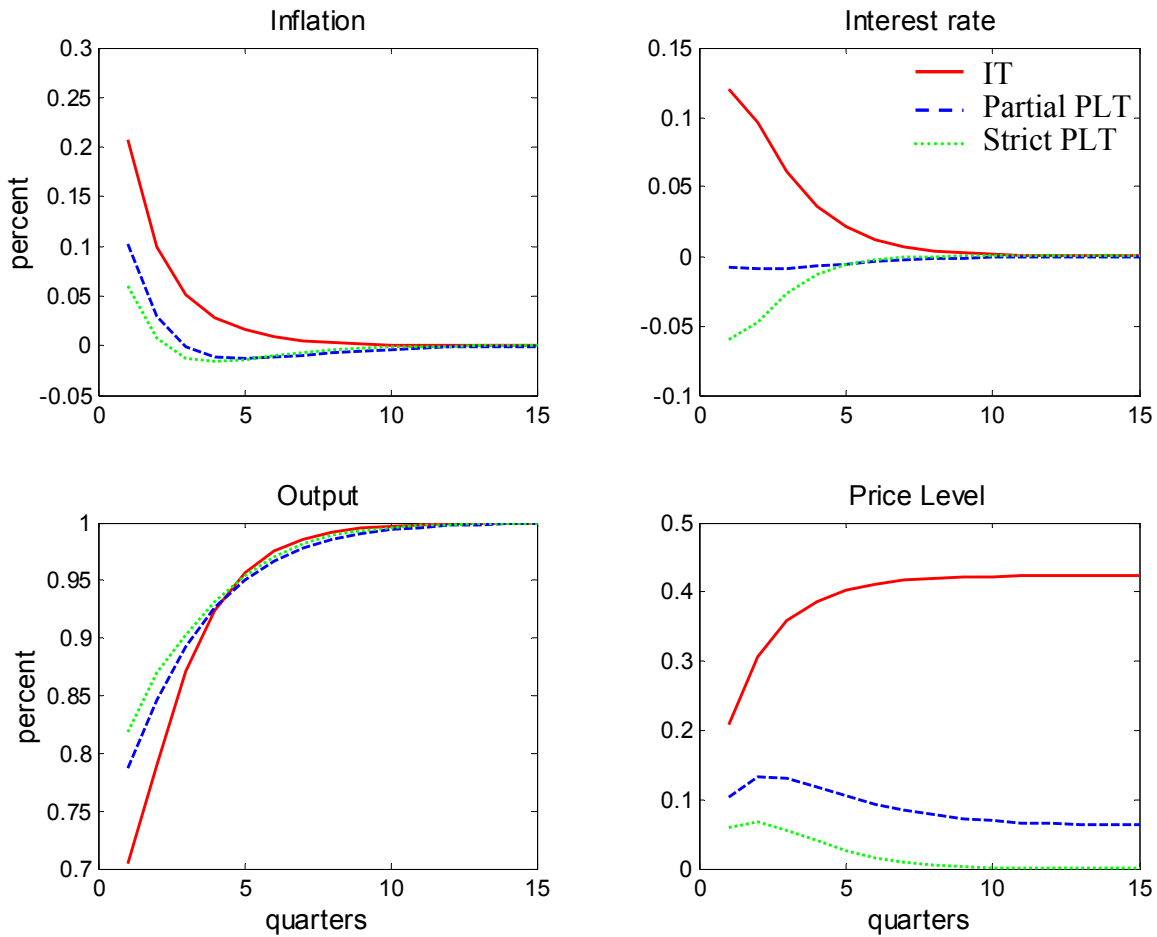Figure 9. Isoloss Maps: No Central Banker Informational Advantage
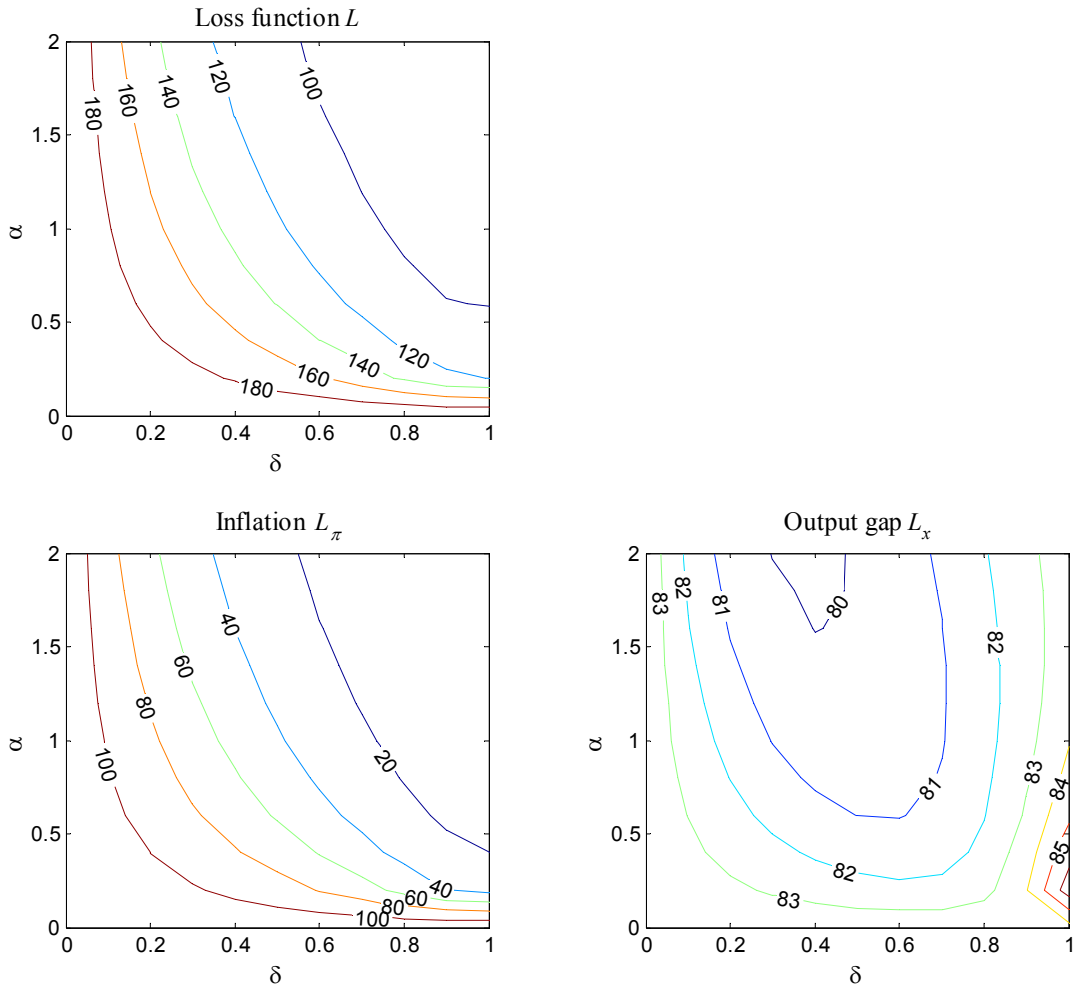
Note: Neither the central banker nor the public can observe potential output. Baseline calibration:

$\gamma = 1,\ \omega_x = 1,\ \theta_1 = \theta_2 = 1,\ \lambda = 0.57,\ \Delta = 0.98,\ \rho = 0,\ \sigma = 1,\ \Lambda = 0.35$.

Appendix B: Robustness checks

Figure A1. Impulse Responses to a Permanent Innovation in Potential Output when There Is Interest Rate Smoothing

Notes: The figure shows percent deviations from steady state. The interest rate smoothing parameter is $\rho_1 = 0.9$. Otherwise baseline calibration. The central banker observes potential output while the public does not. Shock to potential output is one percentage point. Solid line is inflation targeting (IT), dashed line is partial price level targeting (partial PLT), and dotted line is strict price level targeting (strict PLT). See text for details of parameter values.

Figure A2. Isoloss Maps: Sensitivity Analysis: Slope of the Phillips Curve
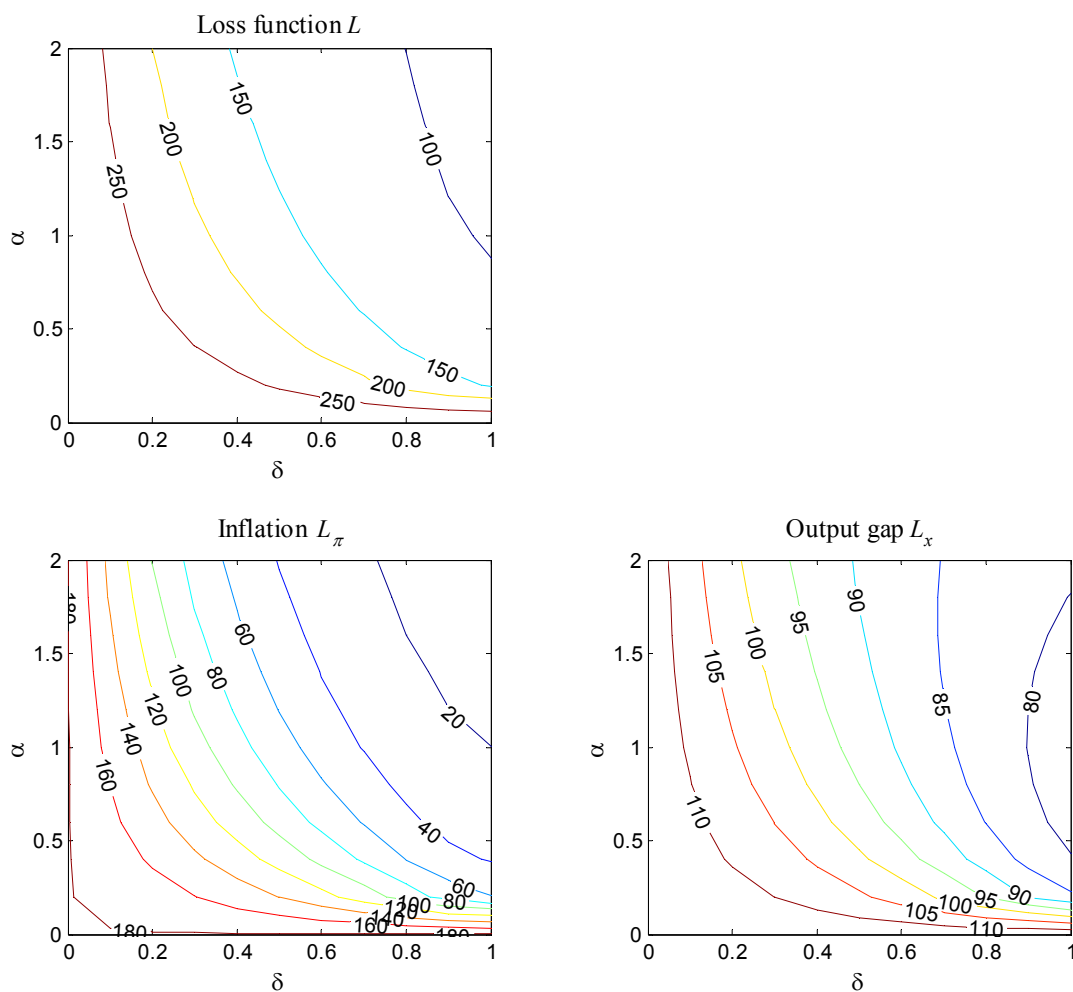
Note: The central banker observes potential output while the public does not. The slope of the

Phillips curve is $\Lambda = 0.25$ (baseline=0.35). Otherwise baseline calibration: $\gamma = 1$, $\omega_x = 1$,

$\theta_1 = \theta_2 = 1$, $\lambda = 0.67$, $\Delta = 0.98$, $\rho = 0$, $\sigma = 1$, $\Lambda = 0.25$.

Figure A3. Isoloss Maps: Sensitivity Analysis: Slope of the IS Curve
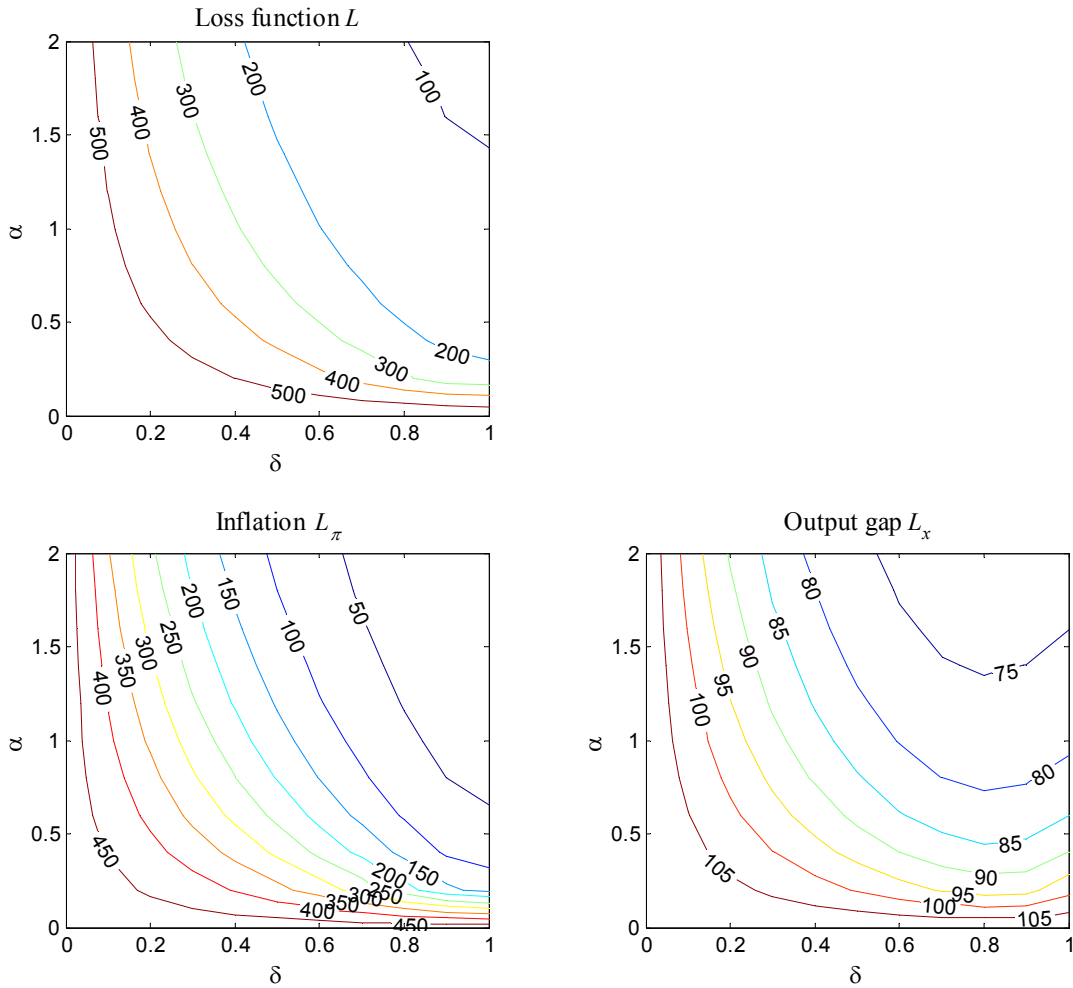
Note: The central banker observes potential output while the public does not. The slope of the IS curve is $1/\sigma = 0.5$ (baseline=1). Otherwise baseline calibration: $\gamma = 1$, $\omega_x = 1$, $\theta_1 = \theta_2 = 1$, $\lambda = 0.57$, $\Delta = 0.98$, $\rho = 0$, $\sigma = 2$, $\Lambda = 0.35$.

Figure A4. Isoloss Maps: Sensitivity Analysis: Signal to Noise Ratio
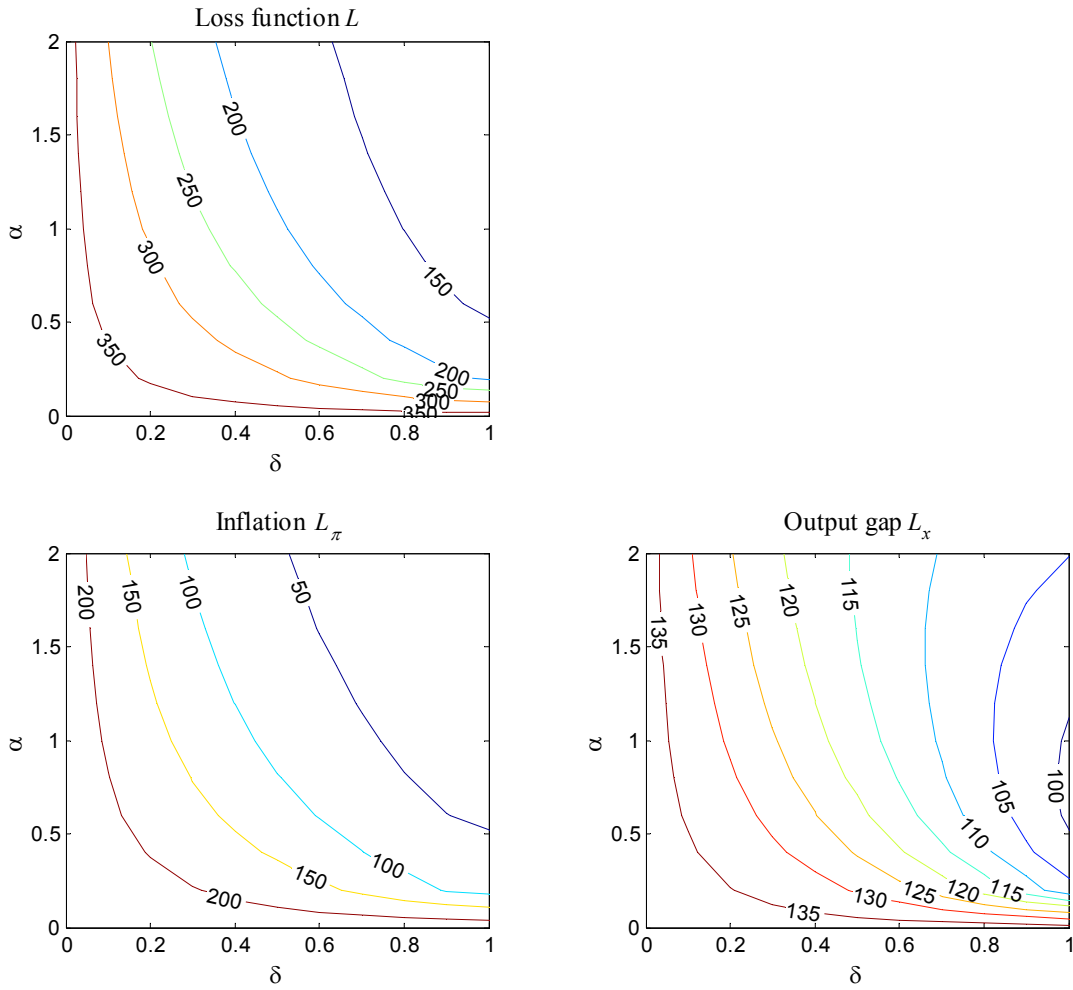
Note: The central banker observes potential output while the public does not. Signal to noise ratio $\sigma_T^2 / \sigma_P^2 = 1$ (baseline=0.34). Otherwise baseline calibration: $\gamma = 1$, $\omega_x = 1$, $\theta_1 = \theta_2 = 1$, $\lambda = 0.71$, $\Delta = 0.98$, $\rho = 0$, $\sigma = 1$, $\Lambda = 0.35$.