Inflation Persistence and the Taylor Principle

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Abstract

Although the persistence of inflation is a central concern of macroeconomics, there is no consensus regarding whether or not inflation is stationary or has a unit root. We show that, in the context of a "textbook" macroeconomic model, inflation is stationary if and only if the Taylor rule obeys the Taylor principle, so that the real interest rate is increased when inflation rises above the target inflation rate. We estimate Markov switching models for both inflation and real-time forward looking Taylor rules. Inflation appears to have a unit root for most of the 1967 – 1981 period, and is stationary before 1967 and after 1981. We find that the Fed's response to inflation is also regime dependent, with both the pre and post-Volcker samples containing monetary regimes where the Fed both did and did not follow the Taylor principle. This contrasts to recent research that suggests the Fed's response to inflation has been time invariant, and that changes in monetary policy only occurred with respect to the output gap

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1. Introduction

The persistence of inflation is a central concern of macroeconomics. In the New Keynesian macroeconomic model, with Taylor (1979) being among the earliest and best known examples, there is no tradeoff between the *level* of unemployment and the *level* of inflation, but there is a tradeoff between the *variability* of unemployment and the *persistence* of inflation.

The standard way to measure persistence in economic time series is through the autoregressive/unit root model. If the unit root null hypothesis can be rejected in favor of the alternative hypothesis of level stationarity, shocks will eventually dissipate and the series will revert to its equilibrium level. Conversely, if the unit root null cannot be rejected, shocks are permanent and the series never returns to its original value.

What do we know about unit roots and inflation? The answer is, not much. There have been a number of studies that test for unit roots in inflation, and the results are all over the map. In some of the studies, the unit root null is rejected in favor of the alternative of stationarity. In others, the unit root null cannot be rejected. In still others, the null can be rejected for some time periods, but not for others. Furthermore, there does not appear to be a clear pattern involving either time periods or techniques that accounts for the variety of results.

What could account for these inconclusive results? One possibility, of course, is that inflation is close enough to having a unit root that existent statistical techniques cannot conclusively answer the question. In that case, the answer itself becomes uninteresting. Whether inflation is stationary with an autoregressive coefficient of 0.999 or a unit root with a coefficient of 1.0 does not make any difference for the study of persistence over any economically relevant time horizon.

The purpose of this paper is to investigate a different, and potentially more interesting, hypothesis. Suppose that inflation is stationary during some time periods and follows a unit root during others. In particular, we will investigate the hypothesis that inflation switches regimes between stationary and unit root states. This would certainly be consistent with inconclusive results from the application of unit root tests.

The hypothesis of regime switching between stationary and unit root states seems problematic for most macroeconomic variables. The choice between stationarity and unit root behavior for real GDP is related to the predictions of various macroeconomic models, and it is difficult to see why the economy would follow one model during some regimes and a different model during others. While it is sometimes postulated that real exchange rates follow some variant of a threshold autoregressive process and exhibit unit root behavior for small deviations from parity and stationary behavior for large deviations from parity, this is based on arbitrage arguments do not seem applicable to inflation. Unit roots in financial variables such as nominal interest rates and nominal exchange rates are often justified based on information acquisition in markets, and it is difficult to see how these would be subject to regime switches across time.

The main idea of this paper is that inflation is a policy variable for which regime switching between stationary and unit root states emerges as a natural outcome of a standard macroeconomic model. We show that, in the context of a "textbook" model with an IS curve, a Phillips curve, and a Taylor rule, inflation will be stationary if and only if the central bank follows the Taylor principle and raises the nominal interest rate more than point-for-point when inflation exceeds the target inflation rate, so that the real interest rate rises.

The two hypotheses of the paper are that inflation can be characterized by regime switching between stationary and unit root states and that the regime switches can be explained by changes in the parameters of the Taylor rule. We first estimate a Markov switching model for quarterly U.S. inflation from 1954:3 to 2007:1. We find that there are two distinct inflationary regimes, one in which inflation has a unit root, and one in which inflationary shocks are transitory. The estimated dates for the unit root state are most of the 1967:3 – 1981:1 period, during which U.S. inflation experienced its highest levels. Beginning in 1981:2, when disinflation began, we estimate that the inflation rate is mean reverting.

We proceed to estimate a Markov switching model for a forward looking Taylor rule, utilizing various real-time inflation forecasts and measure of the output gap. We again find evidence of two separate regimes, where the Fed follows the Taylor principle in one state, but not the other. The dates for which monetary policy is stabilizing, so that the Taylor rule obeys the Taylor principle, correspond closely with the dates for which inflation is characterized by a stationary state. Conversely, the dates for which monetary policy is not stabilizing correspond closely with the dates for which inflation is characterized by a unit root state.

2. The Uncertain Unit Root in Inflation

There is a large literature that investigates unit roots in inflation. Table 1 summarizes the evolution of ideas about the stationarity of inflation in the empirical literature during the last three decades. While Nelson and Schwert (1977) and Barsky (1987) find evidence supporting the presence of a unit root in inflation, Rose (1988) rejects the unit root hypothesis and Neusser (1991) presents evidence, consistent with the stationarity of inflation, that the ex-post real interest rate is stationary. Baillie et al. (1996) find strong evidence of long memory with mean reverting behavior while Culver and Papell (1997) reject the unit root using panel, but not univariate, methods.

A number of studies (endogenously or exogenously) divide the series into sub-samples and examine their properties. For example, McCulloch and Stec (2000) argue that a unit root process governs the U.S. inflation series from the mid 1970's to the mid 1980's; before and after that time period, the U.S. inflation series is nearly stationary. Barsky (1987) divides the time span into two periods and shows that inflation was stationary until 1960 and became integrated thereafter. Brunner and Hess (1993) arrive at the same conclusion by also having 1960 as a threshold year.

More recent work tends to find fewer rejections of the unit root hypothesis. Ireland (1999) and Stock and Watson (1999) report some rejections of the unit root null, but only at the 10% level for some sub-samples. Bai and Ng (2001) and Henry and Shields (2003) cannot reject the unit root null for the U.S. inflation rate.

While the empirical literature on inflation is large, it is not conclusive. The overall impression is that the question of whether U.S. inflation contains a unit root or is stationary has not been answered, and is unlikely to be answered by the application of more unit root tests.

3. The Taylor Rule and Inflation

In this section, we construct a "textbook" macroeconomic model consisting of an IS curve, a Taylor rule, and a Phillips curve and show that inflation has a unit root if and only if the Taylor rule follows the Taylor principle.[1] Following Taylor (1993), the monetary policy rule postulated to be followed by the Fed is

$$r_t^* = \pi_t + \delta(\pi_t - \pi^*) + \omega\hat{y}_t + R^* \quad (1)$$

where r_t^* is the short-term nominal interest rate target (Federal Funds Rate), π_t is the inflation rate, π^* is the target level of inflation (usually considered equal to 2%), $\hat{y}_t$ is the percentage

[1] To our knowledge, the first textbook to present this "textbook" model was Hall and Taylor (1997).

deviation of output from its long run trend (the output gap), and R^* is the equilibrium level of the real interest rate (also usually considered equal to 2%).

According to the Taylor rule, the Fed raises the nominal interest rate if inflation rises above its target and/or if output is above potential output, and lowers the nominal interest rate if inflation falls below its target and/or if output is below potential output. The target level of output deviation from long run trend $\hat{y}_t$ is 0 because, according to the natural rate hypothesis, output cannot be permanently raised above potential. The target level for inflation is positive because it is generally believed that deflation is much worse for an economy than low inflation. According to what has become known as the "Goldilocks Economy" (not too hot, not too cold, but just right), if inflation equals its target of 2% and the output gap is zero, the nominal interest rate would be 4%, the inflation rate would be 2%, and the real interest rate would be 2%.

The parameters π^* and R^* can be combined into one constant term, which leads to the following equation,

$$r_t^* = \quad + (1+\delta)\pi_t + \omega\hat{y}_t \tag{2}$$

The condition $(1+\delta) > 1$, known as the Taylor principle, states that, when inflation rises above target, the Fed raises the nominal interest rate by more than point-for-point, so that the real interest rate rises. This has been emphasized by Taylor as the crucial condition for economic stability. Two aspects of the Taylor principle are worth noting. First, according to Taylor's (1993) original formulation, $\delta = \omega = 0.5$, so that the Taylor principle was automatically satisfied by the Taylor rule. Second, as emphasized by Greenspan (2004), the Taylor principle is essential to the conduct of monetary policy independently of the specific form of the Taylor rule. Suppose that ω was equal to zero, so that the Fed only responded to inflation and not to the output gap. The condition for the Taylor principle would be unchanged.

The textbook macro model is completed by adding an IS curve,

$$\hat{y}_t = -\sigma(R_t - R^*), \tag{3}$$

where the output gap depends negatively on the difference between the real interest rate and the equilibrium real interest rate, and a Phillips curve,

$$\pi_t = \pi_{t-1} + \lambda \hat{y}_t + \varepsilon_t \tag{4}$$

where inflation is above last period's inflation if the output gap is positive and below last period's inflation if the output gap is negative.[2]

Consider the following thought experiment. Start with inflation equal to its target level and the output gap equal to zero. Now suppose there is a positive shock to inflation. If the Taylor principle is satisfied, the Fed would raise the nominal interest rate in Equation (2) more than point-for-point, increasing the real interest rate. The increase in the real interest rate will lead to a negative output gap by the IS curve (3) and, in turn, to a decrease in inflation by the Phillips curve (4). The process will continue until inflation returned to its original, target, level. Since there is no long-run effect of the shock, inflation is stationary if the Taylor principle is satisfied.

Now consider the same shock to inflation if the Taylor principle is not satisfied. Suppose that $\delta = 0$. In this case, the Fed would raise the nominal interest rate in (2) exactly point-for-point, leaving the real interest rate unchanged. With an unchanged real interest rate, the output gap in (3) would stay at 0 and inflation in (4) would not be brought down. Since the effect of the shock never dissipates, inflation has a unit root if the Taylor principle is not satisfied.

4. A Markov Switching Model for Inflation

We first showed that the preponderance of empirical evidence does not support either stationarity or unit root behavior for the full sample of U.S. inflation. We then demonstrated that

[2] Additional lags of inflation can be added as long as they sum to unity so that the natural rate property is satisfied.

the hypothesis that inflation switches between stationary and unit root states is consistent with a "textbook" macro model if the policy followed by the Fed switches between following and ignoring the Taylor principle. We will now investigate whether the behavior of inflation is consistent with switching between stationary and unit root states.

To capture a possible switch in inflation persistence, we estimate a two state Markov Switching autoregressive model for the ex post inflation rate. Since we are focusing on persistence, we estimate an Augmented Dickey-Fuller representation with *k* lags, which is equivalent to an AR(k-1) model. The ADF specification is attractive since the sum of the AR coefficients minus one enters as the coefficient on lagged inflation:

$$\Delta\pi_t = \quad {}_{s_t} + \gamma_{s_t}\pi_{t-1} + \sum_{i=1}^{k}\psi_{s_t,i}\Delta\pi_{t-i} + \varepsilon_t \tag{5}$$

γ_{S_t} is the main parameter of interest. A negative and significant value of γ_{S_t} would imply a stationary inflation rate, while a value of zero would imply that inflation contains a unit root. The unobserved state variable takes on the values zero or one: $S_t = \{0,1\}$. We specify Gaussian innovations, with state dependent variances,

$$\varepsilon_t \sim N(0, \sigma^2_{S_g}),$$

where the unobserved state variable is governed by the following transition probabilities:

$$\Pr[S_t = 0 \mid S_{t-1} = 0] = q$$

$$\Pr[S_t = 1 \mid S_{t-1} = 1] = p\,.$$

To measure inflation, we use the ex post GDP deflator.[3] Our sample runs from 1954:3 – 2007:1. We maximize the exact log likelihood function using Hamilton's (1989) algorithm.

[3] Specifically, we calculate it as a difference between the quarterly seasonally adjusted annual rates of "GDP percent change based on current dollars" and "GDP percent change based on chained 2000 dollars" available from the BEA website at http://bea.gov/bea/dn/gdpchg.xls

We choose an AR(2) model for inflation, which corresponds to $k = 1$ in equation (5). We also estimated AR(1) through AR(5) models as a robustness check. The residuals from the AR(1) model display significant autocorrelation, while the results of higher order AR models are similar to those of the AR(2) model.

Our parameter estimates are presented in Table 1. Figure 1 plots the inflation rate, with the shaded areas corresponding to $S_t = 0$.[4] Our estimates suggest that there are two persistent states of inflation. State zero occurs from the beginning of the sample through 1959:3, and for most of the period from 1967:3 – 1981:1, which contains the so called Great Inflation. Inflation is generally high or growing in this state. We estimate inflation to be in state one from 1954:4 – 1967:2, briefly from 1975:2 – 1976:3, and then permanently beginning the 2nd quarter of 1981. All 3 of these subsamples are periods where inflation is low and/or falling. The volatility of inflation, as measured by the estimated standard deviation, is nearly twice as large in the higher inflation state.

Since inflation the level and growth rate of inflation appear to be regime dependent, we now turn to the question of whether or not the persistence of inflation varies across these 2 regimes. Our parameter estimates suggest that inflation was unstable in state zero. γ_0 is statistically insignificant, which is consistent with a unit root in inflation. In addition, γ_1 is negative and significant, which implies that inflation is stationary in state one. Thus, our results are consistent with inflation switching between stationary and unit root states, where the states correspond to periods of low or high inflation.

For our real time Taylor rule estimates in the following section, our sample begins in 1965:4. Thus, we also estimate a Markov Switching AR(2) for inflation for the 1965:4 – 2007:1

[4] Throughout the paper, we compute smoothed probabilities of being in state zero or one.

subsample. The parameter estimates are also reported in Table 1. The message for this subsample is identical to that of the full sample. State zero lasts through the 1970s, again with the exception of the 1975:2 – 1976:3 period where inflation briefly fell, and the switch to state one occurs in 1981:2. As with the full sample, the estimated values of γ_{S_t} imply that inflation has a unit root for most of the Great Inflation period, and switched to a stationary process in the early 1980s.

5. A Markov Switching Model for the Taylor Rule

5.1 Model

Our goal in this section is to test whether the hypothesis that inflation switches between stationary and unit root regimes is consistent with a "textbook" macro model if the policy followed by the Fed switches from satisfying to not satisfying the Taylor principle. We first demonstrate that our estimates from a Markov switching Taylor rule suggest two separate regimes. We then determine that the Taylor rule parameter, δ, in equation (1) is indistinguishable from zero in one of the regimes and significantly positive in another. Finally, we illustrate how closely the relationship between the periods characterized by the state where the Taylor principle is not satisfied coincides with the periods where inflation is characterized by a unit root.

Before proceeding with the estimation, we modify equation (2) in accordance with previous research on the Taylor rule. We consider forward looking Taylor rules, so that the Fed's interest rate target responds to expectations of current and future inflation:

$$r_t^* = \quad + (1+\delta) E_t \pi_{t+h} + \omega \hat{y}_t \qquad (2)'$$

where $E_t \pi_{t+h}$ is the expectation of the inflation rate at time $t+h$ formed at time t. Rather than making an instantaneous adjustment of the Federal Funds Rate towards its target level, the Fed tends to smooth changes in the interest rate. As is common practice, we assume AR(1) smoothing, so that the actual Federal Funds Rate r_t is the following function of its target level r_t^*:

$$r_t = (1-\rho)r_t^* + \rho r_{t-1} + \varepsilon_t \tag{6}$$

where ρ is the degree of smoothing. The more instantaneous the response to the shocks, the more ρ tends to zero. Substituting (2)' into (6) and allowing the parameters to switch between the two regimes, we get the following two state specification for the nominal interest rate:

$$r_t = (1-\rho_{S_t})\left\{ \ {}_{S_t} + (1+\delta_{S_t})E_t\pi_{t+h} + \omega_{S_t}\ \hat{y}_t \right\} + \rho_{S_t} r_{t-1} + \varepsilon_t\,. \tag{7}$$

Sims and Zha (2006) argue that if the variance is assumed to be constant, one may find spurious structural change in the slope coefficients in monetary policy rules. We allow the Gaussian errors to be heteroskedastic to sidestep this problem.

5.2 Data

Our real time inflation forecasts come from the Greenbook dataset, which is available from the Philadelphia Fed website.[5] The Greenbook forecasts are published with a five year lag, and as of the writing of this paper, end in 2001:4. We extend the Greenbook forecasts through 2007:1 by splicing it with inflation forecasts from the Survey of Professional Forecasters (SPF).[6] The inflation forecasts are predictions of the annualized quarter-over-quarter growth rate of the GNP/GDP price level. To estimate a Taylor rule, we need year-over-year inflation rate forecasts. We thus transform the Greenbook/SPF data by taking the average of four consecutive quarter-over-quarter forecasts. We then have $E_t\pi_{t+h}$ for h = 0, 1,…, 4. Since inflation at time t is not available in real time, $h = 0$ is a forecast of current inflation, or a "nowcast." It is based on four

[5] http://www.philadelphiafed.org/econ/forecast/greenbook-data/phila-data-set.cfm
[6] http://www.philadelphiafed.org:80/econ/spf/index.cfm

quarterly forecasts, from $t-3$, $t-2$, $t-1$, and *t*, the first three of which are actual realized values of inflation. For $h=2$, $E_t\pi_{t+2}$ is the average of $t+2$ and $t+1$ forecasts, the time *t* nowcast, and the $t-1$ realized inflation rate. Only the $h=3$ and $h=4$ year-over-year inflation forecasts are based entirely on unrealized values of inflation. The starting dates for the Greenbook inflation forecasts are 1965:4 for $h=0$ and $h=1$ and 1968:4, 1973:2, and 1974:2 for h = 2, 3, and 4 respectively.

For the output gap, we first consider the real-time measure used by Orphanides (2004), which is based in part on estimates from the Council of Economic Advisors and the Commerce Department. Orphanides' data ends in 1998:4. We update the output gap series through 2007:1 using OECD real-time output gap estimates which are published in the OECD *Economic Outlook*. We convert the annual estimates to quarterly data using quadratic interpolation.

5.3 Empirical Results

We estimate Equation (7) using Hamilton's (1989) algorithm for the nowcast and forecasts of inflation. We use the average Federal Funds Rates of the final month of the quarter as our nominal interest rate. We allow the constant term (and hence the implied inflation target), as well as the coefficient on expected inflation and the output gap, the interest rate smoothing parameter, and innovation variance, to be regime dependent. We assume an equilibrium real interest rate of 2.5%.

Our results are reported in Table 2. Figure 2 plots the Fed Funds Rate, the nowcast of inflation, and the real-time measure of the output gap. The shaded area corresponds to $S_t = 0$. The parameter estimates and estimated state distributions are consistent across the five inflation forecasts. We estimate that what will be seen as the destabilizing Taylor rule state, state zero, occurs from 1973:1 – 1975:1 and again from 1979:4 – 1985:3. State one occurs from the beginning of the sample through 1972:4, from 1975:2 – 1979:3, and again from 1985:4 through the end of the sample.

In state zero, the coefficient on inflation, δ, is insignificant for every inflation forecast. The Fed was not raising the nominal interest rate more than point for point in response to higher inflation. Indeed, as is visually evident in Figure 2, the Taylor principle was not satisfied during the shaded periods. There were a number of times when the nominal interest rate fell as inflation rose. This probably explains why the estimates of δ are all negative in state zero, albeit insignificant.

In contrast, state one implies a significant and positive value of δ for every inflation forecast, suggesting that the Fed followed a stabilizing Taylor rule. $\hat{\delta}_1$ ranges from 0.91 to 1.11, which implies that the Fed was keeping inflation in check by increasing the nominal interest rate by around 2 percentage points when inflation increased 1 percent.

How do we reconcile the timing of our Taylor rule regimes with the univariate inflation results from the previous section? Recall that we estimate inflation to be an unstable (unit root) process for most of the 1970s, except for the six quarter 1975:2 – 1976:3 subsample, and to be stable beginning in 1981:2. This timing is certainly related to the timing of our estimate states for the Taylor rule, but not exact. In particular, we estimate that the 1975:2 – 1979:3 period is characterized as a stabilizing Taylor rule state, even though our univariate inflation estimates from the previous section suggest inflation contains a unit root in the latter half of this subsample. Monetary policy during the four years prceding Paul Volcker's tenure is not generally regarded as being consistent with a stabilizing Taylor rule. However, while inflation was rising during this period, the Fed Funds rates was in fact rising by more than point for point.

We also estimate that the Taylor rule was destabilizing from 1979:4 – 1985:3. This is of course the period during which Paul Volcker lowered inflation. This disinflation came about via targeting nonborrowed reserves, not through an explicit interest rate target. Indeed, while disinflation occurred through most of this period, nominal interest rates were quite erratic, experiencing their highest levels and largest volatility. We would surely not expect our estimates to suggest that the Fed was pulling down inflation via the increasing the Fed Funds rate. Finally, beginning in 1985:4 and lasting through the rest of the sample, we estimate that the Taylor principle held. This is the time frame of what has come to be permanently lower inflation. The switch to this state accords with the beginning of the Great Moderation.

Turning to the output gap, we find that the Fed increased the nominal interest rate when output was above capacity when the Taylor principle held, and with $h = 4$ as the only exception, ignored the output gap when they did not follow the Taylor principle. We will return to this point after discussing alternative measures of the output gap.

We find that there is much more interest rate smoothing in the stable Taylor rule state. The typical $\hat{\rho}$ is state zero is about 0.5, compared to around 0.8 when the Fed follows the Taylor principle. Not surprisingly, the estimated innovation standard deviation is about 4 times larger in state zero than in the stable state one. We also report estimates of the implied inflation target, π^*. When the Fed was actively targeting inflation via changes in the Fed Funds rate, we get estimates of π^* between 2% and 2.5%. In contrast, when the Fed does not follow the Taylor principle, the estimates of π^* range from 21% to 35%. These numbers are so large that they suggest to the authors that the Fed did not have a target level of inflation.

Taylor (2000) has suggested that the real-time output gap from Orphanides (2004) that we utilize in Table 2 was affected by political influence. There is also evidence that Fed Chairman

Burns and then CEA-Chairman Greenspan did not place a large weight on this output gap measure in forming policy decisions.[7] For these reasons, we consider two alternative real-times measures of the output gap based on quadratic detrending, which has become a fairly standard method of constructing an output gap for Taylor rules. We construct our first output gap as deviations from a quadratic trend, with a rolling window of 20 years. We also compute recursive deviations from a quadratic trend. For both output gaps, the observation at time t uses data up through time $t-1$, so that both measures are available to the policy maker in real time.

We present our parameter results for the rolling and recursive output gaps in Tables 3 and 4 respectively. Figure 3 and 4 plot the Fed Funds rate, output gap, and the nowcast of inflation, again with shaded areas corresponding to $S_t = 0$. The timing of the state distribution for the Taylor rule remains unchanged. Qualitatively, the parameter estimate convey the same message as Table 2. For every inflation forecast, $\hat{\delta}$ is insignificant in state zero, and positive and significant in state 1. For the rolling window output gap, the estimates of $(1+\delta)$ are closer to Taylor's (1993) value of 1.5 than we see in Table 2. They range from 1.49 to 1.80. For the recursive output gap, $(1+\hat{\delta})$ ranges from 1.77 – 1.87 for h = 0, 1, and 2. For h = 3 and 4, $(1+\hat{\delta})$ is 2.45 and 2.65 respectively. These estimates for the longer horizons are quite high, and the standard errors on $\hat{\delta}$ are more than twice as large as the lower horizons, which probably reflects the shorter samples for h = 3 and 4.

In terms of the output gap, the results are qualitatively identical to Table 2. The Federal Reserve ignored the output gap when it was not following a stabilizing Taylor rule, and raised/lowered the nominal interest rate when output was above/below its estimated potential in

[7] See Cecchetti et al. (2007) for further discussion.

the stable Taylor rule state. The parameter estimates for the interest rate smoothing coefficient and the innovation standard deviation display no significant differences from Table 2.

5.4 The View from the Trenches

It is useful to compare our results to Orphanides (2004). Using data from 1965:4 – 1995:4, he estimates forward looking Taylor rules for $h = 1 - 4$.[8] He splits the sample into pre and post-Volcker periods, with the change occurring between 1979:2 and 1979:3. He concludes that there was no significant change in the Fed's response to inflation before and after Volcker: in both regimes the Fed was estimated to have followed a stabilizing Taylor rule. $(1+\delta)$ is estimated to be around 1.5 pre-Volcker, and around 2.0 after 1979:3. The one significant change he finds is with respect to the output gap: the Fed responded to deviations of output from its potential before, but not after Volcker became Chair.

Our two main results, the change in the Federal Reserve's response to inflation and the output gap, and their correspondence to the stability of inflation, are noticeably different from Orphanides' findings. Orphanides splits his sample after 1979:2. While this is an intuitive break date, it is chosen exogenously, and implies only two regimes. Our results suggest that when the break date is endogenized via Markov switching, that each of Orphanides' "regimes" contains periods where the Federal reserve both did and did not follow the Taylor principle. We find not only did the Federal Reserve change their response to inflation throughout the entire sample, but that the timing of these changes in not simply pre and post Volcker. Indeed, for the Volcker years, we conclude that it was not until he had less than two years remaining in his term that monetary policy permanently switched to a stabilizing Taylor rule. This starkly contrasts with the conclusion that $(1+\delta) > 1$ for the entire sample.

[8] He uses AR(2) smoothing in the published version, although AR(1) smoothing in a working paper verison leads to the same conclusions.

While Orphanides concludes that the response to the output gap is regime dependent, we find that the regime dependence is a function of whether or not the Fed is trying to stabilize inflation, not whether or not Paul Volcker had yet taken office.

To determine if the difference between our results and Orphanides (2004) is due to endogenizing the timing of the regime switches, or merely an artifact of using a larger sample, we re-estimate our Markov switching Taylor rule for Orphanides' sample ending in 1995:4. The parameter estimates are reported in Table 5, and Figure 5 plots the data and estimated state distribution. The estimated dates of the unstable state are identical to those of the full sample. For every inflation forecast, the estimated value of δ is insignificant in state zero and significant in state one, with $(1+\hat{\delta})$ around 1.5. As in Table 2, which is identical to Table 5 save for the end date, we find that the output gap coefficient is only significant in the stable Taylor rule state (again with $h = 4$ as the exception). Since we are using the exact same data as in Orphanides (2004), we are left with the conclusion that Orphanides' (2004) claim that the Federal Reserve has not changed its response to inflation since 1965 is the result of assuming that the date of a possible regime change coincided with Paul Volcker taking over as Chairman of the Fed.

6. Conclusions

The purpose of this paper is to investigate the relationship between the conduct of monetary policy and the persistence of inflation. We first show that, in the context of a "textbook" macroeconomic model with an IS curve, a Phillips curve, and a Taylor rule, inflation will be stationary if and only if the Taylor rule obeys the Taylor principle so that the real interest rate is increased when inflation rises above the target inflation rate. Since there is no reason to presume that monetary policy is either always stabilizing or always not stabilizing, it is plausible to think that inflation might switch from stationary to unit root behavior.

We proceed to estimate a Markov switching model for inflation, and show that inflation is best characterized by two states, one stationary and the other with a unit root. The unit root state spans most of the period from the 1967 – 1981, and inflation appears stable beginning in 1981:2. Finally, we estimate a Markov switching model for various real-time forward looking Taylor rules. The estimated Taylor rule equation switches between states where the Fed does and does try to stabilize inflation by following the Taylor Principle. We find that the pre and post-Volcker subsamples each contain multiple Taylor rule regimes. In particular, for most of Volcker's tenure at the Fed we find that the Fed did not follow a Taylor rule, but switched to a stabilizing Taylor rule state in 1985:4, which has endured to the present. This is in contrast to previous research which has suggested that the Fed's response to inflation has been time invariant.

References

1. Andrews, Donald W. K. "Exactly Median-Unbiased Estimation of First Order Autoregressive/Unit Root Models" *Econometrica*, Vol. 61, No. 1. (Jan., 1993), pp. 139-165
2. Bai, Jushan and Ng, Serena (2004) "A PANIC Attack on Unit Roots and Cointegration" *Econometrica*, April 2004, 1127-1177
3. Baillie, Richard T, Chung, Ching-Fan, Tieslau, Margie A "Analysing Inflation by the Fractionally Integrated ARFIMA-GARCH Model" *Journal of Applied Econometrics*, 1996 Issue 1, 23-40
4. Barsky, R.B. "The Fisher Hypothesis and the Forecastibility and Persistence of Inflation" *Journal of Monetary Economics*, 19, 3-24
5. Brunner, Allan D. and Hess, Gregory D. "Are Higher Levels of Inflation Less Predictable? A State-Dependent Conditional Heteroscedasticity Approach" *Journal of Business and Economic Statistics*, April 1993, Vol. 11, No 2
6. Clarida, Richard, Gali, Jordy, and Gertler, Mark "Monetary Policy Rules in Practice: Some International Evidence" *European Economic Review*, Vol. 42 (June 1998): 1033-1067
7. Culver, Sarah E and Papell, David H "Is There a Unit Root in the Inflation Rate? Evidence from Sequential Break and Panel Data Models" *Journal of Applied Econometrics*. 1997, Issue: 4 Pages: 435-44
8. Evans, Martin and Wachtel, Paul "Inflation Regimes and the Sources of Inflation Uncertainty" *Journal of Money, Credit and Banking*, Vol 25, No. 3 (Aug. 1993), 475-511
9. Garcia, René "Asymptotic Null Distribution of the Likelihood Ratio Test in Markov Switching Models" Aug. 1998, *International Economic Review*, Vol. 39, No. 3, 763-788
10. Greenspan, Alan "Risk and Uncertainty in Monetary Policy" AEA Papers and Proceedings, May 2004
11. Hall, Robert and Taylor, John (1997) "*Macroeconomics*", 5th edition, (New York: WW Norton)
12. Hamilton, James D "A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle" *Econometrica*, 1989 Vol. 57 (2).
13. Hansen B. E. "The Likelihood Ratio Test Under Nonstandard Conditions: Testing the Markov Switching Model of GNP" *Journal of Applied Econometrics*, Vol. 7, Dec. 1992
14. Henry, Ólan T. and Shields, Kalvinder "Is There a Unit Root in Inflation?" *Journal of Macroeconomics*, March 2004, 481-500
15. Inoue, Atsushi and Kilian, Lutz "How Useful is Bagging in Forecasting Economic Time Series? A Case Study of U.S. CPI Inflation" CEPR Discussion Paper No. 5304, October 2005
16. Ireland, P. (1999), Does the Time-Consistency Problem Explain the Behavior of Inflation in the United States, *Journal of Monetary Economics* 44:2, 279–293.
17. Lahiri, S. N., "Theoretical comparisons of block bootstrap methods" 1999, *Annals of Statistics*, 27, 386-404
18. Marriott, F.H.C. and Pope, J.A. "Bias in the Estimation of Autocorrelations" 1954, *Biometrics*, 41, 390-402

19. McCulloch, Huston and Stec, Jeffery A. "Proxying Inflation Forecasts With Fuller/Roy-Type Median Unbiased Near Unit Root Coefficient Estimates" *Computing in Economics and Finance* 2000
20. Murray, Christian and Charles R. Nelson, "The Great Depression and Output Persistence," 2002, *Journal of Money, Credit and Banking*, 34, 1090-1098.
21. Nelson, Charles R, and Schwert, G William (1977) "Short-Term Interest Rates as Predictors of Inflation: On Testing the Hypothesis That the Real Rate of Interest is Constant", *AER* 1977: 3, 478-86
22. Neusser, Klaus "Testing the long-run implications of the neoclassical growth model" *Journal of Monetary Economics*. 1991, Issue 1, 3-37
23. Ng. S., and P. Perron, "Unit Root Tests in ARMA Models with Data-Dependent Methods for the Selection of the Truncation Lag," *Journal of the American Statistical Association* 90, (1995), 268-281
24. Orphanides, Athanasios, "Monetary Policy Rules Based on Real-Time Data." *American Economic Review*, September 2001, 91(4), pp. 964-985.
25. Orphanides, Athanasios, "Activist Stabilization Policy and Inflation: The Taylor Rule in the 1970s" (November 2002). CFS Working Paper No. 2002/15
26. Rose, Andrew "Is the Real Interest Rate Stable?" *Journal of Finance*. Volume 43, Issue 5 Pages: 1095-1112
27. Rudebusch, G.D., "The Uncertain Unit Root in Real GNP," *American Economic Review* 83 (1993), 264-72
28. Shaman, P., and R. Stine (1988), "The bias of autoregressive coefficient estimators," *J. Am. Statist. Assoc*., 83, 842-848
29. Simon, John "A Markov Switching Model of Inflation in Australia" Reserve Bank of Australia, Discussion Paper 9611, Dec. 1996
30. Sims, Christopher A. and Zha, Tao (2006) "Were There Regime Switches in U.S. Monetary Policy?" American Economic Review, American Economic Association, vol. 96(1), pages 54-81, March.
31. Stock, James H. and Watson, Mark W., 1999. "Forecasting Inflation," *Journal of Monetary Economics*, Elsevier, vol. 44(2), pages 293-335
32. Taylor, John (1979) "Staggered Wage Setting in the Macro Model," *American Economic Review*, May, 108-113.
33. Taylor, John (1993) "Discretion Versus Policy Rules in Practice," Carnegie-Rochester Conference Series on Public Policy, 39: 195-214.
34. Taylor, John (1999) "A Historical Analysis of Monetary Policy Rules," in John Taylor, ed., *Monetary Policy Rules*, (University of Chicago Press), 319-347.
35. Vogel , Richard M. and Shallcross, Amy L. "The moving blocks bootstrap versus parametric time series models" *Water Resource Research*, Vol. 32, No. 6, 1875–1882, June 1996

Table 1 Evolution of Conclusion About the US Inflation Series Properties

Year	Author(s)	Framework	Findings about inflation
1977	Nelson and Schwert	Analysis of autocorrelation structure	Nonstationary behavior of inflation
1987	Barsky	Estimation of autocorrelations	I(0) until 1960 and I(1) thereafter
1988	Rose	Dickey-Fuller tests	I(0)
1991	Neusser	Cointegration tests	I(0)
1993	Brunner and Hess	Dickey-Fuller-type test with bootstrapped critical values	I(0) from 1947 to 1959, and I(0) from 1960 to 1992
1993	Evans and Wachtel	Markov Switching	I(1) during 1965-1985, I(0) elsewhere
1996	Baillie et al	ARFIMA	Long memory process with mean reversion
1997	Culver and Papell	Panel unit root tests	I(0) for 3 countries out of 13 using UR test with breaks, I(1) for 7 of them; the last 3 countries are marginal
1999	Ireland	Phillips-Perron tests	the unit root hypothesis for inflation can be rejected, but only at the 0.10 significance level; in the post-1970 sample, the unit root hypothesis cannot be rejected.
1999	Stock and Watson	DF-GLS tests	p-values are larger that 10% for both CPI and PCE inflations before 1982, and less than 10% after 1985
2000	McCulloch and Stec	ARIMA	In the early portion of our period, a unit root in inflation may be rejected, while in the later portion, it generally cannot be. Whole period: Jan. 1959 - May, 1999
2001	Bai and Ng	PANIC	Cannot reject a UR at 5%
2003	Henry and Shields	Two regime TUR	Cannot reject a UR for the US inflation rate

Note: The table contains the finding of various authors in different times. The right column shows their conclusions about the stationarity of inflation.

Table 1 Real-time GDP deflator inflation ADF-test results: $\Delta\pi_t = \ _{s_t} + \gamma_{s_t}\pi_{t-1} + \psi_{s_t i}\Delta\pi_{t-1} + \varepsilon_t$

	1954:3 – 2007:1		1965:4 – 2007:1	
State S	0	1	0	1
Persistence γ	0.03	-0.09***	0.01	-0.10***
	(0.03)	(0.01)	(0.03)	(0.01)
serial corr. ψ	-0.26***	-0.35***	-0.30***	-0.33***
	(0.12)	(0.07)	(0.14)	(0.07)
St Dev σ	0.40***	0.22***	0.37***	0.22***
	(0.04)	(0.01)	(0.03)	(0.01)
Const μ	0.00	0.22***	0.08	0.24***
	(0.12)	(0.04)	(0.17)	(0.04)
Prob[S|S]	0.95***	0.97***	0.97***	0.98***
	(0.03)	(0.02)	(0.04)	(0.01)

Notes: Inflation is defined as the year-over-year GDP deflator growth rate. Laglength p=1.

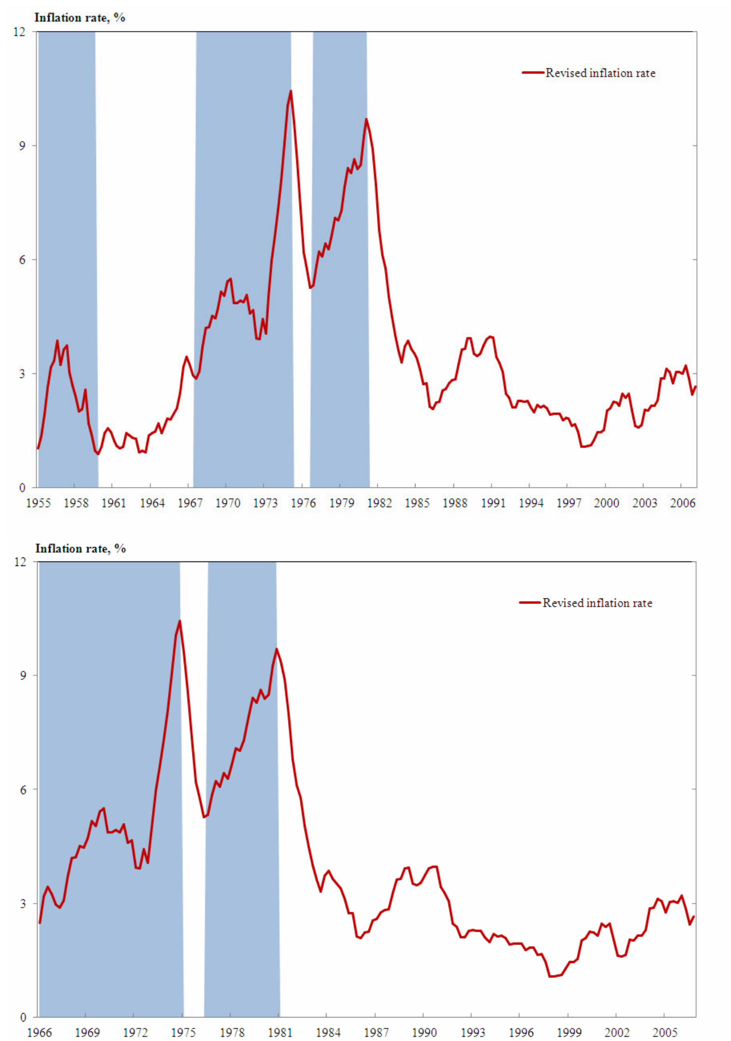

Figure 1 Revised GDP deflator inflation and the state distribution over 1954:3 – 2007:1 sample (at the top) and 1965:4 – 2007:1 sample (at the bottom)

Table 2 Forward-looking Taylor rule estimates over 1965:4-2007:1 sample for the Orphanides (2004) Greenbook real-time output gap and various inflation forecast horizons *h*:

$$r_t = (1-\rho_{S_t})\{ \quad_{S_t} + (1+\delta_{S_t})E_t\pi_{t+h} + \omega_{S_t}\,\hat{y}_t\} + \rho_{S_t} r_{t-1} + \varepsilon_t$$

	h=0		h=1		h=2		h=3		h=4	
State *i*={0,1}	0	1	0	1	0	1	0	1	0	1
Inflation δ	-0.36	0.91	-0.27	0.95	-0.30	0.98	-0.13	1.17	-0.24	1.11
	(0.33)	(0.28)	(0.33)	(0.22)	(0.36)	(0.23)	(0.31)	(0.23)	(0.35)	(0.22)
Output gap ω	0.50	0.70	0.45	0.67	0.40	0.65	0.31	0.77	0.51	0.73
	(0.26)	(0.13)	(0.26)	(0.10)	(0.25)	(0.10)	(0.22)	(0.11)	(0.23)	(0.11)
Smoothing ρ	0.47	0.83	0.50	0.80	0.53	0.80	0.54	0.79	0.38	0.81
	(0.16)	(0.04)	(0.14)	(0.04)	(0.14)	(0.03)	(0.13)	(0.03)	(0.18)	(0.03)
St Dev σ	2.37	0.55	2.30	0.52	2.28	0.49	2.20	0.39	2.34	0.44
	(0.30)	(0.04)	(0.28)	(0.04)	(0.27)	(0.04)	(0.25)	(0.04)	(0.30)	(0.03)
Const μ	10.11	0.55	9.05	0.38	8.98	0.18	7.02	-0.47	10.21	-0.27
	(2.91)	(0.76)	(2.95)	(0.64)	(3.03)	(0.63)	(2.62)	(0.62)	(3.37)	(0.63)
$P[S_t=i\|S_{t-1}=i]$	0.93	0.98	0.93	0.98	0.94	0.98	0.96	0.98	0.95	0.98
	(0.04)	(0.01)	(0.04)	(0.01)	(0.04)	(0.02)	(0.03)	(0.02)	(0.04)	(0.01)
Implied π^*	21.27	2.13	24.41	2.24	21.25	2.37	35.40	2.55	32.39	2.50

Notes: The interest rate r_t is the last month of the quarter average Federal Funds rate. Inflation is defined as the year-over-year GDP deflator growth rate. Greenbook inflation forecasts starting dates are 1965:4, 1968:3, 1968:4, 1973:3, 1974:2 for h=0,…,4 respectively. The Greenbook output gap series comes from Orphanides (2004). The 1999:1-2007:1 output gap series is the OECD real-time estimates of the US production slack; inflation forecasts are from SPF. The equilibrium real interest rate is assumed to be 2.5%.

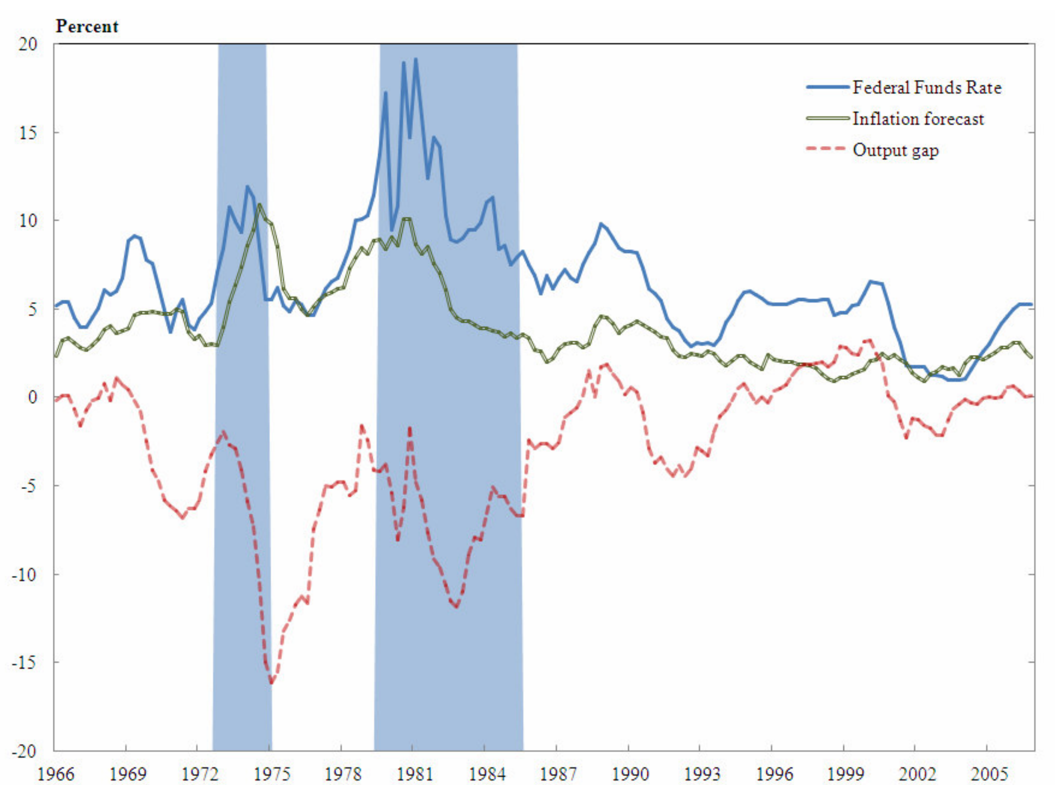

Figure 2 Taylor rule state distributions with the "nowcast" of inflation and Orphanides (2004) real-time output gap estimated over 1965:4-2007:1 sample

Table 3 Forward-looking Taylor rule estimates for the moving window quadratic output gap and various inflation forecast horizons *h* over 1965:4-2007:1 sample:

$$r_t = (1-\rho_{S_t})\{ \ _{S_t} + (1+\delta_{S_t})E_t\pi_{t+h} + \omega_{S_t}\hat{y}_t\} + \rho_{S_t} r_{t-1} + \varepsilon_t$$

	h=0		h=1		h=2		h=3		h=4	
State S	0	1	0	1	0	1	0	1	0	1
Inflation δ	-0.40	0.49	-0.29	0.58	-0.33	0.63	-0.17	0.78	-0.02	0.80
	(0.43)	(0.28)	(0.45)	(0.20)	(0.47)	(0.19)	(0.41)	(0.23)	(1.56)	(0.12)
Output gap ω	0.17	0.67	0.15	0.75	0.17	0.77	0.07	0.75	0.21	0.77
	(0.36)	(0.16)	(0.37)	(0.12)	(0.37)	(0.12)	(0.38)	(0.13)	(0.12)	(0.18)
Smoothing ρ	0.53	0.86	0.53	0.80	0.54	0.78	0.45	0.83	0.46	0.82
	(0.18)	(0.04)	(0.18)	(0.04)	(0.17)	(0.04)	(0.19)	(0.03)	(0.13)	(0.03)
St Dev σ	2.58	0.58	2.57	0.56	2.61	0.55	2.63	0.48	2.69	0.48
	(0.33)	(0.04)	(0.33)	(0.04)	(0.35)	(0.04)	(0.35)	(0.03)	(0.38)	(0.04)
Const μ	7.57	0.73	6.76	0.66	7.18	0.50	6.03	0.09	5.91	0.01
	(3.03)	(0.95)	(3.39)	(0.67)	(3.54)	(0.62)	(3.27)	(0.75)	(11.97)	(0.52)
$P[S_t=i \mid S_{t-1}=i]$	0.92	0.98	0.92	0.98	0.92	0.98	0.95	0.98	0.94	0.98
	(0.05)	(0.01)	(0.05)	(0.01)	(0.05)	(0.01)	(0.04)	(0.01)	(0.05)	(0.01)
Implied π^*	12.59	3.63	14.49	3.21	14.18	3.17	20.98	3.10	172.24	3.11

Notes: The interest rate r_t is the last month in a quarter average Federal Funds rate. Inflation is defined as the year-over-year GDP deflator growth rate. Greenbook inflation forecasts starting dates are 1965:4, 1968:3, 1968:4, 1973:3, 1974:2 for h=0..4 respectively. The 1999:1-2007:1 inflation forecasts come from the Survey of Professional Forecasters. The size of the moving window is 20 years. The equilibrium real interest rate is assumed to be 2.5%.

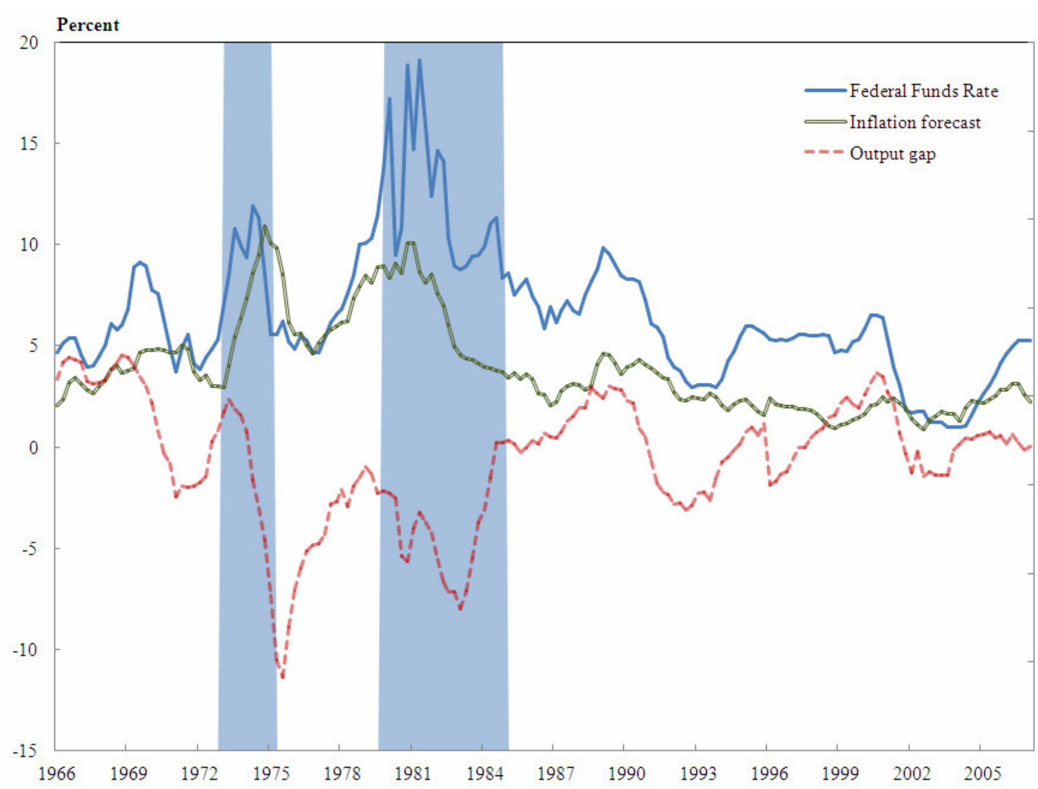

Figure 3 Taylor rule state distributions with the "nowcast" of inflation and Moving Window detrending estimated over 1965:4-2007:1 sample

Table 4 Forward-looking Taylor rule estimates for the recursive window quadratic output gap and various inflation forecast horizons *h* over 1965:4-2007:1 sample:

$$r_t = (1-\rho_{S_t})\{ \quad _{S_t} + (1+\delta_{S_t})E_t\pi_{t+h} + \omega_{S_t}\ \hat{y}_t \} + \rho_{S_t} r_{t-1} + \varepsilon_t$$

	h=0		h=1		h=2		h=3		h=4	
State S	0	1	0	1	0	1	0	1	0	1
Inflation δ	-0.37	0.77	-0.29	0.87	-0.32	0.87	-0.06	1.45	0.18	1.65
	(0.41)	(0.37)	(0.42)	(0.33)	(0.43)	(0.32)	(0.57)	(0.88)	(0.83)	(0.84)
Output gap ω	0.34	0.79	0.28	0.81	0.24	0.74	0.17	0.67	0.12	0.69
	(0.39)	(0.22)	(0.39)	(0.19)	(0.37)	(0.18)	(0.50)	(0.34)	(0.63)	(0.34)
Smoothing ρ	0.52	0.88	0.52	0.86	0.53	0.86	0.45	0.93	0.45	0.93
	(0.17)	(0.03)	(0.16)	(0.03)	(0.16)	(0.03)	(0.22)	(0.03)	(0.25)	(0.03)
St Dev σ	2.54	0.57	2.52	0.56	2.50	0.54	2.94	0.52	3.12	0.52
	(0.33)	(0.04)	(0.32)	(0.04)	(0.32)	(0.04)	(0.51)	(0.04)	(0.55)	(0.04)
Const μ	7.76	-0.86	6.99	-1.06	7.24	-1.12	5.35	-2.53	3.88	-3.07
	(2.97)	(1.37)	(3.16)	(1.19)	(3.13)	(1.15)	(4.82)	(2.81)	(7.17)	(2.79)
$P[S_t=i\|S_{t-1}=i]$	0.92	0.98	0.92	0.98	0.93	0.98	0.88	0.97	0.97	0.86
	(0.05)	(0.01)	(0.05)	(0.01)	(0.05)	(0.01)	(0.09)	(0.02)	(0.02)	(0.10)
Implied π^*	14.07	4.38	15.71	4.10	14.77	4.16	51.71	3.47	-7.70	3.38

Notes: The interest rate r_t is the last month in a quarter average Federal Funds rate. Inflation is defined as the year-over-year GDP deflator growth rate. Greenbook inflation forecasts starting dates are 1965:4, 1968:3, 1968:4, 1973:3, 1974:2 for h=0..4 respectively. The 1999:1-2007:1 inflation forecasts come from the Survey of Professional Forecasters. The equilibrium real interest rate is assumed to be 2.5%.

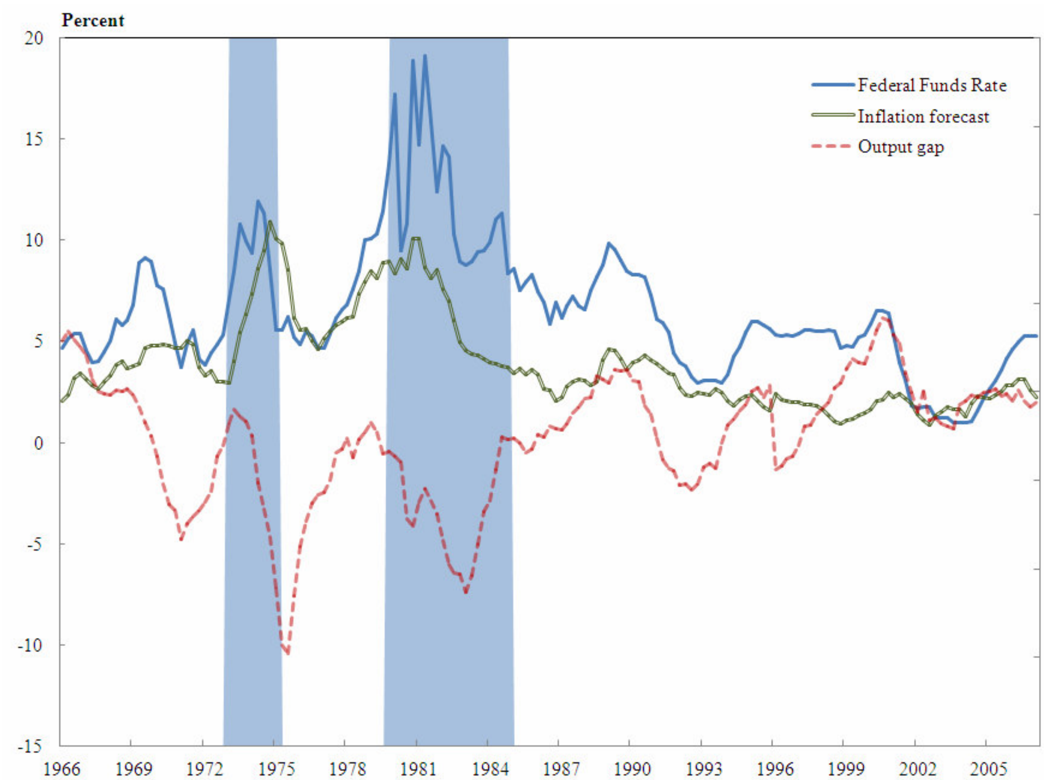

Figure 4 Taylor rule state distributions with the "nowcast" of inflation and Recursive Window detrending estimated over 1965:4-2007:1 sample

Table 5 Forward-looking Taylor rule estimates over 1965:4-1995:4 sample for the Orphanides (2004) Greenbook real-time output gap and various inflation forecast horizons *h*:

$$r_t = (1-\rho_{S_t})\{ \quad _{S_t} + (1+\delta_{S_t})E_t\pi_{t+h} + \omega_{S_t} \ \hat{y}_t \} + \rho_{S_t} r_{t-1} + \varepsilon_t$$

	h=0		h=1		h=2		h=3		h=4	
State *i={0, 1}*	0	1	0	1	0	1	0	1	0	1
Inflation δ	-0.39	0.42	-0.30	0.37	-0.35	0.43	-0.50	0.55	-0.24	0.53
	(0.33)	(0.25)	(0.31)	(0.17)	(0.35)	(0.19)	(0.36)	(0.33)	(0.34)	(0.20)
Output gap ω	0.42	0.52	0.47	0.53	0.44	0.52	0.55	0.47	0.51	0.54
	(0.26)	(0.26)	(0.25)	(0.07)	(0.25)	(0.09)	(0.27)	(0.12)	(0.21)	(0.09)
Smoothing ρ	0.46	0.78	0.48	0.70	0.50	0.71	0.30	0.82	0.36	0.74
	(0.15)	(0.06)	(0.14)	(0.05)	(0.15)	(0.05)	(0.20)	(0.05)	(0.17)	(0.06)
St Dev σ	2.38	0.61	2.30	0.56	2.32	0.56	2.46	0.53	2.35	0.47
	(0.30)	(0.05)	(0.27)	(0.05)	(0.28)	(0.06)	(0.34)	(0.05)	(0.31)	(0.06)
Const μ	10.46	2.37	9.51	2.53	9.67	2.31	12.41	1.73	10.35	1.79
	(2.96)	(086)	(2.82)	(0.63)	(3.08)	(0.74)	(3.98)	(1.18)	(3.18)	(0.75)
$P[S_t=i \mid S_{t-1}=i]$	0.93	0.98	0.93	0.98	0.93	0.97	0.93	0.97	0.95	0.97
	(0.05)	(0.01)	(0.04)	(0.02)	(0.04)	(0.02)	(0.05)	(0.02)	(0.04)	(0.02)
Implied π^*	20.51	0.30	23.33	-0.08	20.63	0.46	19.68	1.37	32.32	1.33

Notes: The interest rate r_t is the last month in a quarter average Federal Funds rate. Inflation is defined as the year-over-year GDP deflator growth rate. Greenbook inflation forecasts starting dates are 1965:4, 1968:3, 1968:4, 1973:3, 1974:2 for h=0..4 respectively. The Greenbook output gap series comes from Orphanides (2004). The equilibrium real interest rate is assumed to be 2.5%.

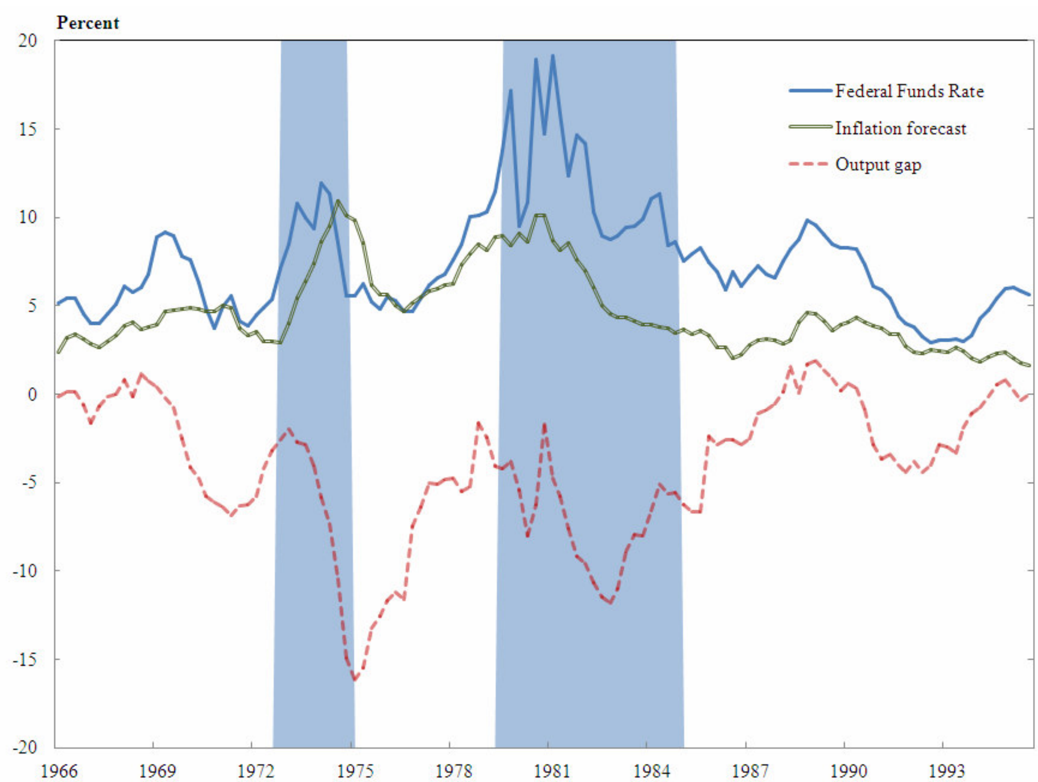

Figure 5 Taylor rule state distributions with the "nowcast" of inflation and Orphanides (2004) real-time output gap estimated over 1965:4-1995:4 sample.