

Estimating Taylor-Type Rules: An Unbalanced Regression?

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Abstract

Relying on Clive Granger's many and varied contributions to econometric analysis, this paper considers some of the key econometric considerations involved in estimating Taylor type rules for US data. We focus on the roles of unit roots, cointegration, structural breaks, and non-linearities to make the case that most existing estimates are based on an unbalanced regression. A variety of estimates reveal that neglected cointegration results in the omission of a necessary error correction term and that Fed reactions during the Greenspan era appear to have been asymmetric. We argue that error correction and non-linearities may be one way to estimate Taylor rules over long samples when the underlying policy regime may have changed significantly.

1. Introduction

How a central bank reacts to changes in economic conditions is of crucial importance in both policy-making and to academics. Attempts to describe a systematic process by which the central bank adjusts a variable that it has control over, such as an interest rate, to changes in economic conditions give rise to the reaction function approach. There are many ways that one can specify monetary policy reaction functions or rules. Several variables have been thought to significantly affect the setting of monetary policy instruments, including monetary aggregates and the exchange rate. In recent years, however, Taylor-type rules have become the most popular way of summarizing how central banks conduct monetary policy. Taylor (1993) showed that US monetary policy, covering a brief period of only five years (1987-1992), is well described by movements in the federal funds rate that respond to deviations of inflation and real GDP from their target or capacity levels. Taylor evaluated the response to these two variables and found that the federal funds rate could essentially be described as a rule of the form:

$$i_t = r^* + \pi_t + \alpha(\pi_t - \pi^*) - \beta(\tilde{y}_t). \quad (1)$$

where i is the nominal federal funds rate, r^* is equilibrium federal funds rate, π is the inflation rate over the previous four quarters, π^* is the target inflation rate and \tilde{y} is the percent deviation of real GDP from its target or potential level. The Federal Reserve (Fed) reacts by changing the federal funds rate in such a manner that i_t is expected to increase when inflation rises above its target or when real GDP rises above its target or potential level.

The above equation can also be rewritten as

$$i_t = \mu + (1 + \alpha)\pi_t + \beta\tilde{y}_t. \quad (2)$$

where $\mu = r^* - \alpha\pi^*$. The parameters α and β reflect the preferences of the monetary authority in terms of their attitude towards the short-run trade-off between inflation and output (see Ball,

1997; Muscatelli, Tirelli, and Trecroci 1999; and Clarida, Gali and Gertler, 1998). Policy makers are assumed to minimize a quadratic loss function in terms of the inflation and output gaps and, possibly, the volatility of interest rates.¹ In Taylor (1993), r^* and π_t^* are both set equal to 2, and a weight of 0.5 is assigned to both α and β . Stability implies that $\alpha > 0$, which means that the response of the monetary authorities to an inflation shock translates into a higher real federal funds rate. Otherwise, the central bank cannot convince markets that it prefers lower future inflation.²

Numerous papers have estimated variants of the above specification. Less thought is given as to whether the right and left hand side variables are of the same order of integration. Banerjee et. al. (1993, pp. 164-66) discuss conditions under which it is preferable to balance regressions where the regressor and the regressand are a mix of I(1) and I(0) series.³ Sims, Stock and Watson (1990) show that estimating (2) in levels, even when the series are non-stationary in levels, need not be problematic.⁴ However, omission of a possible underlying cointegrating relationship leads to a misspecification with implications for forecast performance (Hendry 1995, chapter 8 and Clements and Hendry 1993). This is one point Granger (2004) emphasizes in his Nobel Lecture.

While most monetary economists and central bankers would agree on the fundamental features of a monetary policy rule (if they were inclined to use one), there is still disagreement

¹ Goodhart (2004) casts doubt on the ability of expressions such as (1) to capture the preferences of central bankers if the regressions use the proper data. In particular, if a central bank has an inflation target and successfully meets it then the correlation in historical interest rate data and inflation data ought to vanish as central banks should always set the interest rate consistent with the target level of inflation.

² Stability conditions are not necessarily as clear-cut as suggested above. See Woodford (2003, chapter 2).

³ They credit Mankiw and Shapiro (1985, 1986) for drawing attention to this problem. Also, see Enders (2004, pp. 102, 212).

⁴ For example, an augmented Dickey-Fuller test equation for the presence of a unit root is an unbalanced regression. Note, however, that standard inference on the I(0) series in the test equation is not appropriate. Hence, one must rely on a non-standard distribution for hypothesis testing (e.g., see Hamilton 1994, pp. 554-56).

about the details of the specification. In this paper we are interested in exploring some of the econometric issues that have a bearing on the estimation of Taylor rules, especially ones that stem from the varied seminal contributions of Clive Granger in the field of time series analysis. Most notably, the stationarity and cointegration properties of time series can have a significant impact on the interpretation and forecasts from reaction functions. For example, the real interest rate, r^* , need not be constant as is generally assumed. The difficulty, however, is that the equilibrium real interest rate implied by the rule (r^* in (1)) is unobserved and subject to a great deal of uncertainty (e.g., Laubach and Williams 2003). Nevertheless, depending upon the chosen sample, it can display trend like behavior. Alternatively, relying on a standard Fisher equation decomposition, a unit root in either the inflation rate or the real rate will also produce unit root behavior in the nominal rate. Moreover, economic theory suggests that some of the variables in the Taylor rule, which may be non-stationary in levels, have the property that a linear combination of them is stationary. This suggests a common factor linking these series that gives rise to error correction type models. The nominal interest rate and inflation are candidates for cointegration but other cointegrated relationships are also possible, as we shall see. Perhaps surprisingly, the extant literature has not generally investigated this possibility.

In the next two sections, we outline the principal econometric issues in the estimation of Taylor type equations. Knowing the time series properties of the variables in (1) or (2) is crucial for proper inference. In particular, little thought is given as to whether the right and left hand side variables are of the same order of integration. The dependent variable in equation (2) is treated as a stationary series even though it may be difficult to distinguish it from a unit root process. The fact that it makes less economic sense to assume non-stationarity in nominal interest rates does not detract from the fact that many studies of interest rate behavior use the

first difference of this series in estimation for econometric reasons. Next, following a brief review of existing estimates of Taylor rules for the US, we consider how sensitive estimates of equations such as (1) and (2), and its variants, are to the lessons learned from Granger's work. The paper concludes with a summary and some lessons learned.

2. Selected Econometric Aspects of Taylor Rules

Our aim is to focus our attention on lessons learned from the contributions of Granger. Nevertheless, a few other issues germane in estimating Taylor rules will also be raised though not extensively discussed or considered explicitly in the subsequent empirical work. What follows then is not intended as an exhaustive list of econometric considerations surrounding the estimation of Taylor type reaction functions. Inference from estimates of equations such as (1) and (2) are sensitive to the following:

- i) The inclusion of a term to accommodate interest rate smoothing behavior of central banks. The path of interest rates set by central banks tends to be fairly smooth over time, changing slowly in one direction or the other, with reversals occurring relatively infrequently (e.g., Siklos 2002, Table 4.3). Taylor-type rules have been modified to incorporate interest rate smoothing by including a lagged interest rate term. Sack and Wieland (2000), in a survey, argue that interest rate smoothing may be deliberate or just the result of monetary policy reacting to persistent macroeconomic conditions. If the latter view is correct, one would expect that the coefficient associated with the lagged interest rate to be small and insignificant. However, empirical estimates of Taylor rules find that the coefficient associated with the lagged interest rate is close to unity and statistically significant, suggesting that interest rate smoothing may be

deliberate.⁵ Rudebusch (2002) argues that monetary policy inertia at quarterly frequencies is just an illusion, namely a form of omitted variables bias, and rejects the Taylor rule as a representation of monetary policy although some have rejected his arguments on empirical grounds. There are solid theoretical and practical reasons to believe that central banks do smooth interest rates (e.g., Goodhart 1999, Sack 1998, Sack and Wieland 2000, Collins and Siklos 2004, Bernanke 2004b). Moreover, English, Nelson and Sack (2003) reject on empirical grounds Rudebusch's conjecture. Dueker and Rasche (2004) argue that studies which rely on quarterly or monthly data fail to make an adjustment arising out of the discrete nature of changes in the target fed funds rate. Nevertheless, once the appropriate adjustment is made, interest rate smoothing remains a feature of the data. In any event, these findings highlight the implications of considering unit root behavior in nominal interest rates.

ii) Whether or not the equilibrium real rate is constant. Taylor-type rules contain both an unobserved equilibrium real interest rate and an unobserved inflation target. Judd and Rudebusch (1998), Kozicki (1999), and Clarida, Gali, and Gertler (2000), among others, calculate the equilibrium real interest rate as the difference between the average federal funds rate and the average inflation rate. With this sample specific value, one is able to back out an estimated value for the inflation target from the empirical estimate of the constant term in equation (2) above. One could also begin with an inflation target and back out a value of the real interest rate from the empirically estimated constant term in equation (2). Rudebusch (2001) employs a more elaborate approach to estimating the equilibrium real interest rate from

⁵ Siklos (1999, 2002) also finds that inflation targeting central banks may indulge in relatively less interest rate smoothing behavior. Also, see Goodhart (2004).

empirical estimates of an IS curve. Kozicki (1999) shows that estimates of the equilibrium real interest rate vary over time for the US. Clarida, Gali, and Gertler (2000) use the average of the observed real interest rate as a proxy for the equilibrium real rate but allow it to vary between sub-samples. More recently, Rapach and Wohar (2004) have shown that ex-post real interest rates for the G7 countries have undergone structural shifts over time. They find that these shifts correspond to structural breaks in the inflation rate. Indeed, since the real interest rate variable incorporates one or more possible cointegrating relationships, the absence of an error correction term in most Taylor rule equations is surprising. Further, given well documented shifts in monetary policy, it is conceivable that a cointegrating relationship may be turned on, or off, in a regime-sensitive manner. It is precisely this type of consideration that led Siklos and Granger (1997) to propose regime-dependent cointegration.

- iii) Alternative weights assigned to α and β may be sensitive to the policy regime in place. Different sample periods may yield different results. Judd and Rudebusch (1998) and Hamalainen (2004) estimate Taylor-type rules for different sample periods and find that the Fed has indeed reacted differently overtime to inflation and the output gap. Hence, the possibility of structural breaks, well-known to have a significant impact on the unit root and cointegration properties of the data, also plays a role in influencing policy-type recommendations based on the Taylor rule.
- iv) Different ways in which the inflation rate can be estimated. In the original Taylor rule monetary policy targets inflation as the rate of inflation in the GDP deflator over the previous four quarters. Kozicki (1999) compares the Taylor rule using four different

price indexes to compute the annual inflation rate (GDP price deflator, CPI, core CPI, and expected inflation from private-sector forecasts). Kozicki (1999) then computes what the Federal funds rate would have been had these alternative measure of inflation been used. There is a large variation in computed interest rates using different measures of inflation.

- v) Different measures of potential output. The output gap measure used in the Taylor rule has been interpreted as either representing policymakers objectives relating to output stability as well as a measure of expected inflation (see Favero and Rovelli, 2003). Levin, Wieland and Williams (1999) argue that the coefficient on the output gap should not fall below 0.6 reflecting the Fed's concern with real economic performance. Different methods have been used to construct proxies for potential output. In the original Taylor (1993) paper, potential output was computed by fitting a time trend to real GDP. Judd and Rudebusch (1998) and Clarida, Gali and Gertler (2000) measure potential output using the Congressional Budget Office's (CBO) estimates and by fitting a segmented trend and quadratic trend to real GDP. McCallum and Nelson (1999) and Woodford (2001) have argued against the use of time trends as estimates of potential output. First, because the resulting output gap estimates might be overly sensitive to the chosen sample; second, de-trending ignores the potential impact of permanent shocks on output. The latter consideration proves especially relevant when the time series property of the output gap series is investigated, as we shall see. Other measures of potential output used in the extant literature include the use of the Hodrick-Prescott (HP) filter, a band-pass filter, and measures of potential output compute by the CBO in the US. Kozicki (1999) shows

that different measures of potential output can lead to large variations in Federal Funds rate target movements. Finally, Walsh (2003, 2004) argues that policy makers are best thought of as reacting to the *change* in the output gap. Typically, however, estimated output gap proxies are derived under the implicit, if not explicit, assumption that the series is stationary. Differencing such a series may further exacerbate the unbalanced regression problem noted earlier and may result in over-differencing.⁶

- vi) The timing of information (e.g. backward or forward looking expectations) as well as the use of current versus real time data. In Taylor's original article, the Fed reacts to contemporaneously to the right hand side variables. However, this assumes that the central bank knows the current quarter values of real GDP and the price index when setting the federal funds rate for that quarter. This need not be the case.⁷ Levin, Wieland, and Williams (1999), McCallum and Nelson (1999) and Rudebusch and Svensson (1999) found few differences between the use of current versus lagged values of variables. One explanation is that both inflation and the output gap are very persistent time series. Thus, lagged values of these variables serve as good proxies for current values. Clarida, Gali and Gertler (1998, 2000), Orphanides (2001), and Svensson (2003) emphasize the forward-looking nature of monetary policy and advocate the estimation of forward-looking Taylor-type rules. Orphanides (2001)

⁶ Over-differencing can induce a non-invertible moving average component in the error term. The problem has been known for some time (e.g., Plosser and Schwert 1977) and its emergence as an econometric issue stems from the spurious regression problem made famous by Granger and Newbold (1974).

⁷ For example, in the US, the first (or advance) release of real GDP data for each quarter is not available until about one month after the end of the quarter. The final release is not available until three months after the quarter ends. In addition, historical data are often revised. Hence, while Taylor are usually estimated using final data, policy decisions often necessitate reliance on real time data. See McCallum 1998; Orphanides 2001, 2003a,b; Orphanides and van Norden, 2002.

estimates Taylor-type rules over the period 1987-1992 using ex-post revised data as well as real time forecasts of output gap. He also used Federal Reserve staff forecasts of inflation to investigate whether forward looking specifications describe policy better than backward-looking specifications. Differences in the interpretation of results based on whether models are forward or backward-looking, forecast-based, or rely on real time data strongly points to a potentially important role of the time series properties of the variables that enter the Taylor rule.

- vii) Issues of model uncertainty. Svensson (2003) doubts the relevance of the Taylor rule on theoretical grounds. Levin, Wieland and Williams (1999) and Taylor (1999) argue that Taylor-type rules are robust to model uncertainty.⁸ However, these conclusions concerning robustness under model uncertainty could be challenged on the grounds that the models they use are too similar to each other. A potential solution may be to adopt the “thick modeling” approach of Granger and Jeon (2004; also see Castelnuovo and Surico 2004) which we will not pursue here.⁹

These findings point to the crucial role played by the time series properties of the nominal interest rate, inflation and output gap. The interest rate and inflation rate in equation (2) have often been found to be non-stationary I(1) processes, while the output gap is usually, by construction, a stationary I(0) process (see Goodfriend, 1991; Crowder and Hoffman, 1996; Culver and Papell, 1997). This would suggest that it might be preferable to estimate a first

⁸ See also Smets (1998), Isard, Laxton, and Eliasson (1999), Orphanides (1999), Muscattelli and Trecroci (2000) on Taylor rules and output gap and model uncertainty.

⁹ The basic idea is to generate a wide variety of estimates from different specifications and pool these to form combined estimates and confidence intervals. Indeed, Granger and Jeon (2004) apply their technique to U.S. data with the Taylor rule serving as the focal point of the technique’s illustration.

difference form of the Taylor rule (e.g., as in Siklos 2004, Gerlach-Kristen 2003).¹⁰

Regardless of whether interest rates and inflation are non-stationary or stationary processes, most would agree that these series may be near unit root processes or, rather, that their stationarity property can be regime dependent. There are problems with estimating equations with near unit root processes. It is, therefore, surprising that previous research has ignored to a large degree the time series properties of the variables included in the Taylor-type rules. Phillips (1986, 1989) has shown that if variables are integrated of order 1, or are near unit root processes, then levels regressions may yield spurious results, and standard inference is not asymptotically valid (Elliott and Stock 1994). Lanne (1999, 2000) points out that these considerations explain why the finding of a unit root in nominal interest rates is so common when, in fact, there is likely a structural break that gives rise to the unit root property. Even if one believes that a unit root in interest rates, or any of the other variables in a Taylor rule, is a convenient simplification, there remains the problem with the economic interpretation of a unit root in interest rates. After all, interest rates are bounded from below (and, in practice, from above) and it is inconceivable that they have infinite variance. More importantly, given I(1) series, it is possible for cointegration to exist between these variables. There are also good economic reasons to expect some cointegration among the variables in the Taylor rule. For example, the real interest rate in (2) reflects the Fisher equation relating the nominal interest rate to expected inflation, and these two series may be statistically attracted to each other in the long-run if real interest rates are believed to be stationary. Additionally, the inflation and output gap variables in (1) or (2) capture the trade-off between inflation and output variability and there are sound arguments, since at least

¹⁰ Williams (2004) also points out that estimating a first differenced version of (1) reduces the problems associated with the uncertainty surrounding the measurement of the equilibrium real interest rate (i.e., the constant term in the Taylor rule).

Friedman (1977), to expect that an underlying long-run relationship exists between these two variables.

If variables are found not to be cointegrated a static regression in levels will be spurious (Granger and Newbold, 1974). In a spurious regression the estimated parameter vector is inconsistent and the t and F-statistics diverge. Studies of the Taylor rule which have regression equations with R^2 greater than the DW statistic is an indication of spurious regression.¹¹ If no cointegration is found then there is no long-run relationship between the I(1) variables.

3. Alternative Specifications of the Taylor Rule

Judd and Rudebusch (1998) modify Taylor's rule given in equation (2) above that allows for gradual adjustment in the Federal funds rate. The modified Taylor rule is written as:

$$\dot{i}_t^* = r^* + \pi_t + \alpha(\pi_t - \pi^*) + \beta_1 \tilde{y}_t + \beta_2 \tilde{y}_{t-1} \quad (3)$$

where the adjustment process is given by

$$\Delta \dot{i}_t = \gamma(\dot{i}_t^* - \dot{i}_{t-1}) + \rho \Delta \dot{i}_{t-1}. \quad (4)$$

The coefficient γ is the adjustment to the “error” in the interest rate setting and the coefficient ρ can be thought of as a measure of the “momentum” from last period's interest rate change.¹²

Combining (3) and (4) gives the Taylor-type rule with interest rate smoothing:

$$\Delta \dot{i}_t = \gamma \mu - \gamma \dot{i}_{t-1} + \gamma(1 + \alpha)\pi_t + \gamma\beta_1 \tilde{y}_t + \gamma\beta_2 \tilde{y}_{t-1} + \rho \Delta \dot{i}_{t-1} \quad (5)$$

where $\mu = r^* - \alpha\pi^*$.

¹¹ In the event an interest rate smoothing parameter is present in the Taylor, the DW test statistic is inappropriate. One might instead resort to the use of the Durbin-h test statistic.

¹² Giannoni and Woodford (2003) consider the robustness of alternative policy rules and find in favor of a rule written in regression form as $\dot{i}_t = \mu + \rho_1 \dot{i}_{t-1} + \rho_2 \Delta \dot{i}_{t-1} + \phi_\pi \pi_t + \phi_y \Delta \tilde{y}_t + \varepsilon_t$. The rule is very similar to the one specified by Judd and Rudebusch (1998) except that the Fed here reacts to the *change* in the output gap instead of its level. It is easy to show that in this type of reaction function can be turned into a difference including an error correction term that reflects cointegration between the nominal interest rate and the output gap.

Note, however, that (7) is a difference rule and, as Hendry (2004) points out, its was the dissatisfaction with specifications such as these, notably the fact that such a specification would be valid whether the raw data were I(1) or I(0) which eventually found expression in what eventually came to be called Granger's representation theorem.

The above equation can be rewritten as

$$i_t = \gamma[\mu + \gamma(1 + \alpha)\pi_t + \beta_1\tilde{y}_t + \beta_2\tilde{y}_{t-1}] + (1 - \gamma)i_{t-1} + \rho\Delta i_{t-1} \quad (6)$$

Clarida, Gali, and Gertler (1998, 2000) and McCallum (2001) employ a partial-adjustment form of the Taylor rule that is further modified to reflect forward-looking behavior of monetary policy makers. This interest rate rule is given as:

$$i_t^* = i^* + \varphi(E[\pi_{t+k}|\Omega_t] - \pi^*) + \beta E[\tilde{y}_{t+m}|\Omega_t] \quad (7)$$

where i_t^* is the nominal interest rate to be set; i^* is the desired nominal interest rate when inflation and output are at their target values; π_{t+k} is the inflation rate over the period t to $t+k$; \tilde{y}_{t+m} is a measure of the average output gap between period t and $t+m$; Ω_t is the information set available at the time the interest rate is set. Interest rate smoothing is incorporated through a partial-adjustment process given as:

$$i_t = \rho(L)i_{t-1} + (1 - \rho)i_t^* \quad (8)$$

where

$$\rho(L) = \rho_1 + \rho_2 L + \dots + \rho_n L^{n-1}; \rho \equiv \rho(1)$$

where i_t is the current interest rate set by the monetary authority. Combining (7) and (8) yields the instrument rule to be estimated as:

$$i_t = (1 - \rho)\left[r^* - (\varphi - 1)\pi^* + \varphi\pi_{t+k} + \beta\tilde{y}_{t+m}\right] + \rho(L)i_{t-1} + \varepsilon_t \quad (9)$$

where $r^* = i^* - \pi^*$ is the long-run equilibrium real rate and

$$\varepsilon_t = -(1 - \rho) [\varphi(\pi_{t+k} - E[\pi_{t+k} | \Omega_t]) + \beta(\tilde{y}_{t+m} - E[\tilde{y}_{t+m} | \Omega_t])] \quad (10)$$

Levin, Wieland and Williams (1999) argue that the behavior depicted in equation (9) could be an optimal response for a central bank. Such interest rate smoothing has been employed in the empirical work of Carida, Gali, and Gertler (1998, 2000), Gerlach and Schnabel (2000), and Domenech, Ledo, and Taguas (2002). Empirical work has found estimates of ρ to be positive and statistically significant. This has been interpreted as evidence that central banks deliberately adjust interest rates gradually towards their target rate. The estimate of ρ is an indication of the speed of this adjustment, and a value near unity implies a very slow adjustment process. As noted earlier, the conclusion of a significant estimate of ρ indicating interest rate smoothing has been questioned by Rudebusch (2002) and Söderlind, Söderström, and Vredin (2003), both of whom argue that a Taylor rule augmented with a lagged interest rate imply too much predictability of interest rate changes compared with yield curve evidence. Specifically, Rudebusch (2002) argues that a large coefficient on the lagged interest rate would imply that future interest rate changes are highly predictable. But yield curve evidence suggests that interest rate predictability is low. Hence, Rudebusch concludes that the dynamic Taylor rule is a mis-specified representation of monetary policy. Nevertheless, Rudebusch is not able to obtain any definitive conclusions based on this test because of an observational equivalence problem affecting the analysis. English, Nelson and Sack (2003) note that this observational equivalence problem may be overcome with a model estimated in first differences. Siklos (2004) also recognizes the near unit root nature of nominal interest rates and notes that a Taylor rule in first differences may also be more suitable for the analysis of countries that formally (or informally) target inflation. Using this type of formulation for the Taylor rule in a panel setting he finds that

there are significant differences in the conduct of monetary policy between inflation and non-inflation targeting countries.

While differencing of the variables in the Taylor rule solves one problem it does create another. Castelnuovo (2003) tests for the presence of interest rate smoothing at quarterly frequencies in forward looking Taylor rules by taking into account potentially important omitted variables such as the squared output gap and the credit spread. This result should not be surprising. Collins and Siklos (2004) estimate optimal Taylor rules, and demonstrate empirically, that interest rate smoothing is the trade-off for responding little to the output gap. Uncertainty about the measurement of the output gap is well known (e.g., see Orphanides 2001) but it could just as well be uncertainty about the appropriate structural model of the economy that leads policy members to react cautiously.

While the original Taylor rule was specified as a reacting to two variables only, more recently several papers have explored the potential role of real exchange rate movements (e.g., as in Leitimo and Røisland 1999, and Medina and Valdés 1999) or the role of stock prices (e.g., Bernanke and Gertler 1999, Cecchetti et al. 2000, Fuhrer and Tootell 2004). Lately, there has been interest concerning the impact of the housing sector on monetary policy actions as many central banks have expressed concern over the economic impact of rapidly rising housing prices (e.g., see Siklos, Bohl, and Werner 2004a, 2004b, and references therein). While it is too early to suggest that there is something of a consensus in the literature, it is clear that variables such as stock prices and housing prices may result in the need to estimate an augmented version of Taylor's rule. In what follows, we do not explore what have been referred to as extended Taylor rules.

4. Empirical Evidence on Taylor-type Rules: A Brief Overview of the US

Experience¹³

In Taylor (1993) no formal econometric analysis is carried out. Nevertheless, the simple rule described in equation (1) above was found to visually track the federal funds rate for the period 1987-1992 fairly well. Taylor (1999) estimated a modified version of equation (1), shown as equation (2) above, for different sample periods using OLS. Taylor concluded that the size of the response coefficients had increased over time between the international gold standard era and the Bretton Woods and Post-Bretton Woods period. Using the same specification, Hetzel (2000) examined the sample periods 1965-1979, 1979-1987, and 1987-1999 for the US. He also found that the response coefficients increased over time, but Hetzel questioned whether these could be given any structural interpretation. Orphanides (2001) estimates the Taylor rule for the US over the period 1987-1992 using OLS and IV and employ both ex-post and real time data. He finds that when real time data are used, the rule provides a less accurate description of policy than when ex-post data are used. He also finds that the forward looking versions of the Taylor rule describe policy better than contemporaneous specifications, especially when real time data are used.

Clarida, Gali and Gertler (2000) consider two sub-samples 1960-1979 and 1979-1998 for the US using the same specification and employing the GMM estimator. The error term in equation (9) is a linear combination of forecast errors and thus, it is orthogonal to the information set \mathcal{Q}_t . Therefore, a set of instruments can be extracted from the information set to use in the GMM estimation. They report considerable differences in the response coefficients

¹³ Space constraints prevent a review of Taylor rule estimates outside the US experience. Readers are asked to consult, for example, Clarida, Gali and Gertler (1998), Gerlach and Schnabel (2000), Gerlach-Kristen (2003), Siklos, Bohl and Werner (2004a, b).

over the two different sample periods.¹⁴ The results of Clarida, Gali and Gertler (2000) are challenged by the findings of Domenech, Ledo, and Taguas (2002). They find evidence for activist monetary policy in the US in the 1970s that resembles that of the 1980s and 1990s. On balance, however, as documented by Dennis (2003), Favero and Rovelli (2003), and Ozlale (2003), there is a great deal of consensus that the Volcker-Greenspan era differs markedly from monetary policy practiced by their predecessors at the Fed.

Hamalainen (2004) presents a brief survey of the properties relating to Taylor-type monetary policy rules focusing specifically on the empirical studies of Taylor (1999), (using the original Taylor rule), Judd and Rudebusch (1998), incorporating interest rate smoothing into a modified Taylor rule, and Clarida, Gali and Gertler (2000), incorporating forward-looking behavior into a modified Taylor rule. They employ different measures of inflation and output gaps as well as estimating Taylor rules over different sample periods. They find that the response coefficients are sensitive to the measure of inflation and output gap employed and to the sample estimation period employed. Hamalainen (2004) also notes that small changes in assumptions can yield very different policy recommendations, leading one to question the use of Taylor-type rules.¹⁵

There have only been a small number of papers that have examined the time series properties of the variables within Taylor-type rules.¹⁶ Christensen and Nielsen (2003) reject the traditional Taylor rule as a representation of US monetary policy in favor of an alternative stable

¹⁴ It is far from clear that GMM provides different estimates of the parameters in a Taylor rule. One reason is that the literature has, until recently, almost completely ignored the issue of the choice of instruments and their relevance. Siklos, Bohl and Werner (2004a, 2004b) show that this aspect of the debate may be quite crucial in deriving policy implications from Taylor rules.

¹⁵ In addition, the weights in Taylor-type rules also depend on how the rule interacts with other equations and variables in an economic structural model.

¹⁶ Clarida, Gali and Gertler (1998) perform some unit root tests, however, report mixed results in terms of the order of integration. They argue for the stationarity of the included variables based on the argument that the unit root tests have low power.

long-run cointegrating relationship between the federal funds rate, the unemployment rate, and the long-term interest rate over the period 1988-2002. They find that deviations from this long-run relation are primarily corrected via changes in the federal funds rate.

Osterholm (2003) investigates the properties of the Taylor (1993) rule applied to US, Australian and Swedish data. The included variables are found to be integrated or near integrated series. Hence, a test for cointegration is carried out. The tests find no support for cointegration though the economic rationale for testing for cointegration among the series in the Taylor rule is not justified. Siklos (2004) reports that similar results for a much larger group of countries that includes the US, but whether the Taylor rule represents an unbalanced or spurious regression remains debatable, and one we explore econometrically in greater detail below.

More recently, empirical estimates of Taylor's rule have begun to consider non-linear effects. Siklos (2002, 2004) allows for asymmetric changes in inflation and finds in favor of this view in a panel of OECD countries, as well as for GARCH effects in interest rates. Dolado, Pedrero, and Ruge-Murcia (2004) also permit ARCH-type effects in inflation (i.e., via the addition of the variance in inflation in the Taylor rule) but find that non-linear behavior describes US monetary policy well only after 1983.

While the foregoing survey has concentrated on studies that rely almost exclusively on US data, there has been a veritable explosion of applications to data from several countries. Readers are asked to consult, for example, Clarida, Gali, and Gertler (1998), and Gerdesmeier and Roffia (2003).

In what follows, we rely exclusively on OLS estimation since these are adequate for bringing out the types of econometric problems raised in Granger's work and relevant to our understanding and assessment of Taylor rules.

4. Taylor Rule Estimates for the US

4.1 Data

The data are all sampled or converted to the quarterly frequency via averaging of monthly data.¹⁷ The full sample consists of data covering the period 1959.1-2003.4. The mnemonics shown in parenthesis are the labels used to identify each series by FREDII at the Federal Reserve Bank of St. Louis.¹⁸ The short-term interest rate is the effective federal funds rate (FEDFUNDS). To proxy inflation, evaluated as the first log difference of the price level, we examine a number of price indices. They are: the CPI for all urban consumers and all items (CPIAUCSL), the core version of this CPI (CPILFESL; excludes food and energy prices), and the price index for Personal Consumption Expenditures (PCECTPI), as well as the core version of this index (JCXE). All these data were seasonally adjusted at the source. In the case of output, real Gross Domestic Product (GDPC96), and real potential Gross Domestic Product (these are the Congressional Budget Office's estimates; GDPOT2) were utilized. Again, the real GDP data were seasonally adjusted at the source. We also consider other proxies for output gap including, for example, the difference between the log of output less its HP filtered value.¹⁹

Some studies use a proxy for the unemployment gap. This is defined as the unemployment rate less an estimate of the NAIRU. This can be estimated as in Staiger, Stock and Watson (1997).²⁰ We also relied on other data from time to time to examine the sensitivity of our results to alternative samples or regimes. For example, Romer and Romer's Fed contraction

¹⁷ We intend to make available at <http://www.wlu.ca/~wwwsbe/faculty/psiklos/home.htm> the raw data and any programs used to generate the results. To facilitate access to the results we have relied on Eviews 5.0.

¹⁸ The relevant data were downloaded from <http://research.stlouisfed.org/fred2/>.

¹⁹ Using the standard smoothing parameter of 1600.

²⁰ A simple estimate is based on the regression $\Delta\pi_t = \mu + \beta_1 u_{t-1} + \beta_2 u_{t-2} + \gamma X_t + v_t$ where u is the unemployment rate, π is inflation, and X is a vector of other variables. We set $X=0$ and used the CPI all items to obtain separate estimates for the 1957-1990 and 1991-2003 samples which yielded estimates of 6.05% and 4.29%, respectively, where $NAIRU = -\mu/(\beta_1 + \beta_2)$.

dates (Romer and Romer 1989; 1947.01-1991.12), Boschen and Mills' indicator of the stance of monetary policy (Boschen and Mills 1995; 1953.01-1996.01), Bernanke and Mihov's (1998; 1966.01-1996.12) measure of the stance of monetary policy, and the NBER's reference cycle dates (www.nber.org).²¹

Forecast-based versions of Taylor rules have also proved popular both because they capture the forward-looking nature of policy making and permit estimation of the reaction function without resort to generated regressors. In the present paper we rely on seven different sources of forecasts for inflation and real GDP growth. They are from *The Economist*, Consensus Economics, the OECD, the IMF (World Economic Outlook), the Survey of Professional Forecasters, the Livingston survey regularly updated by the Federal Reserve Bank of Philadelphia, the Greenbook forecasts, and the University of Michigan survey.

4.2 Alternative Estimates and Their Implications

Prior to presenting estimates, it is useful to examine the time series properties of the core series described above. Figure 1A plots the fed funds rate while Figure 1B plots various measures of inflation. Both these figures show a general upward trend until the late 1970s or early 1980s followed by a general downward trend thereafter. Both series are broadly stationary after approximately 1990. Accordingly, it is not difficult to conclude, as have several authors, that both these variables are non-stationary and indeed that they contain a unit root over the full sample, or separate sub-samples consisting of a period of rising rates and inflation versus the era of falling rates and disinflation. This is also true even if the sample is roughly split between the pre-Greenspan era (1987) and the period since the appointment of the Fed Chairman. Not surprisingly, the various core inflation measures are smoother than the ones that include all items

²¹ Other than the NBER dates, the remaining data were kindly made available by Justin Wolfers and can also be downloaded from http://bpp.wharton.upenn.edu/jwolfers/personal_page/data.html.

and while, in general, the CPI and PCE based measures are similar there are some differences in the volatility of the series. Summary statistics and some unit root tests that broadly support the foregoing discussion are shown in Table 1A. Both the standard Augmented Dickey-Fuller test statistic and the statistically more powerful modified unit root tests proposed by Elliott, Rothenberg, and Stock (Ng and Perron 2001) generally lead to the conclusion.

Taylor rule estimates based on available forecasts generally do not consider the time series properties of the variables in question. Figure 2A plots actual CPI inflation against forecasted inflation from 8 different sources. Since data is not available for the full sample from all sources, only the sample since Greenspan has been Fed Chairman is shown. The top portion of the figure collects forecasts that are survey based in addition to those from the Fed's Greenbook. The bottom portion of the figure contrasts forecasts for inflation from international organizations or institutions that collect and average forecasts from several contributors or sources. Survey-based forecasts appear to be far more volatile than the other types of forecasts. Otherwise, neither type of forecast appears outwardly to dominate others over time. Turning to unit root tests shown in Table 1B, one is more likely to reject the null of a unit root in inflation forecasts than in realized inflation, in both the full sample as well as the Greenspan era. When output growth forecasts are considered there is more unit root like behavior in the full sample than in the various output gap proxies considered in Table 1A while the evidence of unit root behavior is just as mixed in the forecast as in the actual data. It is surprising that there have been relatively few estimates that rely on publicly available forecasts. After all, as Governor Bernanke has noted recently, such forecasts are important to policymakers since "...the public does not know but instead must estimate the central bank's reaction function and other economic

relationships using observed data, we have no guarantee that the economy will converge – even in infinite time – to the optimal rational expectations equilibrium (Bernanke 2004a, p.3).

Granger’s work has long focused on the ability of econometric models to forecast time series. An influential contribution was Bates and Granger (1969) in which some linear combination of forecasts often outperforms even the best forecasts. This result, seemingly counter-intuitive, comes about simply because averaging forecasts is a useful device in canceling out biases in individual forecasts. Figure 2B plots a variety of inflation forecasts. Data limitations govern the chosen samples. As we shall see, averaging inflation forecasts results in estimates of forecast-based reaction functions that compare well with Taylor rules based on realized data. This result is not generally obtained when policy rule are estimated with individual inflation forecasts.

Figures 3A and 3B display various plots of output growth and the output gap. The time series properties of these series differ noticeably from the other core variables in the Taylor rule. In top portion of figure 3A we compare the output gap first by taking the difference between the growth of actual real GDP and the growth in potential real GDP and next by simply taking the difference between the log levels of actual and potential real GDP. Potential real GDP estimates are from the CBO. The latter is often the “standard” way of representing the output gap in the empirical literature that relies in US data. The former is an equally valid proxy for the output gap. While perhaps more volatile, the resulting series appears more nearly stationary. The bottom portion of Figure 3A contrasts a measure of the output gap evaluated as the difference between the log level of real GDP and its HP filtered values against the first difference in the “standard” output gap measure shown in levels in the top portion of the same Figure. The latter is sometimes referred to as the “speed limit” measure of the output gap.

Both series are, broadly speaking, stationary. The HP filter suffers from the well-known endpoint problem. Yet, even if one estimates an output gap measure based on a one-sided HP filter where the endpoint is permitted to change over time, this does not seem to affect the unit root property of the resulting time series, with the possible exception of data covering the Greenspan era only (see Table 1A). The speed limit measure is clearly more volatile and more stationary in appearance. Finally, Figure 3B compares the output gap derived from the CBO's measure (i.e., the "standard" proxy shown in Figure 3A) against a de-trended measure of the log level of real GDP. Versions of the latter have been used in some of the studies cited above. In the version shown here, separate trends for the 1959-1990 and 1991-2003 periods were fitted to the log level of real GDP. The time period captures the phenomenon noted by several analysts who have argued the US experienced the a permanent growth in potential output beginning around the 1990s as efficiencies in computing technology began to be felt throughout the economy. Chairman Greenspan has, on a number of occasions, commented on the apparent technological driven boom of the 1990s (based, in part, on evidence as in Oliner and Sichel 2000).²² Although the two series produce broadly similar patterns, the measure of the output gap derived from de-trending comes closest to being I(1) of all the proxies considered. The same result holds when a cubic trend serves to proxy potential real GDP (\tilde{y}^{T3}), especially for the Greenspan sample. If one were instead to rely on the unemployment rate (results not shown) there is a slightly better chance of concluding that the unemployment rate gap is I(1), at least for the separate subsamples 1957-1987 and 1988-2003, but not when an HP filter is applied.

²² This view was not universally shared within the FOMC. Meyer (2004, p. 213), for example, did not believe that "...the Fed's effort to reduce inflation was somehow responsible for the wave of innovation that propelled the acceleration of productivity in the second half of the 1990s".

Notwithstanding the low power of unit root tests, and the presence of structural breaks in the data, ostensibly due to regime changes in monetary policy, there are strong indications that interest rates and inflation are I(1) while the output gap is I(0). Nevertheless, since the output gap (or, for that matter, the unemployment rate gap) is an unobservable series, there is no reason that it cannot be I(1) for some sub-sample. In any event, there is prima facie evidence that the Taylor rule is, as usually estimated, an unbalanced regression.

The possibility that equation (2) contains two or more I(1) series raises the possibility that they are cointegrated. Indeed, if one examines equation (3) and adds an interest rate smoothing parameter, then it is a cointegrating relationship when $|\rho| < 1$. Alternatively, there may be other cointegrating relationships implicit in the standard formulation of Taylor's rule.²³ One must also ask what economic theory might lead these series to be attracted to each other in a statistical sense. Clearly, the nominal interest rate and inflation are linked to each other via the Fisher effect. It is less clear whether the output gap will be related to the interest rate in the long-run not only because it is typically I(0) by construction but also because we know that a central bank's success at controlling inflation is regime specific. Similarly, while inflation and output might be related in the long-run it is by no means clear why their respective gap equivalents ought to be contemporaneously attracted to each other in the long-run. Table 2 then presents a series of cointegration tests.²⁴ We first consider cointegration between the output gap, inflation (in the CPI alone), the fed funds rate and a long-term interest rate. Addition of the long-term interest rate series, proxied here by the yield on 10 year Treasury bonds (GS10), reflects the

²³ As noted previously, using only five years of data, there was no reason to consider the possibility of cointegration. A highly readable account of the inspiration for the cointegration concept is contained in Hendry (2004).

²⁴ The type of cointegration more or less implicit in Giannoni and Woodford (2003) is not generally found in the present data. Hence, we do not pursue this line of enquiry.

possibility that the term spread, often used as a predictor of future inflation, short-term interest rates, or output, affects the determination of the fed funds rate. The results in Table 1 indicate that only the output gap series based on de-trending is I(1) we rely on this series alone in the tests that follow. Not surprisingly, we are able to conclude that the output gap does not belong in the cointegrating relationship. Relying on the full sample, the null that the output gap is zero in the cointegrating vector cannot be rejected. Moreover, if we estimate a vector error correction model the null that the fed funds rate is weakly exogenous also cannot be rejected.²⁵ Both sets of results appear consistent with the notion that the output gap is not an attractor in the specified VAR and that the form of the Taylor rule with the fed funds rate reacting to the inflation and output gap is adequate. One cointegrating vector is found in both models considered. Since the finding of cointegration is clearly sensitive to the output gap definition, we instead investigate whether there is cointegration between inflation, and the short and long rates (model 2). While cointegration ordinarily requires a long span of data, it is conceivable that the sought after property is a feature only of some well-chosen sub-sample. The results in Table 2, at least based on the model that excludes the output gap, suggest that there is cointegration during the Greenspan and full samples. Figure 4 plots the error corrections from the estimated cointegrating vector based on the full and Greenspan samples. Only for the Greenspan sample do the error corrections appear to be roughly stationary. In the case of the full sample estimates, it is apparent that the series tends to behave asymmetrically. In contrast, the error corrections appear more symmetric when the Greenspan sample alone is considered. Based on the usual testing, it is difficult to know whether it is preferable to estimate a relationship covering the full sample or

²⁵ The test statistic for the null that the output gap does not belong in the cointegrating relationship is $\chi_2^2 = 5.80$ (p-value=.05). The test statistic for the null that i_t is weakly exogenous is $\chi_2^2 = 3.92$ (.14). Both results are based on full sample estimates.

some portion of it. As noted previously, there are good reasons to think that the full sample may indeed consist of periods where cointegration is switched on or off (Siklos and Granger 1997). Part of answer depends on the objectives of the study. Clearly, there is some evidence summarized above suggesting that the Taylor rule is a useful way of studying monetary policy over long periods of time, especially for the US experience (e.g., Orphanides 2003a,b). If the purpose is to understand the behavior of a central bank during a well defined policy regime then a sub-sample is clearly preferable. Alternatively, if the point that needs to be made is that monetary policy behaves asymmetrically over time then a longer span of data is clearly preferable. The difficulty is in properly estimating the timing of a regime change. As we have seen above there is no widespread consensus on the precise dating of shifts in regimes. Nevertheless, to maximize comparability with other studies, we retain sub-sample distinctions that reflect the impact of select different Fed Chairman, most notably the tenures of Volcker and Greenspan. More sophisticated analyses of the dating of regime changes, as in Rapach and Wohar (2004) for the real interest rate or Burdekin and Siklos (1999) for inflation, might well choose a slightly different set of dates but the conclusion that distinct policy regimes are a feature of US monetary policy over the sample considered would remain unchanged.

We now turn to estimates of the Taylor rule that capture some of the features of the data discussed above. Table 3 provides the main results. Three versions of the Taylor rule were estimated. The first is (9) setting k, m both to zero yielding:

$$i_t = (1 - \rho) \left[r^* - (\varphi - 1) \pi^* + \varphi \pi_t + \beta \tilde{y}_t \right] + \rho(L) i_{t-1} + \varepsilon_t \quad (11)$$

The second version recognizes the cointegration property described above. In this case we estimate

$$\Delta i_t = \sum_{i=0}^{\omega} (\alpha_i \Delta \pi_{t-i} + \beta_i \Delta \tilde{y}_{t-i} + \omega \Delta i_{t-i}^L) + \delta (\pi - \psi_1 i - \psi_2 i^L)_{t-1} + \rho \Delta i_{t-1} + \zeta_t \quad (12)$$

where all the variables have been defined and $(\pi - \psi_1 i - \psi_2 i^L)_{t-1}$ is the error correction term.²⁶ A third version decomposes the error correction term into positive and negative changes to capture a possible asymmetry in the reaction function based on the momentum model. That specification is written

$$\Delta i_t = \sum (\alpha_i \Delta \pi_{t-i} + \beta_i \Delta \tilde{y}_{t-i} + \omega_i \Delta i_{t-i}^L) + \delta \Delta^+ (\pi - \psi_1 i - \psi_2 i^L)_{t-1} + \delta \Delta^- (\pi - \psi_1 i - \psi_2 i^L)_{t-1} + \rho \Delta i_{t-1} \zeta_t \quad (13)$$

The first four columns of the Table give the steady state coefficient estimates for the equilibrium real interest rate, the inflation and output gap parameters, as well as the interest rate smoothing coefficient when the estimated model ignores cointegration. It is apparent that real interest rates are relatively lower in the Greenspan period than at any other time since the 1960s. Nevertheless, it is also apparent that estimates vary widely not only across time but across techniques used to proxy the output gap.²⁷

The estimates of the interest rate response to the inflation gap are generally not significantly different from one, the norm known as Taylor's principle. It is clear, however, that the Greenspan era stands in sharp contrast with other samples considered, as the inflation gap coefficient is considerably larger than at any other time reflecting more aggressive Fed reactions to inflation shocks. While the sample here is considerably longer with the addition of six years of data the coefficients reported in Table 3 are markedly higher than the ones reported by Kozicki (1999, Table 3) except perhaps when the conventional output gap using CBO potential real GDP

²⁶ Another potential cointegrating relationship is the one between short and long rates (i.e., the term spread) but this variable proved to be statistically insignificant in almost all the specifications and samples considered.

²⁷ Kozicki (1999, Table 1) reports an estimate of 2.34% when CPI inflation is used for the 1987-1997 sample. Hence, our estimates of the equilibrium real rate are sharply higher.

estimates are used.

Turning to the output gap coefficient it is quickly apparent that, as others have found (e.g., Favero and Rovelli 2003, Collins and Siklos 2004), that the output gap is often insignificant and rather imprecisely estimated. Kozicki (1999, Table 3) reaches much the same conclusion. It is only for the full sample that a non-negligible Fed response to the output gap is estimated. Estimates of the interest rate smoothing parameter confirm the largely close to unit root behavior of nominal interest rates with the notable exception of the Volcker era when interest rate persistence is considerably lower. This is to be expected not only because of the sharp disinflationary period covered by this sample but also because the Fed's operating procedure at the time emphasized monetary control over the interest rate as the instrument of monetary policy.

We also considered estimating various versions of inflation forecast based Taylor rules. Since the bulk of the available data are only available since the late 1980s we show only some estimates for the Greenspan era.²⁸ Of eight potential versions of Taylor's rule only two, namely a version that relies on the Greenbook forecasts (of GDP deflator inflation) and the Consensus forecasts produce plausible results.²⁹ Otherwise, estimates of all the coefficients are implausibly large and the interest rate smoothing coefficient is more often than not greater than one.³⁰ It is not entirely clear why such a result is obtained but it is heartening that, since both these forecasts are among the most widely watched, forecasters see Fed behavior much the same way as conventional regression estimates based on actual data. Nevertheless, it should be noted that the plausibility of forecast rule based estimates is highly sensitive to the choice of the output gap

²⁸ Where possible estimates for the full sample were also generated but the results were just as disappointing as the ones discussed below.

²⁹ Interestingly, Kuttner (2004) reaches the same conclusion using an international data set. However, he does not consider the possibility that the averaging of forecasts might produce better results.

³⁰ This conclusion does not change when whether we use actual output gap estimates versus forecasts of real GDP growth or the output gap (OECD) nor when we add an error correction term to the Taylor rule.

measure. The CBO's output gap measure is the only one that yield results such as the ones shown in Table 3. Matters are different when forecasts are averaged. Whether public agencies forecasts are averaged or private sector forecasts are averaged no longer appears to matter. The resulting estimates are now comparable to ones that rely on actual data. Another one of Granger's insights proves useful.

The last set of columns considers the significance of adding an error correction term to the Taylor rule in first differences. In each case, i in (12) and (13) was set to 1 as this seemed adequate. The error correction term was only added in cases where one could reasonably conclude that $\tilde{y} \sim I(1)$ based on earlier reported tests. It is striking that, with the exception of the Volcker era, the error correction term is significant indicating, as argued above, that long-run equilibrium conditions implicit in Taylor's rule, should not be omitted. The Volcker exception makes the case for cointegration having been turned off during that period, and this interpretation is unlikely to be a controversial one. Finally, the last two columns of Table 3 give estimates of the error correction terms when a momentum type asymmetric model is estimated. Given that asymmetry in monetary policy actions is most likely to have occurred during Greenspan's tenure, we only consider estimates for the post 1987 sample. The results suggest that since only $\Delta\delta^+$ is statistically significant this is akin to an interpretation whereby a rise in the term spread, an indicator of higher expected inflation, over inflation (i.e., a negative error correction) prompts the Fed to raise interest rates. The effect does not appear to work in reverse. Therefore, this seems consistent with aggressive Fed policy actions to stem higher future inflation that marks Greenspan's term as Fed Chair.³¹ Clearly, there are other forms of non-linearity that could have been employed. For example, as shown in Table 4, there is evidence of

³¹ The results also lend further support for the findings first reported in Enders and Siklos (2001) who introduced the momentum model in tests for threshold cointegration (also see Enders and Granger 1998).

ARCH-type effects in the residuals of the Taylor rule in every sample although the evidence is perhaps less strong for the Greenspan era. Obviously, a task for future research is to provide not only a more rigorous theory that might lead to a non-linear rule but more extensive empirical evidence.

As a final illustration of the usefulness of the error correction term we examine in-sample forecasts of the fed funds rate during the Greenspan term. Figure 5A plots forecasts that include and exclude the error correction term and it is clear that policy makers would have produced much better forecasts if the difference rule had been employed.³² Figure 5B then shows what the fed funds rate would have been if the coefficients in the Taylor rule estimated for the pre-Volcker era (1959.1-1979.4) had been used to predict interest rates during Greenspan's tenure. While policy would have clearly been too loose until about 1990, interest rates are fairly close to the actual fed funds rate after that. On the face of it is tempting to conclude that there is less to the choice of Fed chairman than priors might lead one to believe. However, if we compare the RMSE based on the implied interest rates we find, on balance, that there is a notable difference in monetary policy performance across various Fed chairmen (also see Romer and Romer 2003).

5. Summary and Lessons Learned

This paper has considered a variety of time series related questions that arise when estimating Taylor's rule. Focusing on the varied contributions of Granger it was argued that most estimates have ignored the consequences of the unbalanced nature of Taylor's original specification. This means that some of the variables that make up Taylor's rule are either under-differenced or possibly over-differenced. Moreover, the extant literature has omitted the

³² The RMSE for the case where the error correction is included is 0.95, and 1.92 when the error correction is excluded. Clements and Hendry (1995) discuss conditions under which incorporating an error correction term can improve forecasts.

possibility of cointegration among the variables in the Taylor. Augmenting Taylor's rule with an error correction term adds significantly to explaining interest rate movements and, consequently, to our understanding of the conduct of monetary policy in the US since the late 1950s. Finally, there is also significant evidence of asymmetries in the conduct of monetary policy, at least during the Greenspan era. This highlights another of Granger's remarkable contributions to econometric analysis, namely the importance of non-linearities inherent in many economic relationships. A growing number of papers (e.g., Rabanal 2004) are beginning to underscore this point.

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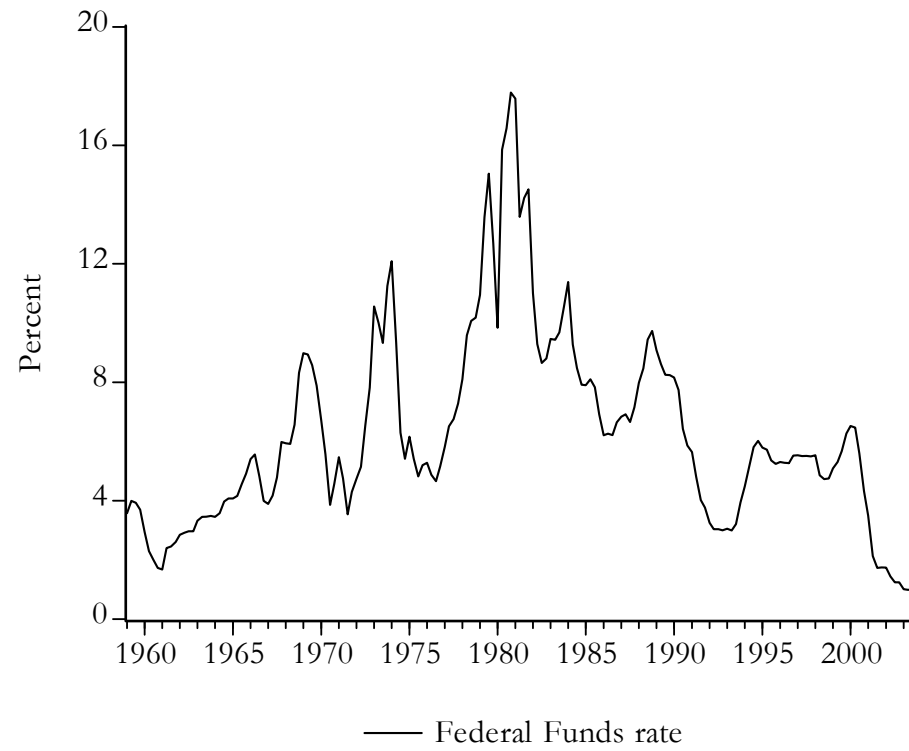
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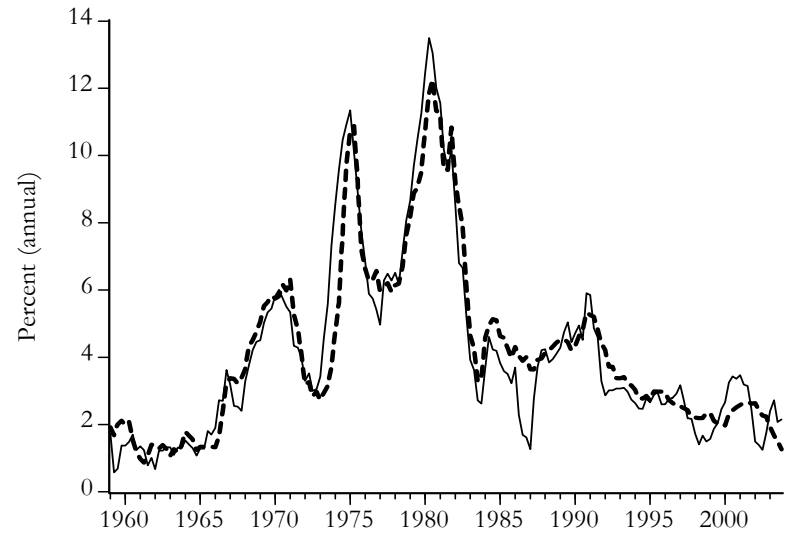
Economic Review 91(2): 232-37.

Figure 1A: Federal Fund Rate, 1959:1-2003:4

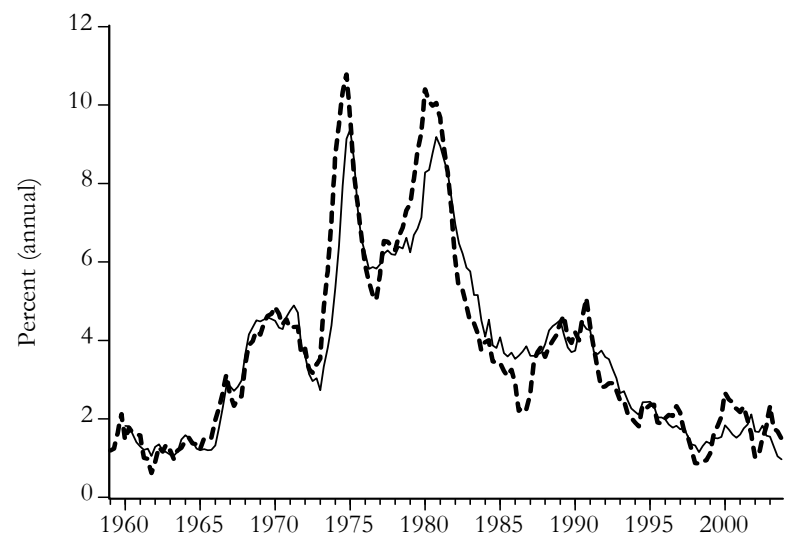


Source: See text.

Figure 1B: Alternative Measures of US Inflation



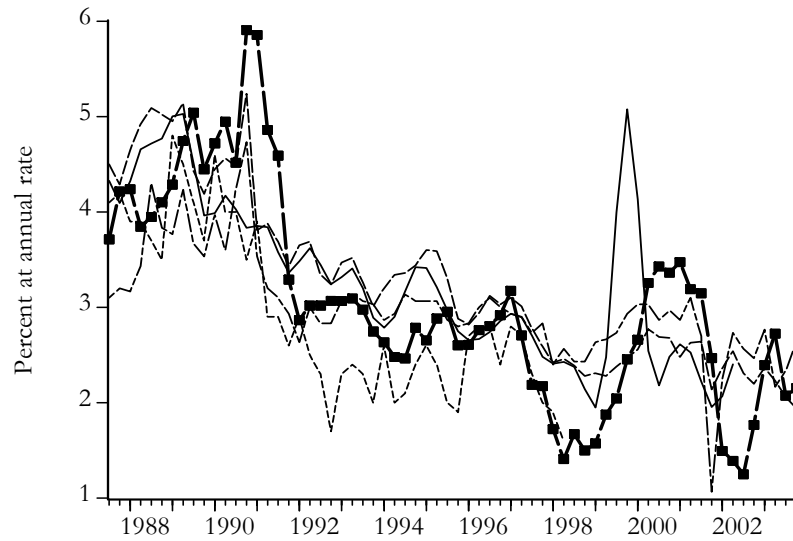
— CPI inflation
- - - Core CPI inflation



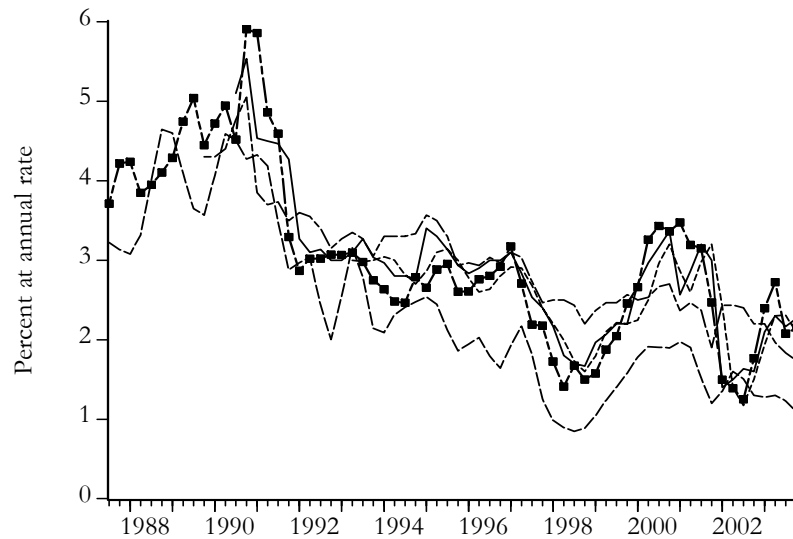
— PCE inflation
- - - core PCE inflation

Source: see text.

Figure 2A Alternative Forecasts of Inflation: 1987-2003



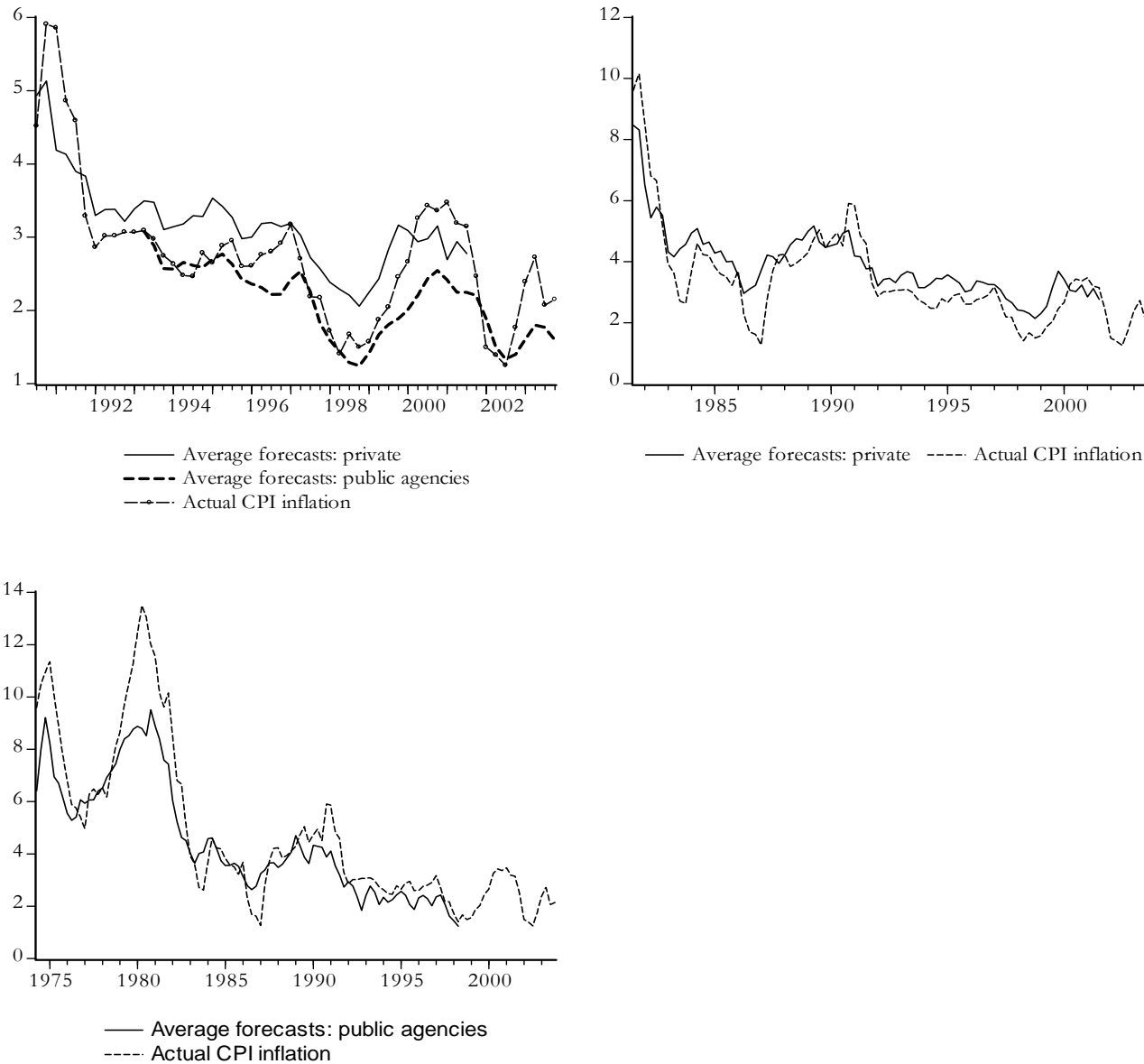
— Livingston survey - - - Survey of Professional Forecasters —■— CPI all items
 ····· Greenbook - · - Michigan Survey



— Economist - - - OECD —■— CPI all items
 ····· IMF - · - Consensus

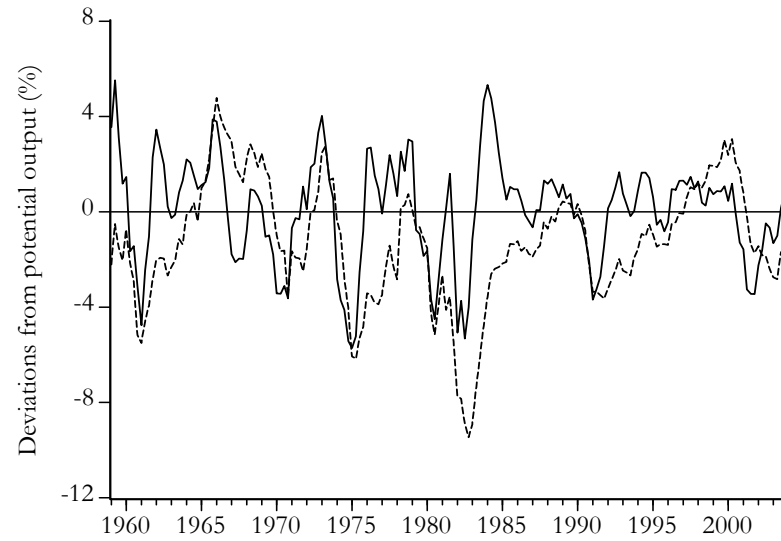
Source: See text.

Figure 2B Average Inflation Forecasts of Inflation: 1975-2002

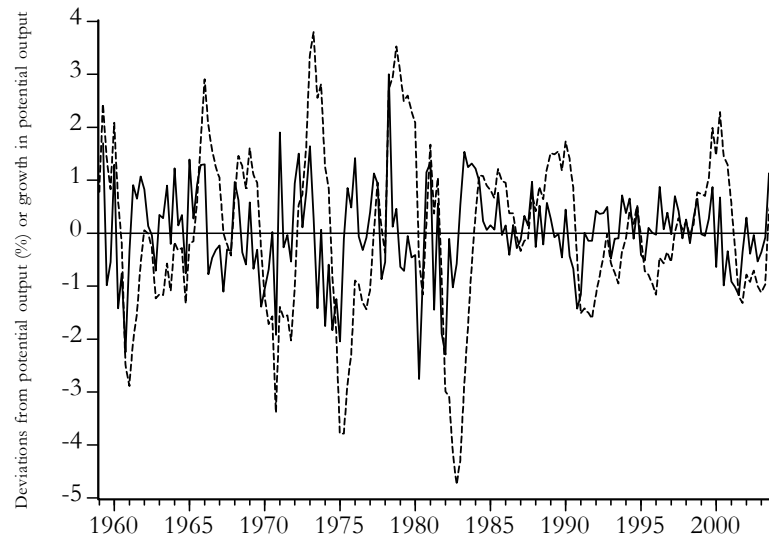


Notes: In the top left Figure, inflation forecasts from the Greenbook, IMF, and OECD (public), Survey of Professional Forecasters (SPF), Livingstone, Economist (ECON), University of Michigan (UMICH), Consensus (CONS); the top right plot is an average of SPF, Livingstone, and UMICH forecasts; the bottom plot is an average of IMF and OECD forecasts. Greenbook and OECD forecasts are for the Implicit Price Deflator.

Figure 3A: Alternative Proxies for the Output Gap



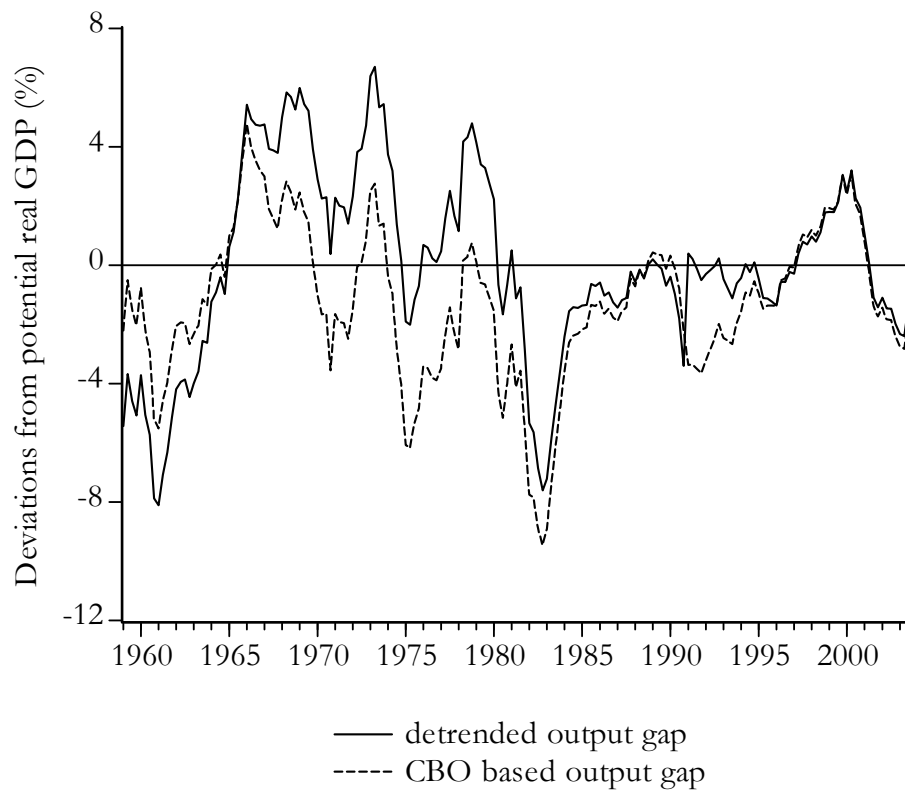
— deviations from growth in potential output
- - - "standard" output gap



— "speed limit" output gap
- - - HP filtered output gap

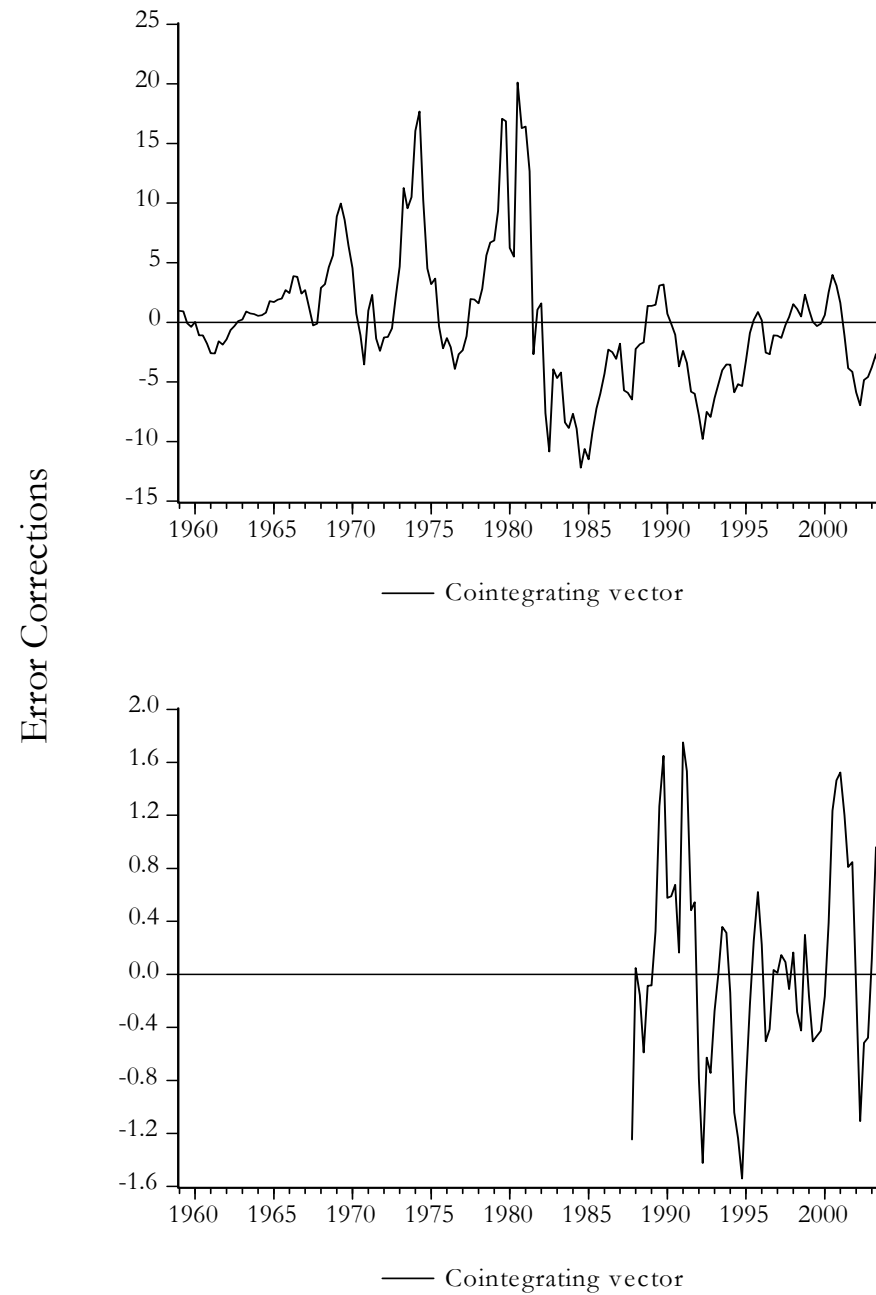
Source: see text. The "standard" output gap measure relies on CBO estimates of potential real GDP.

Figure 3B: Comparing Detrended and CBO Measures of the Output Gap



Source: see text.

Figure 4: Error Corrections



Note: Obtained from Table 2 estimates for model 2 for the full sample (top) and Greenspan samples (bottom).

Figure 5A Forecast Performance During Greenspan's Tenure

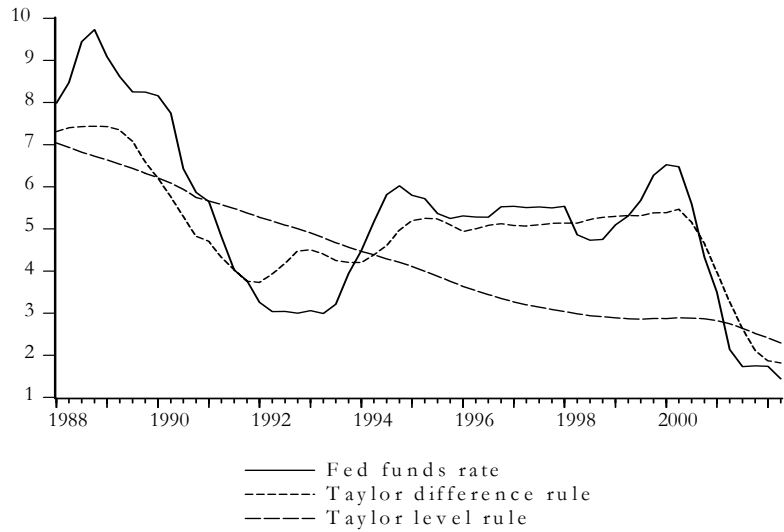
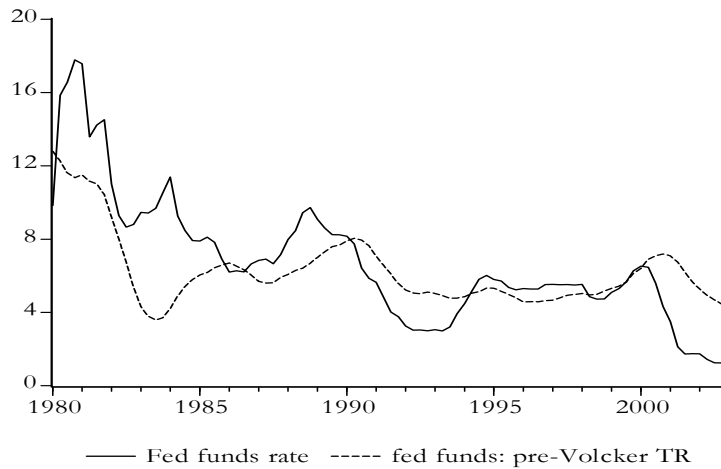


Figure 5B Forecast Performance During Greenspan's Tenure: Using A Pre-Volcker Taylor Rule



Notes: The top figure shows the implied rules during the Greenspan era using a level versus a difference rule. See equations (11) and (12). In Figure B, a counterfactual is conducted wherein a level rule estimated during the Pre-Volcker era is used to generate the implied fed funds rate during the Greenspan sample.

Table 1A Summary Statistics and Unit Root Tests

Series	Sample	Mean	Standard Deviation	ADF ERS(modified)
i	Full	6.26	3.32	-1.89 (0.34) 3.98(7)
π_{cpi}		4.18	2.82	-1.70 (0.43) <i>9.70(12)</i>
$\pi_{cpi-core}$		4.22	2.56	-1.35 (0.60) <i>11.11(13)</i>
π_{pce}		3.65	2.15	-1.40 (0.58) <i>11.29(12)</i>
$\pi_{pce-core}$		3.73	2.43	-1.55 (0.51) <i>8.58(13)</i>
\tilde{y}_{cbo}		-1.29	2.59	-3.46 (0.01) <i>1.59(1)</i>
\tilde{y}_{HP}		-0.03	1.55	-5.85 (0.00) 1.18(0)
\tilde{y}		-0.01	2.16	-4.16 (0.001) <i>11.96(12)</i>
$\Delta\tilde{y}$		0.003	0.86	-7.07 (0.00) <i>13.94(9)</i>
$(y-y^T)$		0.107	3.09	-2.96 (0.04) <i>4.83(2)</i>
\tilde{y}^{T3}		0.000	2.38	-3.94(0.00) <i>1.61(1)</i>
i	Pre-Greenspan	7.05	3.61	-3.52 (0.04) <i>8.55(2)</i>
π_{cpi}		4.85	3.29	-1.07 (0.93) <i>20.44(12)</i>
$\pi_{cpi-core}$		4.88	2.96	-0.45 (0.98) <i>26.69(12)</i>
π_{pce}		4.35	2.33	-1.73 (0.73) <i>17.14(8)</i>
$\pi_{pce-core}$		4.46	2.71	-0.82 (0.96) <i>18.36(12)</i>
\tilde{y}_{cbo}		-1.67	2.94	-2.73 (0.07) <i>7.80(1)</i>
\tilde{y}_{HP}		-0.08	1.81	-4.28 (0.00) <i>6.13(0)</i>
\tilde{y}		-0.004	2.51	-2.80 (0.06) <i>10.44(12)</i>
$\Delta\tilde{y}$		0.004	1.01	-8.49 (0.00) <i>21.78(10)</i>
$(y-y^T)$		0.258	3.78	-2.34 (0.16) <i>16.86(1)</i>
\tilde{y}^{T3}		-0.258	2.61	-3.20(0.02) <i>6.29(1)</i>
i	Greenspan	4.95	2.26	-2.73 (0.23) <i>5.91(1)</i>
π_{cpi}		3.07	1.09	-2.62 (0.27) <i>9.12(4)</i>
$\pi_{cpi-core}$		3.13	1.01	-3.56 (0.04) <i>14.50(4)</i>
π_{pce}		2.49	1.09	-3.35 (0.07) <i>13.80(5)</i>
$\pi_{pce-core}$		2.51	1.08	-2.09 (0.54) <i>14.06(8)</i>
\tilde{y}_{cbo}		-0.65	1.71	-2.52 (0.12) <i>16.11(1)</i>
\tilde{y}_{HP}		0.05	0.99	-3.46 (0.01) <i>11.66(0)</i>
\tilde{y}		-0.03	1.42	-3.29 (0.02) <i>6.40(4)</i>
$\Delta\tilde{y}$		-0.001	0.54	-3.40 (0.01) <i>5.79(1)</i>
$(y-y^T)$		-0.15	1.29	-2.30 (0.17) <i>10.50(0)</i>
\tilde{y}^{T3}		0.45	1.85	-2.43 (0.14) <i>15.85(1)</i>

Notes: The full sample is 1959.1 – 2003.4, Pre-Greenspan is 1959.1 – 1987.2, Greenspan is 1987.3 – 2003.4. ADF is the Augmented Dickey-Fuller statistic with lag augmentation selected according to the Akaike Information criterion. A constant only is used in the full sample; for the interest rate and inflation series, a constant and a trend is used in the other two samples. p – values are given in parentheses. Test statistics in italics are based on the modified ERS tests due to Ng and Perron (2001) using the modified AIC criterion. When the two unit root test contradict each other this is indicated in **bold**. Lag length in the augmentation portion of the test equation shown in parenthesis.

i = interest rate; π = inflation; \tilde{y} = output gap; HP = HP filter; cbo = Congressional Budget Office; pce = Personal Consumption Expenditures; y^T is trend output. The figures in brackets are based on a one-sided HP filter.

Table 1B Additional Unit Root Tests: Forecast of Inflation and Output Growth

Source of Forecast	Full sample	Pre-Greenspan	Greenspan
<i>Inflation</i>			
Livingston	-1.66 (.45)/24.78(11)	-1.40(.58)/23.10(8)	-3.23(.09)T/31.18(8)
Greenbook	-3.77(.02)T/18.81(11)	-2.83(.19)T/6.90(0)	-3.66(.04)T/25.66(3)
Survey of Prof. For.	-4.48(.00)T/13.74(0)		-3.61(.04)T/5.85(1)
Univ. Michigan	-4.70(.00)T/9.55(0)	-2.58(.11)/7.30(5)	-3.68(.03)T/7.11(2)
Economist			-3.74(.03)T/11.89(0)
IMF			-1.53(.51)/7.35(6)
OECD	-1.37(.59)/8.29(11)		-2.59(.29)T/6.80(10)
Consensus			-3.34(.07)T/5.92(0)
<i>Output Growth</i>			
Greenbook	-4.84(.00)/6.40(11)		-2.94(.05)/3.63(2)
Economist			-2.31(.17)/13.13(3)
OECD	-3.57(.01)/8.24(12)		-2.12(.24)/1.33(6)
Consensus			-4.46(.00)/13.13(8)
Livingston	-1.90(.33)/2.11(13)		-2.91(.17)/13.05(8)
Survey of Prof. For.	-1.26(.65)/31.91(0)		-3.45(.05)/7.07(0)

Notes: Test based on the ADF test with lag augmentation chosen as in Table 1A; the test statistics in parenthesis is the modified ERS test as described in Table 1A. "T" indicates that a deterministic trend was added to the test equation. Blanks indicate insufficient or no data to estimate the test equation. *p*-values in parenthesis. OECD and Greenbook inflation forecasts are for the GDP deflator and OECD output growth forecasts are for the OECD's estimate of the output gap.

Table 2 Cointegration Tests

Model 1: [$\tilde{y}^T, \pi_t, i_t, i_t^L$]			
No. of Cointegrating vectors	Full {9}	Pre-Greenspan {9}	Greenspan {4}
0	32.29 (.02)	29.59 (.04)	44.70 (.00)
1	19.90 (.10)	22.30 (.53)	6.98 (.98)
2	9.55 (.38)	15.89 (.20)	5.55 (.84)
3	7.72 (.09)	9.16 (.18)	9.16 (.31)
Model 2: [π_t, i_t, i_t^L]	{9}	{12}	{3}
0	29 (.00)	19.57 (.12)	26.22 (.01)
1	15.19 (.06)	17.21 (.03)	11.27 (.23)
2	5.05 (.28)	3.92 (.92)	2.00 (.78)
Cointegrating equation	$\pi_t - 3.53 i_t^L + 2.53 i_t + 5.15$		$\pi_t - 0.87 i_t^L + 0.26 i_t + 1.40$

Notes: i_t^L is the long-term interest rate. Johansen's λ_{\max} test statistic reported (p -values due to MacKinnon, Haug and Michelis 1999, in parenthesis). Lag length for VARs, shown in brackets, chosen on the basis of the likelihood ratio test except for Model 1, Greenspan sample, where the Final Prediction Error criterion was used.

Table 3 Taylor Rule Coefficient Estimates

Sample	Standard Taylor Rule				Difference Rules		
	$r^*/(1-\rho)$: real rate	$\phi/(1-\rho)$: inflation	$\beta/(1-\rho)$: output gap	ρ : interest smoothing	δ : error correction	$\Delta\delta^+$: pos. momentum	$\Delta\delta^-$: neg. momentum
Pre-Volcker							
\tilde{y}^{T3}	5.90 (.02)	0.91 (.18)	1.40 (.15)	0.91 (9.99)	-0.09 (-2.41)		
$\Delta\tilde{y}$	0.81 (.88)	1.04 (.88)	-6.09 (.49)	1.04 (17.89)	n.a.		
\tilde{y}	5.41 (.26)	0.97 (.85)	4.74 (.56)	0.97 (15.93)	n.a.		
$y-y^T$	8.21 (.17)	0.94 (.33)	1.33 (.38)	0.94 (12.22)	-0.09 (-2.42)		
\tilde{y}_{HP}	5.03 (.00)	0.82 (.01)	1.52 (.00)	0.82 (8.65)	-0.09 (-2.45)		
Volcker							
\tilde{y}^{T3}	6.68 (.00)	0.79 (.17)	-0.09 (.67)	0.50 (3.33)	-0.001 (-0.03)		
$\Delta\tilde{y}$	6.48 (.00)	0.90 (.41)	0.95 (.05)	0.38 (2.44)	n.a.		
\tilde{y}	6.47 (.00)	0.90 (.50)	0.28 (.19)	0.45 (2.86)	n.a.		
$y-y^T$	6.56 (.00)	0.82 (.24)	-0.08 (.73)	0.51 (3.38)	-0.001 (-0.02)		
\tilde{y}_{HP}	6.73 (.00)	0.81 (.20)	-0.09 (.77)	0.52 (3.44)	.002 (.06)		
Greenspan							
\tilde{y}^{T3}	2.96 (.18)	3.80 (.52)	-0.06 (.97)	1.05 (16.87)	-0.03 (-1.93)	-0.05 (-2.61)	-0.01 (-.60)
$\Delta\tilde{y}$	5.09 (.27)	4.31 (.54)	-19.32 (.56)	1.02 (32.71)	n.a.	n.n.	
\tilde{y}	3.02 (.04)	0.37 (.60)	4.29 (.09)	0.95 (27.66)	n.a.	n.n.	
$y-y^T$	3.12 (.02)	3.25 (.13)	0.59 (.44)	1.06 (27.83)	-0.02 (-1.75)	-0.04 (-2.02)	-0.01 (-.79)
\tilde{y}_{HP}	2.75 (.27)	4.39 (.40)	-0.74 (.78)	1.04 (24.05)	-0.02 (-1.72)	-0.05 (-2.26)	-0.01 (-.52)
\tilde{y} -Greenbook	5.12(.13)	0.52(.65)	1.22(.06)	0.89(10.00)			
\tilde{y} -Consensus	1.12(.78)	0.88(.94)	0.88(.03)	0.91(10.36)			
Full							
\tilde{y}^{T3}	4.60 (.00)	.92 (.34)	.83 (.42)	0.91 (25.91)	-0.03 (-1.93)		
$\Delta\tilde{y}$	4.10 (.00)	1.09 (.80)	3.30 (.04)	0.92 (27.11)	n.a.		
\tilde{y}	3.63 (.00)	1.14 (.56)	1.38 (.00)	0.88 (25.21)	n.a.		
$y-y^T$	5.27 (.00)	0.37 (.18)	0.75 (.14)	0.93 (27.67)	-0.02 (-1.75)		
\tilde{y}_{HP}	4.71 (.00)	0.66 (.20)	1.34 (.01)	0.90 (24.53)	-0.02 (-1.72)		
Forecast-based rules							
Public- \tilde{y}_{HP}	2.50 (.07)	1.02 (.43)	0.12 (.47)	0.87 (17.40)			
Private- \tilde{y}_{HP}	1.36 (.10)	0.95 (1.16)	0.29 (.60)	0.92 (15.33)			
Mix I- \tilde{y}_{HP}	2.54 (.07)	0.98 (.32)	0.05 (.03)	0.88 (22.00)			
Mix II- \tilde{y}_{HP}	3.30 (.07)	0.89 (.36)	0.30 (.26)	0.86(17.20)			

Notes: See text and Table 1 for variable definitions. Pre-Volcker = 1959.1 – 1979.2; Volcker = 1979.3 – 1987.2; Greenspan = 1987.3 – 2003.4; Full = 1959.1 – 2003.4. Equations estimated are OLS. In parenthesis, p-value for Wald test (F-statistic) that $i^*/(1-\rho) = 0$, $\phi / (1-\rho) = 1$, and $\beta/(1-\rho) = 0$. For ρ , δ , $\Delta\delta^+$, $\Delta\delta^-$ t-statistic in parenthesis. δ is the coefficient on the error correction term in the first difference form of the Taylor rule. $\Delta\delta^+$, $\Delta\delta^-$ are the coefficient estimates for the positive and negative changes in the error correction term based on the first difference form of the Taylor rule. Greenbook and Consensus are forecast rule estimates. Estimates based on average forecast-based rules are for 1974q2-1998q2 (Public); 1981q3-2001q3 (Private); 1960q1-2002q2 (Mix I); 1690q4-1987q2 (Mix II). Mix I and II represent average forecasts of inflation from the Livingston and OECD sources. Other forecast combinations are described in Figure 2B.

Table 4 Test for ARCH in Taylor Rule Residuals

<i>Sample</i>	<i>Test Statistic</i>	<i>Rule Type</i>
Full	11.64(.00)	\tilde{y}
	14.15(.00)	\tilde{y}^{HP}
Pre-Greenspan	6.61(.01)	\tilde{y}
	11.20(.00)	\tilde{y}^{HP}
Greenspan	0.69(.41)	\tilde{y}
	3.26(.07)	\tilde{y}^{HP}
	2.82(.09)	\tilde{y}^{T3}
	0.12(.73)	\tilde{y}
	1.36(.24)	$\tilde{y} - \tilde{y}^{\text{T}}$

Notes: LM test statistic for the presence of ARCH (1) in the residuals for the Taylor rules defined in the last column. All Taylor rules use CPI inflation and the output gap proxy shown in the last column. p-values given in parenthesis.