The Policy Preferences of the US Federal Reserve*

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Abstract

In this paper we model and explain US macroeconomic outcomes subject to the discipline that monetary policy is set optimally. Exploiting the restrictions that come from optimal policymaking, we use economic outcomes and the economy's evolution through time to estimate the parameters in the Federal Reserve's policy objective function together with the parameters in its optimization constraints. Focusing on the period following Volcker's appointment to Federal Reserve chairman, we estimate the implicit inflation target to be around 1.38% and show that during this period policymakers assigned a statistically significant weight to interest rate smoothing. We show that the policy regime estimates that we obtain generate policy predictions that are consistent with estimated policy rules, and that the estimated optimal policy provides a good description of US data for the 1980s and 1990s.

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1 Introduction

This paper uses economic outcomes and macroeconomic behavior to estimate the policy objective function and the implicit inflation target for the US Federal Reserve. Under the assumption that the Federal Reserve sets monetary policy optimally, the parameters in the objective function, which indicate how different goals are traded-off in response to shocks, are estimated together with the implicit inflation target and the parameters in the optimization constraints.

Ever since Taylor (1993) showed that a simple three parameter rule provided a good description of short-term interest rate movements in the US, it has become common practice to use estimated policy rules to summarize monetary policy behavior (Clarida, Galí, and Gertler, 2000). One reason why using estimated rules to describe monetary policy behavior is attractive is that estimated rules capture the systematic relationship between interest rates and macroeconomic variables and, as such, they can be viewed as approximations to central bank decision rules. However, while estimated policy rules can usefully summarize fluctuations in interest rates, their main drawback is that they are unable to address questions about the policy formulation process. This drawback is evident in the fact that the feedback coefficients in estimated rules do not have a structural interpretation, and that they do not identify key policy parameters, such as the implicit inflation target.

Alongside the literature that estimates monetary policy rules, there is an extensive literature that analyzes optimal monetary policy (Fuhrer and Moore, 1995; Levin, Wieland, and Williams, 1999; Dennis, 2003a). While optimal policy rules are attractive because the policymaker's objective function is explicit, the resulting rules often conflict with estimated policy rules because they say that policymakers should be very aggressive in response to macroeconomic shocks and these aggressive responses cannot be found in the data. Consequently, when it comes to describing how interest rates move over time, optimal policy rules do not perform well. Of course, the key reason why optimal policies fail to adequately explain interest rate movements is that the policy objective function is invariably parameterized without reference to the data.

Given the strengths and weaknesses of estimated rules and optimal rules it is natural to combine the two approaches to obtain an optimal rule that is also compatible with observed data. In fact, there are many advantages to being able to describe monetary policy behavior at the level of policy objectives and not just at the level of policy rules. One advantage is that it becomes possible to assess whether observed economic outcomes can be reconciled and accounted for within an optimal policy framework. Two further advantages are that it facilitates formal tests of whether the objective function has changed over time and that it allows key parameters, such as the implicit inflation target, to be estimated. Furthermore, estimating the objective function reveals what the policy objectives must be if conventionally estimated rules are the outcome of optimal behavior.

This paper assumes that US monetary policy is set optimally and estimates the policy objective function for the Federal Reserve. With the Rudebusch and Svensson (1999) model providing the optimization constraints, we estimate the parameters in the constraints and the parameters in the policy objective function that best conform to the data. Of course, trying to explain US macroeconomic outcomes within the confines of an optimal policy framework offers a number of challenges. Even if the analysis is limited to after the mid-1960s, one must contend with the run-up in inflation that occurred in the 1970s, the disinflation in the 1980s, several large oil price shocks, the Kuwait war, and the recessions that occurred in the early 1980s and 1990s. Indeed, a central message that emerges from estimated policy rules is that while the 1980s and 1990s can be characterized in terms of rules that are empirically stable and that satisfy the Taylor principle,[1] the 1970s cannot (Clarida et al, 2000). Instead, when analyzed in the context of standard macro-policy models, policy rules estimated for the 1970s typically produce instability (in backward-looking models) or indeterminacy (in forward-looking models). In effect, these rules explain the rise in inflation that occurred during the 1970s either in terms of the economy being on an explosive path, which is incompatible with optimal policymaking, or in terms of sun-spots and self-fulfilling expectations.

Because of these difficulties, although we present estimates for data prior to the Volcker disinflation, simply in order to see how the 1960s and 1970s can be best de-

[1] The Taylor-principle asserts that in order to stabilize output and inflation the short-term nominal interest rate should respond more than one-for-one with expected future inflation.

scribed in terms of optimal policymaking, we focus largely on the 1980s and 1990s. For the period following Volcker's appointment to Federal Reserve chairman[2] we investigate how – or even whether – the Volcker-Greenspan period can be characterized in terms of optimal policymaking. We find that the parameters in the policy objective function that best fit the data differ in important ways to the values usually assumed in studies that analyze optimal monetary policy. In particular, we do not find the output gap to be a significant variable in the Federal Reserve's objective function, which suggest that the output gap enters estimated policy rules because of its implications for future inflation, rather than because it is a target variable itself. In addition, we find that describing the data in terms of optimal policymaking requires a much larger weight on interest rate smoothing than is commonly entertained, but that this is not a product of serially correlated policy shocks (c.f. Rudebusch, 2002). The results show that the model does a very good job of explaining economic outcomes during the 1980s and 1990s, and that its impulse response functions are consistent with the responses generated from estimated policy rules. We show that the Federal Reserve's policy objective function changed significantly in the early 1980s and compare our policy regime estimates to the estimates in Favero and Rovelli (2003) and Ozlale (2003).

The structure of this paper is as follows. In the following Section we introduce the model that is used to represent the constraints on the Federal Reserve's optimization problem and present initial estimates of these constraints. The policy objective function that we estimate is introduced and motivated in Section 3. Section 3 also describes how the optimal policy problem is solved and how the model, with the cross-equation restrictions arising from optimal policymaking imposed, is estimated. Section 4 discusses the estimation results and compares them to estimated policy rules and to the estimates in other studies. Section 5 presents looks at the pre-Volcker period and contrasts that period with the Volcker-Greenspan period. Section 6 concludes.

[2] Volcker's tenure as Federal Reserve chairman began in 1979.Q4 and continued until 1987.Q3 when Greenspan was appointed.

2 The Policy Constraints

When central banks optimize they do so subject to constraints dictated by the behavior of other agents in the economy. How well these constraints explain economic behavior is important if useful estimates of the policy preference parameters are to be obtained. In this paper the economy is described using the model developed in Rudebusch and Svensson (1999). We use the Rudebusch-Svensson model in this analysis for several reasons. First, the model is data-consistent, which is important because it will limit what the Federal Reserve can achieve through its actions. Second, the model embeds neo-classical steady-state properties, which prevents policymakers from permanently trading off higher output for higher inflation. Third, the model has been used previously to examine optimal (simple) monetary policy rules (Dennis, 2003a), which allows us to build on the results in those studies.

Of course, it would be interesting to consider other macroeconomic structures, in particular, structures in which private agents are forward-looking. However, forward-looking models tend not to fit the data as well as the Rudebusch-Svensson model (Estrella and Fuhrer, 2002), and the estimation problem becomes significantly more complicated because time-inconsistency issues must be addressed. In this paper we analyze the Rudebusch-Svensson model, paying careful attention to parameter instability. In a companion paper, Dennis (2003b) estimates the policy objective function for the US using an optimization-based New Keynesian sticky-price model in which both households and firms are forward-looking.

According to the Rudebusch-Svensson model, output gap and inflation dynamics are governed by

$$y_t = a_0 + a_1 y_{t-1} + a_2 y_{t-2} + a_3 [i^a_{t-1} - \pi^a_{t-1}] + g_t \quad (1)$$

$$\pi_t = b_0 + b_1 \pi_{t-1} + b_2 \pi_{t-2} + b_3 \pi_{t-3} + (1 - b_1 - b_2 - b_3)\, \pi_{t-4} + b_4 y_{t-1} + v_t, \quad (2)$$

where y_t is the output gap, π_t is annualized quarterly inflation, and i_t is the annualized quarterly federal funds rate. From these variables, annual inflation, $\pi^a_t = \frac{1}{4}\sum_{j=0}^{3} \pi_{t-j}$, and the annual average federal funds rate, $i^a_t = \frac{1}{4}\sum_{j=0}^{3} i_{t-j}$, are constructed. For estimation, $y_t = \log(\frac{Y_t}{Y^p_t}) \times 100$, where Y_t is real GDP and Y^p_t is the Congregational Budget Office measure of potential output, and $\pi_t = \log(\frac{P_t}{P_{t-1}}) \times 400$, where P_t is the GDP chain-weighted price index. The error terms g_t and v_t are interpreted as demand shocks and supply shocks, respectively.

To illustrate the basic characteristics of the model, we estimate equations (1) - (2) using SUR, which allows for the possibility that the demand and supply shocks may be correlated. The sample period considered is 1966.Q1 – 2000.Q2, which covers the oil price shocks in the 1970s, the switch to non-borrowed reserves targeting in late 1979, the Volcker recession in the early 1980s, the oil price fluctuations during the Kuwait war in 1991, and the Asian financial crisis of 1997. In terms of Federal Reserve chairmen, the sample includes all or part of the Martin, Burns, Miller, Volcker, and Greenspan regimes. At this stage, equations (1) and (2) are estimated conditional on the federal funds rate; in Section 4 we estimate these constraints jointly with an (optimization-based) equation for the federal funds rate. Baseline estimates of equations (1) and (2) are shown in Table 1.

Table 1	SUR Parameter Estimates: 1966.Q1 – 2000.Q2				
IS Curve			Phillips Curve		
Parameter	Point Est.	S.E	Parameter	Point Est.	S.E
a_0	0.157	0.110	b_0	0.051	0.088
a_1	1.208	0.080	b_1	0.638	0.084
a_2	-0.292	0.079	b_2	0.023	0.100
a_3	-0.067	0.031	b_3	0.186	0.100
			b_4	0.146	0.035
σ_g^2	0.639		σ_π^2	1.054	

Dynamic homogeneity in the Phillips curve cannot be rejected at the 5% level (p-value = 0.413) and is imposed, ensuring that the Phillips curve is vertical in the long run. A vertical long-run Phillips curve insulates the steady-state of the real economy from monetary policy decisions and from the implicit inflation target, but it also means that the implicit inflation target cannot be identified from the Phillips curve. To estimate the economy's implicit inflation target it is necessary to augment the model with an explicit equation for the federal funds rate, as is done in Section 4. Both lags of the output gap are significant in the IS curve. These lagged output gap terms are important if the model is to have the hump-shaped impulse responses typically found in VAR studies (King, Plosser, Stock, and Watson, 1991; Galí, 1992). From the IS curve, the economy's neutral real interest rate over this period is estimated to be 2.34%.[3]

The point estimates in Table 1 are similar to those obtained in Rudebusch and Svensson (1999), who estimate the model over 1961.Q1 – 1996.Q2, and broadly similar to those obtained in Ozlale (2003), who estimate it over 1970.Q1 – 1999.Q1. However, a potentially important difference between Ozlale's estimates and those in Table 1 (and those in Rudebusch and Svensson, 1999), are that in Ozlale (2003) the parameters a_1 and a_2 sum to more than one, which implies that policymakers must concentrate on stabilizing output if their system is to have a stationary equilibrium.

Subsequent analysis focuses on the period following Volcker's appointment to Federal Reserve chairman, which we term the Volcker-Greenspan period for convenience. However, to compare how the Volcker-Greenspan period differs from the pre-Volcker period, we also estimate the model on data prior to Volcker's appointment, which raises the issue of whether the model's parameters are invariant to the monetary policy regime in operation. Rudebusch and Svensson (1999) use Andrews' (1993) sup-LR parameter stability test to examine this issue. They find no evidence for parameter instability in either the IS curve or the Phillips curve. Ozlale (2003) tests whether the model's parameters are stable using a sup-LR test and a sup-Wald test and does not find any evidence of instability. Reinforcing their results, when we apply Chow tests to dates when parameter breaks might have occurred, such as 1970.Q2, 1978.Q1, 1979.Q4, and 1987.Q3, when changes in Federal Reserve chairman took place, we do not find any evidence of parameter instability.

3 Optimal Policy and Model Estimation

3.1 The Policy Objective Function

The policy objective function that is estimated in this paper takes the standard form

$$Loss = E_t \sum_{j=0}^{\infty} \beta^j [(\pi^a_{t+j} - \pi^*)^2 + \lambda(y_{t+j})^2 + \nu\,(i_{t+j} - i_{t+j-1})^2], \tag{3}$$

where $0 < \beta < 1$, $\lambda, \nu \geq 0$, and E_t is the mathematical expectations operator conditional on period t information. With this objective function, the Federal Reserve is assumed to stabilize annual inflation about a fixed inflation target, π^*, while keeping

[3] From equation (1) the neutral real interest rate can be estimated from $r^* = i^* - \pi^* = -\frac{a_0}{a_3}$.

the output gap close to zero and any changes in the nominal interest rate small. It is assumed that the target values for the output gap and the change in the federal funds rate are zero. The policy preference parameters, or weights, λ and ν, indicate the relative importance policymakers place on output gap stabilization and on interest rate smoothing relative to inflation stabilization.

Equation (3) is an attractive policy objective function to estimate for several reasons. First, from a computational perspective, a discounted quadratic objective function together with linear policy constraints provides access to an extremely powerful set of tools for solving and analyzing linear-quadratic stochastic dynamic optimization problems. Second, equation (3) is overwhelmingly used as the policy objective function in the monetary policy rules literature (see the papers in Taylor, 1999, among many others). Consequently, the estimates of λ and ν that we obtain can be easily interpreted in light of this extensive literature. Third, Bernanke and Mishkin (1997) argue that the Federal Reserve is an implicit inflation targeter and Svensson (1997) shows that equation (3) captures the ideas that motivate inflation targeting. Finally, Woodford (2002) shows that objectives functions like equation (3) can be derived as a quadratic approximation to a representative agent's discounted intertemporal utility function.

In addition to inflation and output stabilization goals, equation (3) allows for interest rate smoothing. Many reasons have been given for why central banks smooth interest rates (see Lowe and Ellis, 1997, or Sack and Wieland, 2000, for useful surveys). These reasons include the fact that: policymakers may feel that too much financial volatility is undesirable because of maturity mis-matches between banks' assets and liabilities (Cukierman, 1989); monetary policy's influence comes through long-term interest rates and persistent movements in short-term interest rates are required to generate the necessary movements in long-term rates (Goodfriend, 1991); smoothing interest rates mimics the inertia that is optimal under precommitment (Woodford, 1999); large movements in interest rates can lead to lost reputation, or credibility, if a policy intervention subsequently needs to be reversed; and, model uncertainty makes it optimal for policymakers to be cautious when changing interest rates (Brainard, 1967). An alternative explanation, based on political economy considerations, is that it is useful to allow some inflation (or disinflation) to occur following shocks because this provides an ex post verifiable reason for policy interventions. Accordingly, policymaker's make interventions that appear smaller than optimal, allowing greater movements in inflation than they might otherwise have, to ensure that they have sufficient grounds to defend their intervention (Goodhart, 1997).

To illustrate the separation that exists between optimal policy rules and estimated policy rules, we solve for an optimal simple forward-looking Taylor-type rule and compare it to the equivalent rule estimated over 1982.Q1 – 2000.Q2. Taking equation (3) as the policy objective function, and setting $\lambda = 1, \nu = 0.25$, and $\beta = 0.99$, the optimal simple Taylor-type rule is[4]

$$i_t = 2.633 E_t \pi^a_{t+1} + 1.750 y_t + 0.172 i_{t-1}. \tag{4}$$

The equivalent empirical specification is[5] (standard errors in parentheses)

$$i_t = \underset{(0.142)}{0.478} E_t \pi^a_{t+1} + \underset{(0.038)}{0.131} y_t + \underset{(0.051)}{0.807} i_{t-1} + \widehat{\omega}_t. \tag{5}$$

There are obvious important differences between equations (4) and (5). In particular, the coefficients on expected future inflation and on the output gap are much bigger in the optimal policy rule than they are in the estimated policy rule. Conversely, the coefficient on the lagged interest rate is around 0.81 in the estimated policy, but only around 0.17 in the optimal policy rule. Clearly, the objective function parameters used to generate this optimal policy rule – which are typical of the values considered in the literature on optimal policy rules – do not reproduce the gradual, but sustained, policy responses that are implied by the estimated policy rule.

3.2 State-Space Form and Optimal Policy

To solve for optimal policy rules we first put the optimization constraints in the state-space form

$$\mathbf{z}_{t+1} = \mathbf{C} + \mathbf{A}\mathbf{z}_t + \mathbf{B}\mathbf{x}_t + \mathbf{u}_{t+1} \tag{6}$$

[4] To solve for this optimal simple Taylor-type rule, the optimization constraints are expressed in terms of deviations-from-means and, without loss of generality, the inflation target, π^*, is normalized to equal zero. the solution algorithm used is presented and discussed in Dennis (2003a).

[5] Equation (5) is estimated using instrumental variables, with the predetermined variables in equations (1) and (2) serving as instruments.

where $\mathbf{z}_t = \begin{bmatrix} \pi_t & \pi_{t-1} & \pi_{t-2} & \pi_{t-3} & y_t & y_{t-1} & i_{t-1} & i_{t-2} & i_{t-3} \end{bmatrix}'$ is the state vector, $\mathbf{u}_{t+1} = \begin{bmatrix} v_{t+1} & 0 & 0 & 0 & g_{t+1} & 0 & 0 & 0 & 0 \end{bmatrix}'$ is the shock vector, which has variance-covariance matrix $\mathbf{\Sigma}$, and $\mathbf{x}_t = \begin{bmatrix} i_t \end{bmatrix}$ is the policy instrument, or control variable. For equations (1) and (2), the matrices in the state-space form are

$$\begin{aligned} \mathbf{C} &= \begin{bmatrix} b_0 & 0 & 0 & 0 & a_0 & 0 & 0 & 0 & 0 \end{bmatrix}', \\ \mathbf{B} &= \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{a_3}{4} & 0 & 1 & 0 & 0 \end{bmatrix}', \end{aligned}$$

and

$$\mathbf{A} = \begin{bmatrix} b_1 & b_2 & b_3 & 1-b_1-b_2-b_3 & b_4 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{a_3}{4} & -\frac{a_3}{4} & -\frac{a_3}{4} & -\frac{a_3}{4} & a_1 & a_2 & \frac{a_3}{4} & \frac{a_3}{4} & \frac{a_3}{4} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}.$$

Next we require that the objective function

$$Loss = E_t \sum_{j=0}^{\infty} \beta^j [(\pi^a_{t+j} - \pi^*)^2 + \lambda (y_{t+j})^2 + \nu \left(i_{t+j} - i_{t+j-1}\right)^2] \tag{7}$$

be written in terms of the state and control vectors as

$$\begin{aligned} Loss &= E_t \sum_{j=0}^{\infty} \beta^j [(\mathbf{z}_{t+j} - \overline{\mathbf{z}})' \mathbf{W} (\mathbf{z}_{t+j} - \overline{\mathbf{z}}) + (\mathbf{x}_{t+j} - \overline{\mathbf{x}})' \mathbf{Q} (\mathbf{x}_{t+j} - \overline{\mathbf{x}}) \\ &\quad + 2(\mathbf{z}_{t+j} - \overline{\mathbf{z}})' \mathbf{H} (\mathbf{x}_{t+j} - \overline{\mathbf{x}}) + 2(\mathbf{x}_{t+j} - \overline{\mathbf{x}})' \mathbf{G} (\mathbf{z}_{t+j} - \overline{\mathbf{z}})], \end{aligned} \tag{8}$$

where $\mathbf{W}$, $\mathbf{Q}$, $\mathbf{H}$, and $\mathbf{G}$ are matrices containing the policy preference parameters and $\overline{\mathbf{x}}$ and $\overline{\mathbf{z}}$ are the implicit targets for the vectors $\mathbf{x}_t$ and $\mathbf{z}_t$, respectively. Notice that the target vectors ($\overline{\mathbf{x}}$ and $\overline{\mathbf{z}}$) are not necessarily independent of each other; from equation (6) they must satisfy $\mathbf{C} + \mathbf{A}\overline{\mathbf{z}} + \mathbf{B}\overline{\mathbf{x}} - \overline{\mathbf{z}} = \mathbf{0}$ to be feasible.

To write equation (7) in terms of equation (8), we first note that the interest rate smoothing component $\nu \left(i_t - i_{t-1}\right)^2$ can be expanded into the three terms $\nu(i_t^2 - 2i_t i_{t-1} + i_{t-1}^2)$. The first of these three terms represents a penalty on the policy instrument; it is accommodated by setting $\mathbf{Q} = [\nu]$. The second term implies a penalty on the interaction between a state variable and the policy instrument. This term is captured by setting $\mathbf{H}' = \mathbf{G} = \begin{bmatrix} \mathbf{0}_{1\times 6} & -\frac{\nu}{2} & \mathbf{0}_{1\times 2} \end{bmatrix}$. The third term represents a penalty on i_{t-1}, which is a state variable. To allow for the penalty terms on the state variables, we introduce a vector of target variables, $\mathbf{p}_t$. Let $\mathbf{p}_t = \mathbf{P}\mathbf{z}_t$ where $\mathbf{P} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$. The first element in $\mathbf{p}_t$ defines annual inflation, the second element is the output gap, and the third element is the lagged federal funds rate. The weights on annual inflation, the output gap, and the lagged federal funds rate are unity, λ, and ν, respectively. Thus, $\mathbf{W} = \mathbf{P}'\mathbf{R}\mathbf{P}$, where $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \nu \end{bmatrix}$.

Following Sargent (1987), for this stochastic linear optimal regulator problem the optimal policy rule is $\mathbf{x}_t = \mathbf{f} + \mathbf{F}\mathbf{z}_t$, where

$$\mathbf{f} = \overline{\mathbf{x}} - \mathbf{F}\overline{\mathbf{z}} \tag{9}$$

$$\mathbf{F} = -(\mathbf{Q} + \beta\mathbf{B}'\mathbf{M}\mathbf{B})^{-1}(\mathbf{H}' + \mathbf{G} + \beta\mathbf{B}'\mathbf{M}\mathbf{A}) \tag{10}$$

$$\mathbf{M} = \mathbf{W} + \mathbf{F}'\mathbf{Q}\mathbf{F} + 2\mathbf{H}\mathbf{F} + 2\mathbf{F}'\mathbf{G} + \beta(\mathbf{A} + \mathbf{B}\mathbf{F})'\mathbf{M}(\mathbf{A} + \mathbf{B}\mathbf{F}). \tag{11}$$

Equations (9) - (11) can be solved by substituting equation (10) into equation (11) and then iterating over the resulting matrix Riccati equation until convergence, thereby obtaining a solution for $\mathbf{M}$. Once a solution for $\mathbf{M}$ has been found, $\mathbf{F}$ and $\mathbf{f}$ can be determined recursively. Alternatively, $\mathbf{F}$ and $\mathbf{M}$ can be solved jointly using a method like Gauss-Seidel, with the constant vector $\mathbf{f}$ then determined recursively.

When subject to control, the state variables evolve according to

$$\mathbf{z}_{t+1} = \mathbf{C} + \mathbf{B}\mathbf{f} + (\mathbf{A} + \mathbf{B}\mathbf{F})\mathbf{z}_t + \mathbf{u}_{t+1}, \tag{12}$$

and the system is stable provided that the spectral radius of $\mathbf{A} + \mathbf{B}\mathbf{F}$ is less than unity. Where this stability condition is met, $\mathbf{z}_t$ is a vector of covariance stationary variables whose unconditional variance-covariance matrix, $\mathbf{\Omega}$, can be evaluated by solving for the fix-point of[6]

$$\mathbf{\Omega} = (\mathbf{A} + \mathbf{B}\mathbf{F})\mathbf{\Omega}(\mathbf{A} + \mathbf{B}\mathbf{F})' + \mathbf{\Sigma}. \tag{13}$$

Notice that the stability condition depends on $\mathbf{F}$, but not $\mathbf{f}$, which implies that $\mathbf{Q}$, $\mathbf{H}$, $\mathbf{G}$, and $\mathbf{W}$, but not $\overline{\mathbf{z}}$ or $\overline{\mathbf{x}}$, influence the system's stability properties.

[6] Once $\mathbf{\Omega}$ has been found using equation (13), it is a simple matter to then solve for the variances of i_t and Δi_t. Let $\mathbf{S} = \begin{bmatrix} \mathbf{0}_{1\times6} & 1 & \mathbf{0}_{1\times2} \end{bmatrix}$ be the selection vector that picks i_{t-1} out of the state vector, then $Var[i_t] = \mathbf{F}\mathbf{\Omega}\mathbf{F}'$ and $Var[\Delta i_t] = (\mathbf{F} - \mathbf{S})\mathbf{\Omega}(\mathbf{F} - \mathbf{S})'$.

3.3 Estimating the System

As shown above, for given values of $a_0 - a_3$, $b_0 - b_4$, λ, ν, and π^*, which are the parameters to be estimated, the system can be written as

$$\mathbf{z}_{t+1} = \mathbf{C} + \mathbf{A}\mathbf{z}_t + \mathbf{B}\mathbf{x}_t + \mathbf{u}_{t+1} \tag{14}$$

$$\mathbf{x}_t = \mathbf{f} + \mathbf{F}\mathbf{z}_t. \tag{15}$$

Having obtained the solution to the optimal policy problem, we rewrite the solution in structural form by writing the model equations as

$$\pi_t = b_0 + b_1\pi_{t-1} + b_2\pi_{t-2} + b_3\pi_{t-3} + (1 - b_1 - b_2 - b_3)\,\pi_{t-4} + b_4 y_{t-1} + v_t \tag{16}$$

$$y_t = a_0 + a_1 y_{t-1} + a_2 y_{t-2} + a_3[i^a_{t-1} - \pi^a_{t-1}] + g_t \tag{17}$$

$$\begin{aligned} i_t = {} & f + F_1\pi_t + F_2\pi_{t-1} + F_3\pi_{t-2} + F_4\pi_{t-3} + F_5 y_t + F_6 y_{t-1} \\ & + F_7 i_{t-1} + F_8 i_{t-2} + F_9 i_{t-3}. \end{aligned} \tag{18}$$

Now defining $\mathbf{y}_t = \begin{bmatrix} \pi_t & y_t & i_t \end{bmatrix}'$, $\boldsymbol{\epsilon}_t = \begin{bmatrix} v_t & g_t & 0 \end{bmatrix}'$, $\mathbf{A}_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -F_1 & -F_5 & 1 \end{bmatrix}$, $\mathbf{A}_2 = \begin{bmatrix} b_1 & b_4 & 0 \\ -\frac{a_3}{4} & a_1 & \frac{a_3}{4} \\ F_2 & F_6 & F_7 \end{bmatrix}$, $\mathbf{A}_3 = \begin{bmatrix} b_2 & 0 & 0 \\ -\frac{a_3}{4} & a_2 & \frac{a_3}{4} \\ F_3 & 0 & F_8 \end{bmatrix}$, $\mathbf{A}_4 = \begin{bmatrix} b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ F_4 & 0 & F_9 \end{bmatrix}$, $\mathbf{A}_5 = \begin{bmatrix} 1 - b_1 - b_2 - b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ 0 & 0 & 0 \end{bmatrix}$, and $\mathbf{A}_1 = \begin{bmatrix} b_0 \\ a_0 \\ f \end{bmatrix}$, the model becomes

$$\mathbf{A}_0\mathbf{y}_t = \mathbf{A}_1 + \mathbf{A}_2\mathbf{y}_{t-1} + \mathbf{A}_3\mathbf{y}_{t-2} + \mathbf{A}_4\mathbf{y}_{t-3} + \mathbf{A}_5\mathbf{y}_{t-4} + \boldsymbol{\epsilon}_t, \tag{19}$$

which is an over-identified structural VAR(4) model.

Let $\boldsymbol{\Psi}$ denote the variance-covariance matrix of the disturbance vector, $\boldsymbol{\epsilon}_t$, and let $\boldsymbol{\theta} = \{a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3, b_4, \lambda, \nu, \pi^*\}$, then by construction $\mathbf{A}_0$, $\mathbf{A}_1$, $\mathbf{A}_2$, $\mathbf{A}_3$, and $\mathbf{A}_4$ are each functions of $\boldsymbol{\theta}$. The subjective discount factor, β, is set to its conventional value of 0.99, but the sensitivity of the estimates to different values of β is examined.

The joint probability density function (PDF) for the data is

$$P\left(\{\mathbf{y}_t\}_1^T; \boldsymbol{\theta}, \boldsymbol{\Psi}\right) = P\left(\{\mathbf{y}_t\}_5^T | \{\mathbf{y}_t\}_1^4; \boldsymbol{\theta}, \boldsymbol{\Psi}\right) P\left(\{\mathbf{y}_t\}_1^4; \boldsymbol{\theta}, \boldsymbol{\Psi}\right),$$

where T is the sample size, including initial conditions. Now we postulate that $\boldsymbol{\epsilon}_t | \{\mathbf{y}_j\}_1^t \sim N(0, \Psi)$ for all t, then, from equation (19), the joint PDF for $\{\mathbf{y}_t\}_1^T$ can be expressed as

$$P\left(\{\mathbf{y}_t\}_1^T;\boldsymbol{\theta},\boldsymbol{\Psi}\right)=\left[\frac{1}{(2\pi)^{\frac{n(T-4)}{2}}}\left|\mathbf{A}_0\right|^{(T-4)}\left|\boldsymbol{\Psi}^{-1}\right|^{\frac{n}{2}}\exp\sum_{t=5}^{T}\left(-\frac{1}{2}\boldsymbol{\epsilon}_t'\boldsymbol{\Psi}^{-1}\boldsymbol{\epsilon}_t\right)\right]P\left(\{\mathbf{y}_t\}_1^4;\boldsymbol{\theta},\boldsymbol{\Psi}\right),$$

where n equals the number of stochastic endogenous variables, i.e., three. We assume that the initial conditions $\{\mathbf{y}_t\}_1^4$ are fixed and thus that $P\left(\{\mathbf{y}_t\}_1^4;\theta,\Psi\right)$ is a proportionality constant. From this joint PDF the following quasi-loglikelihood function is obtained

$$\ln L\left(\boldsymbol{\theta},\boldsymbol{\Psi};\{\mathbf{y}_t\}_1^T\right)\propto-\frac{n(T-4)}{2}\ln(2\pi)+(T-4)\ln\left|\mathbf{A}_0\right|-\frac{n}{2}\ln\left|\boldsymbol{\Psi}\right|-\frac{1}{2}\sum_{t=5}^{T}\left(\boldsymbol{\epsilon}_t'\boldsymbol{\Psi}^{-1}\boldsymbol{\epsilon}_t\right).$$

The QMLE of $\boldsymbol{\Psi}$ is

$$\widehat{\boldsymbol{\Psi}}(\theta)=\sum_{t=5}^{T}\frac{\widehat{\boldsymbol{\epsilon}}_t\widehat{\boldsymbol{\epsilon}}_t'}{T-4},\tag{20}$$

which can be used to concentrate the quasi-loglikelihood function, giving

$$\ln L_c\left(\boldsymbol{\theta};\{\mathbf{y}_t\}_1^T\right)\propto-\frac{n(T-4)}{2}(1+\ln(2\pi))+(T-4)\ln\left|\mathbf{A}_0\right|-\frac{n}{2}\ln\left|\widehat{\boldsymbol{\Psi}}(\theta)\right|.\tag{21}$$

In the following Section we estimate $\boldsymbol{\theta}$ by maximizing equation (21), and then use equation (20) to recover an estimate of $\boldsymbol{\Psi}$. As the problem currently stands, however, $\boldsymbol{\Psi}$ is not invertable because there are three variables in $\mathbf{y}_t$, but only two shocks in $\boldsymbol{\epsilon}_t$. Consequently, $\ln|\boldsymbol{\Psi}|=-\infty$ and $\ln L_c\left(\boldsymbol{\theta};\{\mathbf{y}_t\}_1^T\right)=\infty$ for all $\boldsymbol{\theta}$, and the model parameters cannot be estimated. This singularity is a standard hurdle for estimation problems involving optimal decision rules. Following Hansen and Sargent (1980), the approach we take is to assume that the econometrician has less information than the policymaker and that, therefore, the decision rule that the econometrician estimates omits some variables. These omitted variables are captured through a disturbance term, ω_t, which is appended to equation (18) when the model is estimated. This disturbance term, which we will refer to as the policy shock (for lack of a better name), eliminates the singularity in $\boldsymbol{\Psi}$, allowing estimation to proceed.

To test the significance of the estimated parameters, the variance-covariance matrix for $\widehat{\boldsymbol{\theta}}$ is constructed using

$$Var(\widehat{\boldsymbol{\theta}})=\left[\mathbf{H}(\boldsymbol{\theta})|_{\widehat{\boldsymbol{\theta}}}\right]^{-1}\left[\mathbf{G}(\boldsymbol{\theta})|_{\widehat{\boldsymbol{\theta}}}\right]\left[\mathbf{H}(\boldsymbol{\theta})|_{\widehat{\boldsymbol{\theta}}}\right]^{-1},\tag{22}$$

where $\mathbf{H}(\boldsymbol{\theta}) = -\left[\frac{\partial^2 \ln L_c(\boldsymbol{\theta};\{\mathbf{y}_t\}_1^T)}{\partial\boldsymbol{\theta}\partial\boldsymbol{\theta}'}\right]$ is the inverse of the Fisher-Information matrix and $\mathbf{G}(\boldsymbol{\theta}) = \left[\frac{1}{T-4}\sum_{t=5}^{T}\left(\frac{\partial \ln L_c^t(\boldsymbol{\theta};\{\mathbf{y}_j\}_{t-4}^t)}{\partial\boldsymbol{\theta}}\frac{\partial \ln L_c^t(\boldsymbol{\theta};\{\mathbf{y}_j\}_{t-4}^t)}{\partial\boldsymbol{\theta}'}\right)\right]$ is the outer-product variance estimator; both $\mathbf{H}(\boldsymbol{\theta})$ and $\mathbf{G}(\boldsymbol{\theta})$ are evaluated at $\widehat{\boldsymbol{\theta}}$. Equation (22) is the quasi-maximum-likelihood estimator for the variance-covariance matrix of the parameter estimates (White, 1982). For an alternative estimation method, see Chow (1981) or Salemi (1995).

4 Estimation Results

In this Section we apply the estimation approach developed in Section 3 to estimate jointly the parameters in equations (1), (2), and (3). The sample period that we estimate the model over begins in 1982.Q1 and ends in 2000.Q2, a period we will refer to as the Volcker-Greenspan period. We begin the sample in 1982.Q1 to exclude the period when first non-borrowed reserves and then total reserves were targeted.[7] We are interested in examining whether economic outcomes during the Volcker-Greenspan period can be explained within an optimal policy framework, and what the policy objective function parameters are that best explain US macroeconomic data. We are also interested in estimating the implicit inflation target that enters the policy objective function. The results are shown in Table 2.

Table 2	Quasi-FIML Parameter Estimates: 1982.Q1 – 2000.Q2				
IS Curve			Phillips Curve		
Parameter	Point Est.	S.E	Parameter	Point Est.	S.E
a_0	0.035	0.098	b_0	0.025	0.092
a_1	1.596	0.073	b_1	0.401	0.104
a_2	-0.683	0.052	b_2	0.080	0.111
a_3	-0.021	0.017	b_3	0.407	0.115
			b_4	0.144	0.042
σ_g^2	0.312		σ_π^2	0.492	
	Policy Regime Parameters				
Parameter	Point Est.	S.E	Other Results		
λ	2.941	5.685	$\widehat{r}^* = 1.66$	$\ln L = -198.106$	
ν	4.517	1.749	$\widehat{\pi}^* = 1.38$	$\widehat{\sigma}_\omega^2 = 0.318$	

[7] This is a period when short-term interest rates were very volatile and for which it is implausible to treat the federal funds rate as the policy instrument.

The parameter estimates in the optimization constraints are precisely estimated and they have the conventional signs. Relative to the full sample estimates in Table 1, although the sample period is shorter here, it is clear that the cross-equation restrictions that stem from optimal policymaking greatly improve the efficiency with which the parameters in the constraints are estimated.

Table 2 shows that over the Volcker-Greenspan period the neutral real interest rate is estimated to be 1.66% and that the implicit inflation target is estimated to be 1.38%. One of the most interesting results is that the relative weight on the output gap in the objective function, λ, is insignificantly different from zero. This result suggests that the Federal Reserve does not have an output gap stabilization goal and that the reason the output gap is statistically significant in estimated policy rules is not that it is a target variable, but rather that it contains information about future inflation. While it contrasts with the assumptions underlying flexible inflation targeting (Svensson, 1997), the fact that λ is statistically insignificant is completely consistent with other studies. Favero and Rovelli (2003) estimate λ to be close to zero, as do Castelnuovo and Surico (2001). Using calibration, Söderlind, Söderström, and Vredin (2002) argue that a small, or zero, value for λ is necessary to match the low volatility in inflation and the high volatility in output that are observed in US data. Dennis (2003b) finds λ to be insignificant in a model where households and firms are forward looking.

The second interesting finding is that the interest rate smoothing term is significant. This result supports the widely held belief that central banks, including the Federal Reserve, smooth interest rates (McCallum, 1994; Collins and Siklos, 2001). Importantly, the estimates that we obtain quantify – in terms of policy objectives – the interest rate smoothing that takes place, which allows the importance that the Federal Reserve places on interest rate smoothing to be assessed relative to other goals.

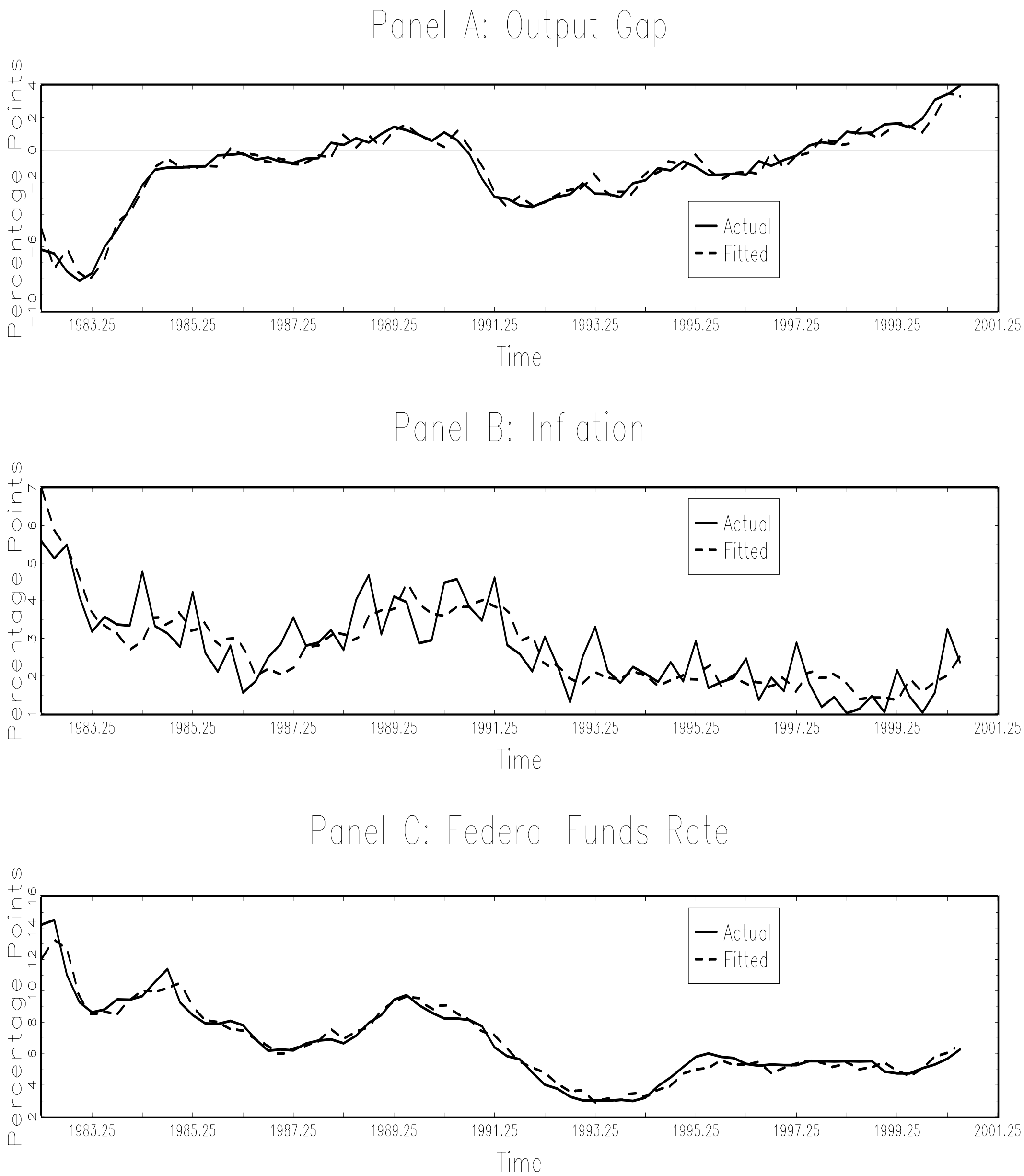

Figure 1: The Model's Fit to the Data

Figure 1 shows the data for the output gap, inflation, and the federal funds rate and the corresponding fitted values from the model. The model clearly does a good job of fitting the data over this period, capturing without difficulty the decline in inflation that occurred in the early 1980s, the Volcker-recession and the 1990 recession, the high growth of the late 1990s, as well as the changes to the federal funds rate that occurred in response to the changing economic environment. Moreover, the residuals for the three series do not display any obvious serial correlation and their properties do not change in late 1987 when Greenspan became chairman. Nevertheless, we formally test whether the policy shocks are serially independent later in the Section.

Before leaving this sub-section, it is interesting to test whether monetary policy was set optimally during the Volcker-Greenspan period. To perform this test, we estimate equations (1) and (2) jointly with an equation for the federal funds rate that contains all of the variables in the state vector. Estimating the three-equation system using maximum likelihood, we obtain the following equation for the federal funds rate (standard errors in parentheses)

$$\begin{aligned} i_t &= \underset{(0.234)}{-0.278} + \underset{(0.511)}{0.054}\pi_t + \underset{(0.243)}{0.202}\pi_{t-1} + \underset{(0.095)}{0.293}\pi_{t-2} - \underset{(0.236)}{0.063}\pi_{t-3} \\ &\quad + \underset{(0.273)}{0.965}y_t - \underset{(0.261)}{0.775}y_{t-1} + \underset{(0.099)}{0.854}i_{t-1} - \underset{(0.125)}{0.207}i_{t-2} + \underset{(0.085)}{0.192}i_{t-3} + \widehat{\omega}_t, \end{aligned} \tag{23}$$

where, $\widehat{\sigma}_\omega = 0.589$. For this three-equation system in which the coefficients in the policy rule are unrestricted, the value for the loglikelihood function is -190.587. The structure of the output gap and inflation equations are the same and there are 10 freely estimated parameters in equation (23), but only 3 freely estimated parameters, λ, ν, and π^*, in the optimal policy model, so optimal policymaking implies 7 restrictions on the unrestricted policy rule (equation, 23). With 7 degrees of freedom, a likelihood ratio test can reject the null hypothesis that monetary policy was set optimally over this period at the 5% level, but not at the 1% level.

To put this result in context, if we constrain the parameters in equation (23) so that they conform to an outcome-based Taylor-type rule and re-estimate the three-equation system, then we obtain (standard errors in parentheses)

$$i_t = \underset{(0.214)}{0.094} + \underset{(0.136)}{0.442}\pi_t^a + \underset{(0.037)}{0.150}y_t + \underset{(0.053)}{0.812}i_{t-1} + \widehat{\omega}_t, \qquad \widehat{\sigma}_\omega = 0.586. \tag{24}$$

When monetary policy is restricted to follow a Talyor-type rule, the value of the log-likelihood function is -201.885, which implies that the null hypothesis that monetary policy was set according to this Taylor-type rule can be rejected using a likelihood ratio test both at the 5% level and at the 1% level. Interestingly, while it does not constitute a formal hypothesis test (because the models are non-nested) the loglikelihood function is higher when policy is set optimally than when policy is set according to the outcome-based Taylor-type rule (equation, 24).

4.1 Serially Independent Policy Shocks

While the results above suggest that the Federal Reserve does smooth interest rates, it is possible that the persistence in the federal funds rate is actually an "illusion" caused by serially correlated shocks to the policy rule (Rudebusch, 2002). The basic argument in Rudebusch (2002) is that when policy rules are freely estimated, rules with lagged dependent variables and rules with serially correlated shocks are statistically difficult to disentangle using direct testing methods. For this reason, it is possible that the lagged interest rates that typically enter estimated policy rules simply soak up persistence introduced by serially correlated policy shocks.

When monetary policy is set optimally, however, the variables that enter the policy rule are determined by the system's state vector. Consequently, the lagged interest rate variables in the state vector enter the optimal rule because they help policymakers forecast output and inflation. Because they are part of the state vector these lagged interest rates would enter the optimal policy rule even if $\nu = 0$. Thus, testing whether lagged interest rates are significant in the policy rule does not necessarily amount to a test for interest rate smoothing. But, when monetary policy is set optimally, additional structure is introduced that facilitates a direct test between interest rate smoothing ($\nu > 0$) and serially correlated shocks.

While Figure 1 does not suggest that the monetary policy shocks are serially correlated, to formally test whether serially correlated policy shocks are spuriously making ν significant we re-estimate the system allowing ω_t to follow an AR(1) process, i.e., $\omega_t = \rho\omega_{t-1} + \eta_t$, $|\rho| < 1$, and modify the quasi-loglikelihood function accordingly. The quasi-loglikelihood function becomes

$$\begin{aligned} \ln L\left(\rho, \boldsymbol{\theta}, \boldsymbol{\Phi}; \{\mathbf{y}_t\}_1^T\right) \quad \propto \quad & -\frac{n(T-5)}{2}\ln(2\pi) + (T-5)\ln|\mathbf{A}_0| - \frac{n}{2}\ln|\boldsymbol{\Phi}| + \frac{1}{2}\ln(1-\rho^2) \\ & -\frac{1}{2}\sum_{t=6}^{T}\left(\boldsymbol{\varsigma}_t'\boldsymbol{\Phi}^{-1}\boldsymbol{\varsigma}_t\right), \end{aligned}$$

where $\boldsymbol{\varsigma}_t = \begin{bmatrix} v_t & g_t & \eta_t \end{bmatrix}'$ is postulated to be $N[0, \boldsymbol{\Phi}]$. Then, in the notation of Section 3.3, $\boldsymbol{\epsilon}_t = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \rho \end{bmatrix} \boldsymbol{\epsilon}_{t-1} + \boldsymbol{\varsigma}_t$. Results are shown in Table 3.

Table 3	Quasi-FIML Parameter Estimates with AR(1) Correction: 1982.Q1 – 2000.Q2				
IS Curve			Phillips Curve		
Parameter	Point Est.	S.E	Parameter	Point Est.	S.E
a_0	0.036	0.091	b_0	0.025	0.091
a_1	1.596	0.076	b_1	0.401	0.104
a_2	-0.682	0.054	b_2	0.080	0.110
a_3	-0.021	0.014	b_3	0.406	0.117
			b_4	0.144	0.041
σ_g^2	0.312		σ_π^2	0.492	
	Policy Regime Parameters				
Parameter	Point Est.	S.E	Other Results		
λ	2.823	4.515	$\widehat{r}^* = 1.70$	$\ln L = -198.096$	
ν	4.455	1.897	$\widehat{\pi}^* = 1.41$	$\widehat{\sigma}_\omega^2 = 0.319$	
ρ	0.016	0.221			

The most notable aspect of Table 3 is that ρ, the autocorrelation coefficient in the policy shock process, is not significantly different from zero. Moreover, allowing for serially correlated policy shocks does not alter the other parameter estimates and the estimate of ν, while falling slightly, remains significant; λ is still insignificantly different from zero. These results show that the fact that ν is significant is not due to serially correlated policy shocks.

4.2 Sensitivity to the Discount Factor

We now examine how the policy regime estimates change as the discount factor, β, is varied. Here we re-estimate the model while varying β between 0.95 and 1.00, the plausible range for quarterly data. As before, the sample period is 1982.Q1 – 2000.Q2. Results are shown in Table 4; standard errors are in parentheses.

Table 4	Regime Parameters as β Varies		
β	$\widehat{\lambda}$	$\widehat{\nu}$	$\widehat{\pi}^*$
0.95	1.16 (1.75)	1.69 (0.80)	1.56
0.96	1.40 (2.20)	2.07 (0.93)	1.52
0.97	1.73 (2.87)	2.59 (1.07)	1.48
0.98	2.20 (3.88)	3.35 (1.29)	1.43
0.99	2.94 (5.69)	4.52 (1.75)	1.38
1.00	4.23 (9.27)	6.56 (3.36)	1.33

Table 4 shows that qualitatively the results are not sensitive to the assumed value for β. In each case the weight on output gap stabilization is insignificant and the weight on interest rate smoothing is significant. The inflation target varies between 1.33% and 1.56%. Interestingly, as β falls the estimates of λ and ν both decline, while the estimate of π^* rises. Greater discounting leads to policymakers having less concern for the future and for the economic implications of their policy interventions. In turn, less concern for the future is associated with a smaller interest rate smoothing parameter because less concern for the future is also associated with less need to make large policy interventions to offset shocks. The fact that $\widehat{\lambda}$ and $\widehat{\nu}$ decline with β is consistent with Favero and Rovelli's policy regime estimates, which are very small.[8]

4.3 Optimal Policy Estimates and Estimated Policy Rules

In this Section, we examine how the estimated optimal policy model responds to demand and supply shocks. In particular, we compare the impulse responses that are generated using the estimated optimal policy preferences in Table 2 against a benchmark model and against the policy preferences estimated in Favero and Rovelli (2003) and in Ozlale (2003). Using models similar to that estimated in this paper, Favero and Rovelli (2003) estimate $\widehat{\lambda} = 0.00125$ and $\widehat{\nu} = 0.0085$ and Ozlale (2003) estimates $\widehat{\lambda} = 0.488$ and $\widehat{\nu} = 0.837$. Not only are Favero and Rovelli's and Ozlale's estimates very different to each other, but they are also quite different to the estimates we obtain. Given this wide variation in results, it is interesting to see how the various policy regime estimates compare to the timeseries properties of US data, as summarized by a benchmark model.

For this exercise, the benchmark model consists of equations (1), (2), and the outcome-based Taylor-type rule, equation (24), that was estimated jointly using maximum-likelihood over 1982.Q1 – 2000.Q2 in Section 4. This benchmark model – with monetary policy set according to a Taylor-type rule – is used to generate baseline impulse responses showing how output, inflation, and the federal funds rate respond to unit demand and supply shocks, and to generate 95% confidence bands for these impulse responses.[9] Then we take the policy preferences estimated in Table 2, in Favero and Rovelli (2003), and in Ozlale (2003), solve for their corresponding

[8] Favero and Rovelli (2003) assume that policymakers discount the future with $\beta = 0.975$, and ignore outcomes that occur after four periods (i.e., $\beta = 0$ is applied to economic outcomes that occur five or more quarters into the future).

[9] The 95% confidence bands were generated using 50,000 simulations.

optimal policy rules, and use these rules to construct impulse response functions for output, inflation, and the federal funds rate. The impulses for the different policy preferences and those for the benchmark model and their 95% confidence bands are shown in Figure 2.

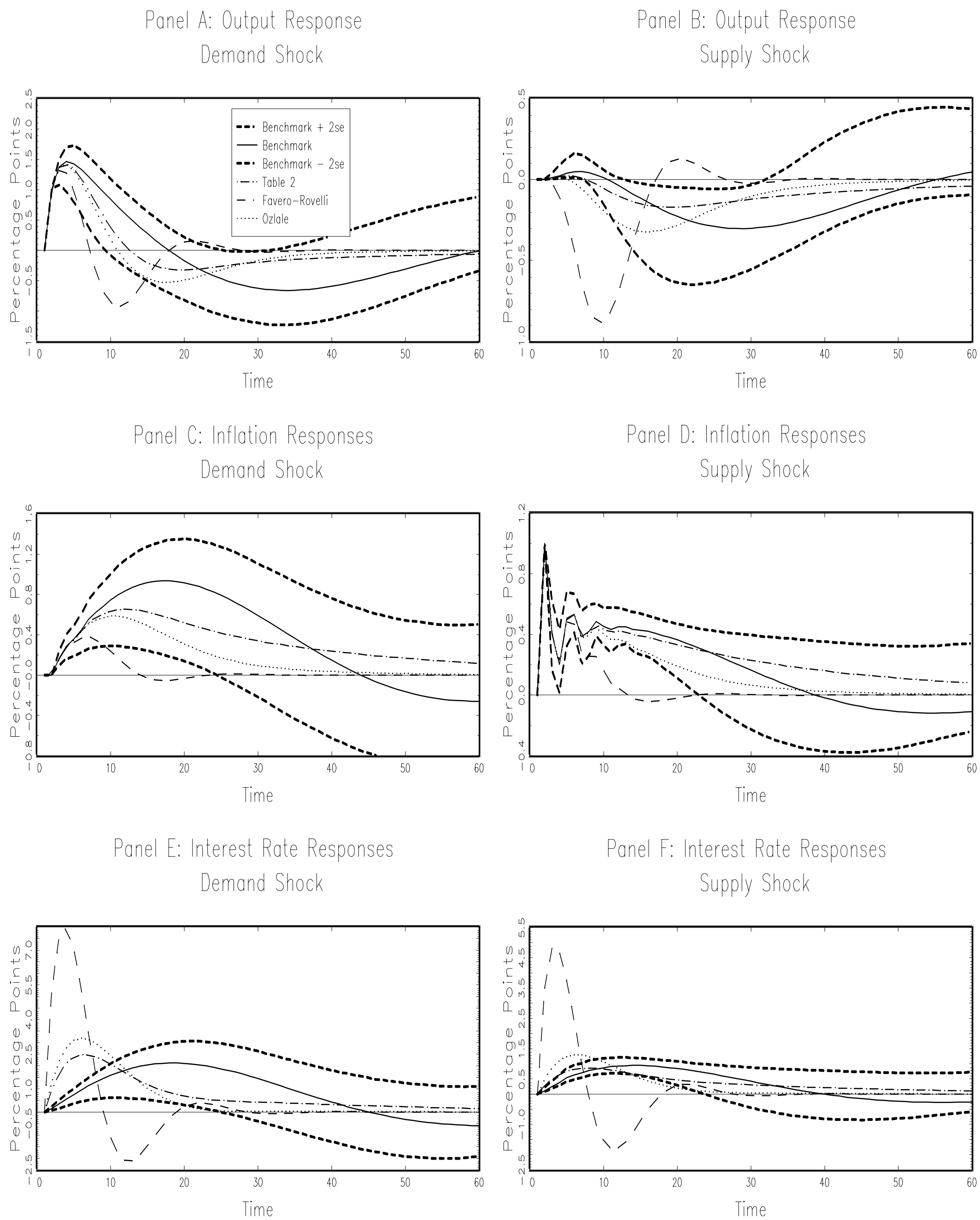

Figure 2: Optimal Policy Rules and Estimated Policy Rules

Figure 2 illustrates that the policy rule resulting from the policy preferences estimated in Table 2 produces impulse response functions that are consistent with those generated from the benchmark model. Only for the interest rates response immediately following the demand shock (Panels E) are there any significant deviations from the benchmark responses. However, the interest rate responses based on estimates in Favero and Rovelli (2003) and in Ozlale (2003) deviate even further from the benchmark responses (see Panels E and F). As the estimated coefficients in equation (24) show, the policy rule in the benchmark model contains a very weak response to movements in the output gap, and this weak response is difficult to reconcile with optimal policy behavior. Nevertheless, in most respects, the policy preference parameters that we estimate for the Volcker-Greenspan period produce a monetary policy rule that captures the central features of the estimated policy rule.

The impulse responses based on Ozlale's policy preference estimates are qualitatively similar to the impulses generated by our estimates. The greater weight placed on interest rate smoothing that we obtain does impart a noticeable level of persistence that is not present when Ozlale's estimates are used, but in other respects the impulses tell similar stories. Still, when Ozlale's estimates are used the impulse responses are significantly different from the benchmark responses in a number of important respects. In particular, the output gap and interest rate responses to both demand and supply shocks violate the 95% confidence bands (see Panels A and B and Panels E and F).

Turning to the impulse response functions generated from the policy preferences estimated in Favero and Rovelli (2003), Figure 2 demonstrates that these responses are very different to the responses that come from our estimates and from Ozlale's estimates. More importantly, Favero and Rovelli's policy preferences produce large swings in the interest rate and the output gap responses to demand and supply shocks that are very different to the benchmark responses.

Given that the Ozlale (2003) and the Favero and Rovelli (2003) policy preference estimates are based on a similar model for the optimization constraints and on the same specification for the policy objective function, it is useful to consider why the policy preference estimates are so different. One reason is that they use different sample periods to estimate λ and ν.[10] Other possible reasons are that Favero and Rovelli (2003) use a simplified version of the Rudebusch-Svensson model, limiting the inflation dynamics in the Phillips curve, and that Ozlale (2003) uses a different output gap variable when estimating the Rudebusch-Svensson model.[11] The fact that the lagged output gap coefficients in Ozlale's IS curve sum to more than one appears to be a consequence of using this different output gap variable.

Other areas where the studies differ are in the values assumed for the discount factor. Ozlale (2003) assumes that $\beta = 1$ whereas our baseline estimates assume that $\beta = 0.99$. However, even if we set $\beta = 1$ the estimates that we obtain are still very different to Ozlale's (see Table 4). Favero and Rovelli (2003), on the other hand, assume that the Federal Reserve only looks four quarters ahead, and that these four quarters are discounted with $\beta = 0.975$. Truncating the policy horizon in the objective function, which Favero and Rovelli must do to implement their GMM estimator, may account for the very small estimates of λ and ν that they obtain. Finally, an important difference between Ozlale's estimation approach and the approach we take is that Ozlale (2003) estimates the optimization constraints over 1970.Q1 – 1999.Q1, and then conditions on these estimates when estimating λ and ν for the Volcker-Greenspan period. In contrast, when analyzing the Volcker-Greenspan period, we estimate the constraints and the policy regime parameters jointly, along with their standard errors.

5 A Look at the Pre-Volcker Period

In this Section we re-estimate the optimal policy model, but this time for the period 1966.Q1 – 1979.Q3. The estimation period begins in 1966.Q1, because only after 1966.Q1 did the federal funds rate trade consistently above the discount rate. Thus, prior to 1966.Q1 it seems implausible to assume that the federal funds rate was the policy instrument (Fuhrer, 2000). The sustained rise in inflation that occurred in the 1970s makes it a difficult period to analyze within an optimal policy framework. However, estimating the model over this period gives us a consistent framework within

[10] Favero and Rovelli (2003) estimate their model over 1980.Q3 – 1998.Q3 while Ozlale (2003) estimates his model over 1979.Q3 – 1999.Q1.

[11] Ozlale (2003) uses a quadratic trend in place of the Congressional Budget Office measure of potential output to construct his output gap variable.

which to compare the pre-Volcker period to the Volcker-Greenspan period. Moreover, it allows us to quantify how economic outcomes during the pre-Volcker period can be best explained within the confines of an optimal policy environment. The model estimates are shown in Table 5.

Table 5	Quasi-FIML Parameter Estimates: 1966.Q1 – 1979.Q3				
IS Curve			Phillips Curve		
Parameter	Point Est.	S.E	Parameter	Point Est.	S.E
a_0	0.125	0.144	b_0	0.010	0.194
a_1	1.133	0.165	b_1	0.749	0.142
a_2	-0.175	0.189	b_2	-0.062	0.173
a_3	-0.170	0.117	b_3	0.026	0.156
			b_4	0.178	0.067
σ_g^2	0.834		σ_π^2	1.647	
	Policy Regime Parameters				
Parameter	Point Est.	S.E	Other Results		
λ	3.141	8.229	$\widehat{r}^* = 0.74$	$\ln L = -229.920$	
ν	37.168	57.847	$\widehat{\pi}^* = 6.96$	$\widehat{\sigma}_\omega^2 = 0.680$	

For the pre-Volcker period the parameter estimates are clearly less precisely estimated than they are for the Volcker-Greenspan period, largely due to the shorter sample length, but the key characteristics of the Rudebusch-Svensson model come through. Over the pre-Volcker period, the neutral real interest rate is estimated to be 0.74% and the implicit inflation target is estimated to be 6.96%. However, the estimates of the policy preference parameters are not significantly different from zero. Their insignificance suggests that the policy preference parameters are only weakly identified, which may simply be due to the sample's short length, or it may indicate that the policy regime was not stable. The latter could be the case because the sample period spans three Federal Reserve chairmen.[12] For this reason, the policy regime estimated in Table 5 is perhaps best viewed as the "average" regime in operation over the period. The estimates in Table 5 show, however, that to interpret the pre-Volcker period in terms of an optimal policy regime requires a large implicit inflation target, with the sustained deviations from this implicit inflation target ascribed to a strong preference for interest rate smoothing.

[12] Unfortunately, the sample period is too short to use to analyze the policies of the three chairmen individually.

Comparing the estimates in Table 5 with those in Table 2, it is clear that the residual standard errors for all three equations are much smaller for the Volcker-Greenspan period than they are for the pre-Volcker period. The fact that the volatility of the shocks impacting the economy have declined in the 1980s and 1990s relative to the 1960s and 1970s is discussed in Sims (1999) and is noted in Favero and Rovelli (2003). Turning to the policy preference parameters, the estimates suggest that policymakers were much more likely to smooth interest rates, and to adjust policy in small increments, during the pre-Volcker period than subsequently, but that the relative weight on output stabilization has not changed much over time.

A useful way to illustrate the differences between the pre-Volcker regime and the Volcker-Greenspan regime is through impulse response functions.[13] In Figure 1 unit demand and supply shocks are applied to the model and the resulting dynamics are graphed for both policy regimes. Panels A and C correspond to the pre-Volcker period, complementing Panels B and D, which relate to the Volcker-Greenspan period. Results for supply shocks are shown in Panels A and B; Panels C and D present the responses to the demand shock.

Considering the 1% supply shock impulse responses first, the greatest difference between the two regimes is apparent in how interest rates respond to the shock. For the Volcker-Greenspan regime policymakers raise the federal funds rate more quickly, and by more, than they do for the pre-Volcker regime. The outcome of this more aggressive policy intervention is that output falls more under the Volcker-Greenspan regime than it does under the pre-Volcker regime and, consequently, as inflation returns to target, the average deviation between π_t and π^* is smaller. Under both regimes the real interest rate actually falls when the supply shock occurs, leading to a small boost in output relative to potential. Over the longer term, however, policymakers raise the nominal interest rate by more than the increase in inflation, the real interest rate rises, which damps demand pressure and causes inflation to return to target.

[13] To underscore the economic differences that are due to the change in regime, the impulse responses in Figure 1 are produced using the IS curve and Phillips curve estimates from Table 1. Given the same dynamic constraints, Panels A - D indicate how policymakers respond to demand and supply shocks between the two regimes.

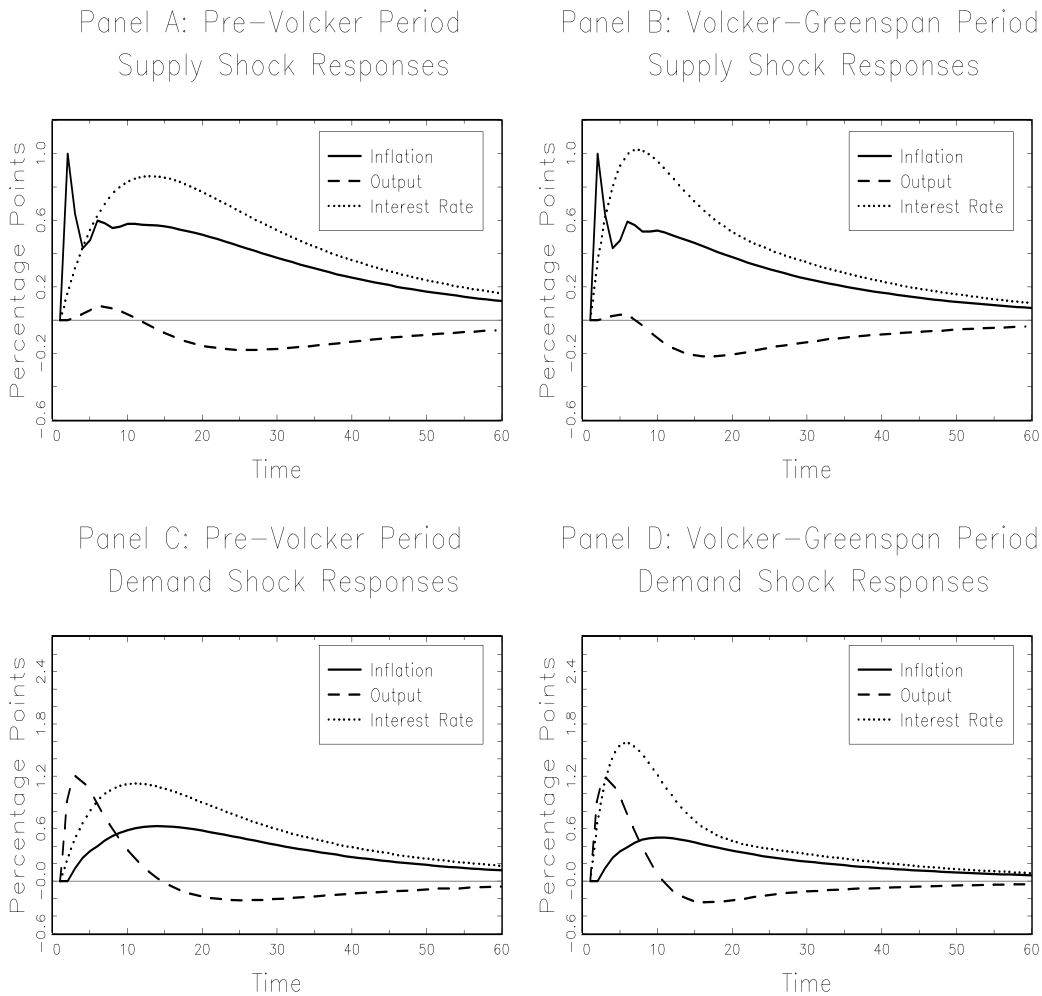

Figure 3: Impulse Response Functions for Volcker-Greenspan and Pre-Volcker Periods

Greater differences between the two regimes can be seen in the responses to the demand shock. Comparing Panel C with Panel D, it is clear that policymakers respond to the demand shock far more aggressively under the Volcker-Greenspan regime than they do under the pre-Volcker regime. For a 1% demand shock, the federal funds rate is raised as much as 160 basis points under the Volcker-Greenspan regime, but only about 100 basis points under the pre-Volcker regime. Moreover, under the Volcker-Greenspan regime the federal funds rate is raised much more quickly in response to the shock. Because policymakers respond to the demand shock by tightening policy more quickly and more aggressively, inflation responds less, staying closer to target.

To test whether the monetary policy regime in operation has remained constant from 1966.Q1 – 2000.Q2, we estimate the optimal policy model for the full sample and then re-estimate the model allowing a break in the monetary policy regime (λ, ν, π^*) to occur at the time Volcker became chairman. The value for the loglikelihood is -558.259 when a single policy regime is imposed, rising to -545.147 when a break with Volcker's appointment in introduced. With three parameter restrictions and a likelihood-ratio statistic of 26.224, the null hypothesis that the policy regime did not change when Volcker became chairman can be easily rejected at the 1% level.

6 Conclusion

This paper estimated the policy objective function for the Federal Reserve from 1966 onward using a popular data-consistent macroeconometric model to describe movements in output and inflation. To estimate the policy regime parameters we assumed that monetary policy was determined as the solution to a constrained optimization problem. The solution to this constrained optimization problem determines the decision rule, or optimal policy rule, that the Federal Reserve uses to set the federal funds rate. With interest rates set optimally, the estimation process then involved backing out from the way macroeconomic variables evolve over time, and relative to each other, the objective function parameters and the parameters in the optimization constraints that best describe the data. This approach avoids the need to estimate an unconstrained reduced form policy rule, which is advantageous because reduced form policy rules are subject to the Lucas critique.

On the basis that US monetary policy is set optimally, and that the Federal Reserve's policy objective functions is within the quadratic class standard for the literature, we use FIML to jointly estimate the parameters in the optimization constraints and the policy regime parameters, including the implicit inflation target. Focusing on the Volcker-Greenspan period, we estimate the implicit inflation target to be around 1.4% and find that the Federal Reserve placed a large and statistically significant weight on interest rate smoothing, providing further evidence that central bank's, like the Federal Reserve, dislike making large changes in interest rates. Allowing for serially correlated policy shocks does not affect the magnitude or the significance of the interest rate smoothing term. Consistent with other analyses, we do not find the output gap to be a statistically significant term in the Federal Reserve's policy objective function. For the pre-Volcker period the weight on interest rate smoothing is numerically large, but not statistically significant, possibly because the pre-Volcker period may not be a single policy regime. The implicit inflation target is estimated to be around 7%, and again the weight on output stabilization is not statistically significant.

There are a number of areas where the analysis in this paper could be usefully extended. For the pre-Volcker period, the rise in inflation that occurred during the 1970s makes the assumption that the implicit inflation target was constant difficult to mesh with the data. An alternative would be model the pre-Volcker period while allowing the inflation target to evolve according to some stochastic process. It would also be interesting to allow for issues related to real-time policymaking. In particular, in light of the issues raised in Orphanides (2001), it would be interesting to investigate whether the results change in any material way if we restrict policy decisions to be based only on information available when policy decisions were made. However, tackling the issue of real-time data when the model is dynamic, and estimating the model using systems-methods, is non-trivial. A third important extension is to allow private agents to be forward-looking. When private agents are forward-looking the issue of time-inconsistency arises and must be allowed for, which complicates the estimation problem. Along inroads have been made, work in this area is still preliminary; see Söderlind (1999), Salemi (2001), and Dennis, (2003) for three different approaches to estimating policy preferences using forward-looking models.

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