Does the Fed Act Cautiously? Evaluating Monetary Policy from Central Bank's Preferences[*]

Efrem Castelnuovo and Paolo Surico[†]
Bocconi University and FEEM; Bocconi University

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Abstract

The design of monetary policy depends upon the targeting strategy adopted by the central bank. This strategy describes a set of policy preferences, which are actually the structural parameters to analyze monetary policy making. Accordingly, we develop a novel calibration method to identify central bank's preferences from the estimates of an optimal (US) data-consistent Taylor-type rule. The empirical analysis shows that output stabilization has not been an independent argument in the Fed's objective function during the Greenspan's era. This suggests that the output gap has entered the policy rule only as leading indicator for future inflation. Furthermore, the preference estimates imply that the responses of policy rates to inflation and output gaps have been more moderate than those recommended by the optimal rule. This cautiousness can be rationalized by incorporating model uncertainty about the relevant macroeconomic dynamics into the derivation of the optimal policy responses.

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[†] Corresponding author: Paolo Surico, Università Bocconi, Via Sarfatti 25, 20136 Milan, Italy. E-mail: paolo.surico@uni-bocconi.it

1 Introduction

A burgeoning empirical literature has established interest rate rules as a convenient representation of central bank's behaviour. Since the in‡uential paper of John Taylor (1993) numerous speci…cations of the policy rule have been proposed to describe the response of monetary authorities to the developments in the economy. The main focus has been the evaluation of monetary policy as well as the identi…cation of policy regime shifts from the estimates of alternative Taylor-type reaction functions[1].

From a theoretical point of view, interest rate rules have been modeled as the solution of a constrained optimization problem in which policy makers pursue in a quadratic fashion the stabilization of several goal variables around the relative targets. According to this modeling, the estimated policy rule coe¢cients can only be interpreted as convolutions of the parameters describing central bank's preferences (i.e. the coe¢cients in the objective function) and the parameters framing the structure of the economy (i.e. the coe¢cients in the constraints). It follows that those are reduced form estimates and therefore they cannot be used to analyze the structural features of policy making that characterize a monetary regime.

In contrast, the preference parameters in the central bank's objective function capture those structural features and they are worthy to identify for three main reasons. First, to improve our understanding of policy actions because any decision can be more easily interpreted once the scope is identi…ed. Second, to assess the performance of monetary policy by establishing

[1] These include Bernanke and Mihov (1997 and 1998), and Bagliano and Favero (1998) who specify the policy rule as a part of monetary policy vector autoregressions; Judd and Rudebusch (1998), and Clarida, Galì and Gertler (1998 and 2000) that formulate a simple ad-hoc reaction function; and Rudebusch (2001), and Muscatelli, Tirelli and Trecroci (2000) who model an optimal state-contingent feedback rule, among many others.

if the policy outcome is the pursued result of targeted policies rather than the random payo¤ of favorable macroeconomic conditions. Third, to carry out policy evaluations from the comparison between optimal and observed interest rates, since a sample-speci…c optimal rule can only be derived once the preference parameters are estimated over that sample.

Accordingly, we develop a novel calibration method to extract central bank's preferences from the estimates of the reaction function that solves the policy makers' optimization problem. In particular, we select among a fairly wide class of alternative targeting policies, the set of preference parameters that makes the associated optimal path of policy rates closest to the estimated path. We apply our identi…cation method to US data by identifying the policy preferences of the Federal Reserve during the Greenspan's chairmanship. The empirical analysis shows that the stabilization of output over the cycle has not been a …nal concern of monetary authorities, although the Fed has set policy rates in response to both in‡ation and output gaps. This implies that any deviation of output from its potential value has been regarded as a leading indicator for future in‡ation, thus being only instrumental to stabilize in‡ation rather than important per sè.

Our work is closely related to several recent studies. Favero and Rovelli (2001) identify central bank's preferences by estimating via GMM the Euler equations for the solution of alternative speci…cations of the optimization problem. Cecchetti and Ehrmann (2001) capture the dynamics of the economy in a VAR framework and then recover policy makers' preferences from the estimates of the output-in‡ation variability and those obtained via VAR. Dennis (2001) uses FIML to jointly estimate the policy preferences in the central bank's objective function and the structural parameters in the constraints of the economy. While our purpose stands by those of previous studies, we departure from them along two lines. First, we employ a di¤erent identi…cation method since we estimate (in a loose sense) the preference parameters via calibration. Second, we use these estimates to derive the path that would have characterized interest rates if the central bank had historically implemented the optimal policy rule, thereby delivering a benchmark for policy evaluation. Indeed, the preference estimates imply that the Fed has conducted a less activist monetary policy than recommended by the optimal rule. For this reason, we investigate whether the lack of knowledge that policy makers face about the macroeconomic dynamics may rationalize such a result. By implementing the approach to model uncertainty developed in Granger (2000), we …nd that a simple average of all optimal rules in a given class of models can account for much of the observed cautiousness.

The paper is organized as follows. Section 2 sets up the model and solves the optimization problem relevant to the central bank. Section 3 discusses in details the calibration method, which is applied in section 4 to estimate the preference parameters and evaluate the conduct of monetary policy during the Greenspan's tenure. The task of section 5 is to solve the uncertainty about the relevant structure of the economy by delivering a robust interest rate rule. Section 6 concludes, while the appendix provides a guideline to solve numerically the optimal control problem.

2 The model

The central bank faces a dynamic optimal control problem whose solution describes its policy actions. These are the optimal response of monetary authorities to the evolution of the economy as captured by the structural relationships among the state variables. We describe such a dynamics by means of a simple closed economy-two equation framework made up of an aggregate supply and an aggregate demand, which actually represent the constraints of the policy makers' optimization problem.

2.1 The structure of the economy

The empirical evidence from VAR studies shows that monetary policy affects the economy at different lags (see Christiano, Eichenbaum and Evans, 1996, and Bernanke and Mihov, 1998). Furthermore, if the central bank faces an intertemporal optimization problem, then forecasting the behaviour of the state variables (i.e. inflation and output gap) becomes crucial to set policy rates as the optimal response to the developments in the economy. It follows that for the purpose of monetary policy making, which relies on forecasting method, a backward-looking model is likely to be prefered to a forward-looking one since the former overperforms the latter in fitting the data (see Fuhrer, 1997).

Accordingly, we let the structure of the economy evolve as follows:

$$\pi_{t+1} = \alpha_1\pi_t + \alpha_2\pi_{t-1} + \alpha_3\pi_{t-2} + \alpha_4\pi_{t-3} + \alpha_5 y_t + \varepsilon_{t+1} \tag{1}$$

$$y_{t+1} = \beta_1 y_t + \beta_2 y_{t-1} + \beta_3(\bar{i}_t - \bar{\pi}_t - \bar{r}) + u_{t+1} \tag{2}$$

where π_t is the quarterly inflation in the GDP chain-weighted price index, p_t, calculated at annual rate, that is $4(p_t - p_{t-1})$, and $\bar{\pi}_t$ is four-quarter inflation constructed as $\frac{1}{4}\sum_{j=0}\pi_{t-j}$. The quarterly average federal funds rate, i_t, is expressed in percent per year whereas the four quarter average federal funds rate, $\bar{i}_t$, is computed as $\frac{1}{4}\sum_{j=0} i_{t-j}$. The constant $\bar{r}$ stands for the average real interest rates, and ε_t and u_t are supply and demand iid shocks respectively. All variables but the funds rate are in logs, demeaned and rescaled upward on a 100 point basis such that the output gap, say, is $y_t = 100 \times (\log(Q_t) - \log(Q_t^*))$ where Q_t and Q_t^* are respectively actual and potential GDP, both in levels. Therefore, no constants appear in the equations and μ is set equal to zero.

The aggregate supply (AS) equation in (1) captures the inflation dynamics by relating inflation to its lagged values and to current and lagged output gap, the latter being defined as the difference between actual and potential GDP. On the other hand, the aggregate demand (AD) equation in (2) explicitely models the transmission mechanism through which monetary policies have an impact on the economy by relating the output gap to its lagged values and most importantly to past real interest rate (see Rudebusch and Svensson, 1999 and 2001).

This structural model, although parsimonious, embodies the minimal set of variables one may want to include for the purpose of monetary policy analyses (see, for instance, Christiano, Eichenbaum and Evans, 1998), and, as argued in Rudebusch and Svensson (1999), it appears to be broadly in line with the view that policy makers hold about the dynamics of the economy (see the Bank for International Settlements report, 1995). Moreover, monetary policy affects (through the instrument i_t) aggregate demand with one lag and aggregate supply with two lags, in accordance to the model in Ball (1999) and Svensson (1997). Finally, the dynamics summarized in (1) and (2) have a nice modeling feature. They can be interpreted either as structural relationships, as we do, or as a reduced-form VAR, thus being reconciled with most of the literature that uses unrestricted VARs to describe monetary transmission dynamics.

2.2 The loss function and the optimal monetary policy

We assume that monetary authorities operate according to a targeting rule as defined in Svensson (1999a), and Rudebusch and Svensson (1999)[2]. Thus, they use all available information to bring at each point in time the target variables in line with their targets by penalizing any future deviation of the former from the latter. This type of rule seems to be closer than an instrument rule, which is a prescribed rule coming from an 'once and for all' decision making (see McCallum, 1999), to the actual practice of policy makers since it embodies some degree of commitment (to a loss function) and some degree of discretion (through a state-contingent rule)[3]. Following Rudebusch and Svensson (1999 and 2001), we let the central bank pursue the stabilization of the four-quarter inflation around the inflation target, the stabilization of the output around its potential value and the smoothing of interest rate. The inflation target is assumed to be constant over time and it is normalized to zero because all variables are demeaned[4]. Then, policy rates are set to minimize the following objective function:

$$\lambda_{\pi} Var[\bar{\pi}_t] + \lambda_y Var[y_t] + \lambda_{\Delta i} Var[\Delta i_t] \qquad (3)$$

The quarterly average short-term interest rate, i_t, is regarded as the instrument under policy makers' control whereas Δi_t represents its first difference. The parameters λ_{π} and λ_y are the focus of our analysis. They represent the

[2] Accordingly, we label 'target variables' the variables in the objective function (and not those in the reaction function). Our terminology lines up with the one in Cecchetti (1997), Walsh (1998, Ch. 8), Clarida, Galì and Getler (1999), Rudebusch and Svensson (1999), and Svensson (1999c).

[3] See McCallum (2000) for a stimulating discussion of rule-based versus discretionary targeting regime.

[4] Our analysis is meant to identify the central bank's preferences over the target variables rather than to estimate the targets per sè. A number of papers cover the issue, including Judd and Rudebusch (1998), Sack (2000), Favero and Rovelli (2001) and Dennis (2001).

(potentially time-variant) central bank's policy preferences towards in‡ation and output stabilization respectively. We constrain both parameters to be non negative meaning that the central bank values any deviation of either in‡ation or output from the target as a bad. Finally, we normalize the weights in the objective function to sum to one and in accordance to Rudebusch and Svensson (1999 and 2001) we assume ¸$_{¢ i}$ = 0:2.

While we admit that the speci…cation in (3) is quite ad-hoc, we stress that the inclusion of an interest rate smoothing term in the objective function improves the ability of the associated policy rule to match the data (see Clarida, Galì and Gertler, 1998 and 2000, and Muscatelli, Tirelli and Trecroci, 2000)[5]. A rationale for why interest rate behaviour displays policy inertia is beyond the scope of this paper, although several explanations are provided in the literature[6].

The optimal control problem described in (1)-(3) falls in the class of dynamic programming problems characterized by a quadratic objective function and a linear law of motion. This speci…cation leads to the stochastic optimal linear regulator problem according to which the decision rule for

[5] Goodfriend (1987), Walsh (1998, Ch. 10), Miskin (1999), Svensson (1999b) and Woodford (2001) interestingly discuss why interest rate smoothing may be an explicit objective into policy makers' preferences. Alternatively, the observed policy inertia can be rationalized either by imposing some form of partial adjustment of actual interest rates towards the equilibrium value or by introducing strong serial correlation and long lags in monetary policy e¤ects throught the economic dynamics. However, to remain consistent with other empirical studies, we take the …rst view and we let interest rate smoothing enter the central bank's objective function.

[6] These include persistence in the structure of the economy (Sack, 2000 and Rudebusch, 2001a), serially correlated shocks rule (Rudebusch, 2001b), uncertainty about the e¤ects of movements in policy rates (Sack, 1998), uncertainty about the structure of the economy and parameter instability (Favero and Milani, 2001), commitment of the authorities which want to have a quick and strong impact on the economy by simply reversing the direction of policy rate changes (Woodford, 1999), or fear of disruption of …nancial markets (Goodfriend, 1991).

interest rates is a linear function of the state variable vector

$$X_t' = \begin{bmatrix} \pi_t & \pi_{t-1} & \pi_{t-2} & \pi_{t-3} & y_t & y_{t-1} & i_{t-1} & i_{t-2} & i_{t-3} \end{bmatrix}$$

In particular, the central bank minimizes the loss (3) subject to the dynamic constraints (1) and (2). In so doing, it determines an optimal reaction function that can be expressed in the compact form[7]:

$$i_t = f X_t \tag{4}$$

The coefficients in the vector f represent some convolution of the central bank's preferences, λs, and the structural parameters of the economy, αs and βs, such that for any given distribution of weights in (3) there exists a different optimal f in (4).

3 Identifying central bank's preferences

Once defined the object of our analysis, we have to search for a strategy to move from the reduced form parameters in the policy rule to the structural ones in the objective function. In this section we propose a calibration method to extract the policy preferences, λs, from the vector of feedback coefficients, f.

We estimate the reaction function in (4) and we solve numerically the stochastic optimal linear regulator problem for alternative targeting policies (i.e. for alternative distribution of weights λs in the loss function). Among those, we select the pair $[\lambda_\pi, \lambda_y]$ that makes the associated optimal interest rate path closest to the estimated path. In so doing, we calibrate the central bank's preferences to deliver the fitted behaviour of policy rates that comes

[7] The appendix provides a full derivation of the feedback rule that solves the stochastic optimal linear regulator problem.

from the estimation of the optimal state-contingent rule derived in (4). By defining our measure of distance upon fitted rather than actual rates we restrict our attention to the systematic component of policy rate behaviour, that is, to the component we can explain within an optimal control framework.

The strategy can be seized in five steps:

i) constraint estimates: we estimate the AD-AS system as specified in (1) and (2). The estimates roughly summarize the structure of the economy over a given sample and they will enter the recursive formulation of our simulated economy.

ii) reaction function estimates: we estimate the reduced form reaction function derived in (4) and we call $\hat{\imath}_t = \hat{f} X_t$ the fitted value of policy rate at time t, where $\hat{f}$ is the vector of feedback coefficient estimates.

iii) optimal control problem solution: since changing the set of policy makers' preferences, $[\lambda_\pi, \lambda_y]$, changes the feedback coefficients in the optimal rule, we solve the stochastic optimal linear regulator problem for alternative targeting policies. In other words, we compute numerically as many vectors of optimal feedback coefficients f in (4) as the number of possible permutations of the λs over the range $[0; 1 - \lambda_{\Delta i}]$, where steps are one percent point basis.

iv) implied optimal interest rate path: we first substitute, period by period, the actual values of the state variables into the derived rules, and then we compute for each optimal f the interest rate path implied by the relative control problem. We define it as $i_t = f(\lambda_\pi; \lambda_y) X_t$ to stress that any optimal path depends upon the specification of a set of central bank's preferences.

v) policy preference calibration: we select the set of policy preferences capable to deliver the minimum distance between fitted and optimal interest rate according to a canonical measure of the type proposed in Sack(2000), and Cecchetti, McConnell and Perez-Quiros (1999):

$$\sum_t [i_t(\lambda_\pi, \lambda_y) - \hat{i}_t]^2 \tag{5}$$

With an identification strategy at hand, we can evaluate the monetary policy making over a specific sample. This is the focus of the next section.

4 The conduct of monetary policy in the US

In this section we apply our identification method to US data. Our goal is to estimate the Federal Reserve policy preferences over a given period and to establish the sensitivity of these results to robustness and stability analyses. A natural time-break candidate for sample selection is the appointment of Paul Volker in the October 1979 since it has represented the watershed for the US economy from an high to a low inflation era. However, with a backward.looking model, the selection of a long time-horizon may undermine the stability of the structural parameters, which is an important condition for drawing inference and surviving the Lucas critique (1976). This consideration motivates our focus on a single tenure, namely the one of Alan Greenspan. Indeed, one may argue that this period has been characterized not only by an increased stability and a lower inflation (see Cecchetti, Flores-Lagunes and Krause, 2001, and Mishkin and Schmidt-Hebbel, 2001) but also by the expectations of some form of inflation targeting. For this reason, we first recover the Fed policy preferences over the period 1987:3-2001:1 and then, given those, we determine the path that the policy rates would have followed if the derived optimal rule had been implemented since

Greenspan's appointment. Such a simulated behaviour provides a benchmark for the evaluation of monetary policy over the sample.

4.1 A small empirical model of the US economy

We capture the dynamics of the US economy by applying OLS method to the AD-AS system described in (1) and (2). The potential output is obtained from the Congressional Budget Office whereas all other data are taken from the web-site of the Federal Reserve Bank of St. Louis. In particular, we collect monthly time-series for the Fed funds rate, quarterly data for the GDP chain-weighted 1996 commodity price index and quarterly data for the potential output. All series are seasonally adjusted. We then convert monthly data in quarterly data by taking end-of-quarter observations. Lastly, we de-mean all variables.

The estimates are as follows, standard errors in parenthesis:

$$\pi_{t+1} = \underset{(0.133)}{0.282}\pi_t - \underset{(0.134)}{0.025}\pi_{t-1} + \underset{(0.134)}{0.292}\pi_{t-2} + \underset{(0.136)}{0.385}\pi_{t-3} + \underset{(0.054)}{0.141}y_t + \varepsilon_{t+1} \quad (6)$$

$$y_{t+1} = \underset{(0.136)}{1.229}y_t - \underset{(0.149)}{0.244}y_{t-1} - \underset{(0.078)}{0.073}(\bar{i}_t - \bar{\pi}_t) + \eta_{t+1} \quad (7)$$

The system displays a reasonably good empirical fit with an Adjusted R^2 equal to 0.58 for the AS and 0.93 for the AD[8]. All estimates have the expected sign but the second lag of inflation in the AS, although it is not significantly different from zero.

Given the backward-looking nature of the problem, the derivation of the optimal policy rule in (4) relies on the assumption that the structure of the economy is invariant to monetary policy, and therefore it is subject to the Lucas critique (1976). However, we show below not only that the policy

[8] Moreover, the cross-correlation of the errors is 0.137, implying that the parameter estimates are not affected by the estimation method.

preference estimates are stable over the sample but also that the associated optimal path of interest rates displays substantial policy inertia and limited deviations from the estimated one. It follows that one may reasonably expect structural parameters to be stable as well, thereby reducing the significance of the Lucas critique.

Then, we make the model consistent with our implementation by the timing assumption that although the Fed sets policy rates in response to contemporaneous changes in the underlying economy, the former do not have any contemporaneuos impact on the latter. Hence, we estimate by OLS the stochastic version of the optimal rule derived in (4). The estimates yield the following results:

$$\begin{aligned} i_t = {} & \underset{(0.07)}{0.212}\pi_t + \underset{(0.08)}{0.043}\pi_{t-1} + \underset{(0.08)}{0.151}\pi_{t-2} - \underset{(0.09)}{0.177}\pi_{t-3} + \underset{(0.10)}{0.346}y_t + \\ & - \underset{(0.11)}{0.265}y_{t-1} + \underset{(0.14)}{1.259}i_{t-1} - \underset{(0.20)}{0.398}i_{t-2} - \underset{(0.12)}{0.008}i_{t-3} + \varepsilon_t \end{aligned} \tag{8}$$

with an Adjusted R^2 of 0.96. The coefficients show that monetary authorities adjust gradually funds rates in response to both inflation and output gaps since the relevant parameters are significantly different from zero. In particular, the first lag of the funds rate implies that the Fed tends to move its instrument in a particular direction over sustained periods, while the second lag confirms the potential for few reversals in the policy rate path (see Rudebusch, 1995, and Goodhart, 1997).

The reduced form estimates of the feedback coefficients are convolutions of the very structural parameters described above and thus, they are not well-suited to address structural issues as the characterization of a monetary regime. Conversely, our method serves to extract from those feedback estimates the component that refer to central bank's preferences.

4.2 The Fed policy preferences

The behaviour of policy rates in our framework can be determined by three factors: the (variability of) supply and demand shocks, the dynamics of the economy and the policy preferences of the central bank. In a linear model with a quadratic loss function the certainty equivalence principle holds, and hence the solution to the control problem is unaffected by the additive uncertainty in the constraints. Furthermore, we assume that the Fed knows with certainty the dynamics of the economy as described by the point estimates in the AS and AD. It follows that our identification strategy, which selects the optimal interest rate path closest to the observed path, turns out to be particularly well-suited to recover policy makers' preferences as these remain the main determinant of interest rate movements.

The optimal path of policy rates is derived given the actual history of the economy at each point in time, that is, it is obtained by substituting the vector of actual state variables, period by period, into the optimal policy rule. Since the optimal path depends upon the specification of a set of policy preferences, we use our calibration method to identify the preferences of the US Federal Reserve over the sample. Then, we compute for any quarter the optimal level of funds rate, given that the Fed has behaved in accordance to the estimated policy preferences and that it has previously implemented the actual level of interest rates. Figure 1 plots the optimal values of policy rates that the preference estimates imply whereas Figure 2 plots the actual series of inflation. In particular, the first graph displays the optimal policy rule associated to the estimates $\lambda_{\pi} = 0.80$ and $\lambda_{y} = 0.00$, after having imposed $\lambda_{\Delta i} = 0.20$.

Insert Figure 1 and 2 about here

The optimal policy effectively captures the main features of funds rate movements under the Greenspan's chairmanship, although it predicts an higher level of interest rates both at the beginning and at the end of the sample. Since inflation is found to be the only final concern of the Fed and since it is affected by interest rates with two lags, we look at the structural relationship between forwarded inflation and current interest rates. Interestingly, a comparison between Figures 1 and 2 shows that whenever observed policy rates are lower (higher) than those predicted by the optimal rule, inflation is high (low) and above (below) its target, which is zero by construction[9]. This seems to call for a time-varying inflation target over the sample. However, to be consistent with other empirical analyses, we keep a constant inflation target. Our findings line up with those in Sack (2000), although we use a different specification of the economic structure and most importantly a different set of policy preferences.

The preferences estimates are not significantly affected by imposing other values for the interest rate-smoothing weight, $\lambda_{\Delta i}$, since the value of λ_π turns out to be always the complement to one of any $\lambda_{\Delta i}$ value. Furthermore, the higher the preference parameter on inflation stabilization, the better is the match between optimal and estimated rates for any given value of the interest rate-smoothing coefficient. This suggests that the conduct of monetary policy in the US is successfully described by a strict inflation targeting as defined in Rudebusch and Svensson (2001) and Ball (1999), and according to which the stabilization of output around its potential value has not been a final concern of monetary authorities (i.e. $\lambda_y = 0.00$). However, we do not mean that the output gap has not been important in policy

[9] It can be shown in our set up that demeaning all variables corresponds to target inflation to its sample mean. In particular, such a mean is 2.49, which seems to be a reasonable value for the inflation target over the sample.

actions. Indeed, the feedback rule estimates show that it has been regarded as a leading indicator for future inflation rather than as a goal variable (i.e. it is an argument in the reaction function rather than in the loss), consistently with the results in Favero and Rovelli (2001), and Dennis (2001).

4.3 Sensitivity analysis

The estimates of the central bank's policy preferences rely on the assumption that the AD-AS system specified in (1) and (2) is actually the macroeconometric model that policy makers have in mind. Indeed, researchers are uncertain about what it is, along both the parameter and the model dimension. In particular, monetary authorities may use sub-sample windows to capture the changing of the economic structure or may employ a different dynamics specification of their empirical model. For this reason, we relax in turn the assumptions that both the structural parameters and the model specification are time-invariant in order to assess the robustness of our estimates. First, given the model (1)-(2), we perform rolling sub-sample estimates to identify the associated values of the US policy makers' preferences for five-year moving windows. The estimates over time of the inflation stabilization coefficient, λ_π, are plotted in Figure 3 for the benchmark case (i.e. $\lambda_{\Delta i} = 0.2$).

Insert Figure 3 about here

The results are overwhelming and more general than those shown in the graph. For any value of $\lambda_{\Delta i}$, the parameter on inflation stabilization turns out to be fairly stable. Moreover, once we eliminate for the outlayer in the first quarter of 1999, its full sample mean is virtually equal to 0.8, implying that the monetary policy of the Fed can be evaluated within a single policy regime.

We turn now the attention on alternative specifications of the economic structure that might as well be relevant to monetary authorities. The goal is to identify of a set of policy preferences robust to model uncertainty[10]. To this end, we apply our calibration method to a number of structural models that display a good empirical fit. These come from the combination of the top ten AS with the top ten AD in a given class of specifications. The ranking is based on the Akaike model selection criterion while the class of models includes all combinations of the first four lags of inflation and outputgap respectively, and the first lag of interest rate in the AD-AS system. In ninty out of one hundred cases, a strict inflation targeting overperforms any other targeting strategy and not surprisingly the outlayers are the specifications combining the alternative AS equations with the only 'theoretically not plausible' AD, namely the one that positively depends on interest rate.

This evidence shows that our findings are stable and robust to both model and parameter uncertainty, and therefore they accurately describe the Fed policy preferences under the Greenspan's chairmanship.

4.4 A benchmark for policy evaluation

Once policy preferences are identified, it is possible to simulate the path that funds rates would have followed if the Fed had historycally implemented the optimal policy rule. Such a path is plotted in Figure 4 and it is derived by substituting, period by period, the simulated dynamics of the state variables into the reaction function. It should be noticed that in contrast to Figure 1, Figure 4 considers simulated rather than actual values for the evolution of the vector X. In other words, we allow the Fed to optimize recursively taking at each point in time the optimal policy rates as those that have been

[10] We stress that the source of model uncertainty here is the unknown view that policy makers hold about the economy rather than the unknown dynamics of the real world.

previously implemented. In so doing, we provide a benchmark compared to which monetary policy can be evaluated over the last thirteen years.

Insert Figure 4 about here

The graph shows that estimated and simulated policy rates comove over time, although they display signi…cant di¤erences in magnitude. In particular, whenever the optimal rule predicts high policy rates the actual values increase but they are are never that high. The picture is reversed for the middle sample where the estimated policy rates do not decrease as much as those simulated by the optimal rule. As a result, the recommended funds rate path is more volatile and less smooth than the observed one. The qualitative di¤erence between the two series is quantitatively con…rmed by the results in Table 1.

Insert Table 1 about here

Panel A shows the feedback estimates whereas Panel B reports the simulated coe¢cients for the most signi…cant and explicative variables in the policy rule, namely the contemporaneous in‡ation, the contemporaneous output gap and the …rst lagged interest rate. As one may expect from the graph, the observed central bank's responses to both in‡ation and output gaps are smaller than those predicted by the optimal rule. In contrast, the policy inertia coe¢cient is halfed moving from the actual to the simulated interest rate path. Moreover, we reject the null that the three parameter estimates are equal to their optimal counterpart both individually and jointly.

These …ndings seems to call for the cautiousness in monetary policy making that has been recently advocated in the literature and according to which observed policy rates respond to the evolution of the economy less aggressively than suggested by the optimal rule (see Rudebusch, 2001a; Sack, 2000 and Söderström, 1999b; Goodhart, 1999).

5 Model uncertainty

Recent empirical studies show that uncertainty can provide a rationale for the observed cautiousness in the US monetary policy. Such a …nding is in line with those in the seminal paper of Brainard (1967) from which this literature originates. While there exists a consensus by now on this view, whether the relevant source of Fed timidity be model or parameter misspeci…cation it is still an open debate. Indeed, by using a parsimonious structural model and a simple policy rule, Brainard-type multiplicative parameter uncertainty is found to generate only negligible attenuations of policy action (see Rudebusch, 2001a; Estrella and Miskin, 1999; and Peersman and Smets, 1999). Conversely, by employing unrestricted VARs and unrestricted policy rules, parameter uncertainty results in a moderate conduct of monetary policy (see Sach, 1998, and Söderström, 1999b). However, as argued in Rudebusch (2001a) the rich parametrization that characterizes unrestricted rule is derived from the large set of variables included in the VAR. Therefore, the latter result is likely to re‡ect the small-sample estimates of the numerous econometrically super‡ous regressors rather than those of the minimal set of variables relevant to analize monetary policy (see Christiano, Eichenbaum and Evans, 1998).

Given our parsimonious speci…cation of both the structure of the economy and the policy rule, we line up with the former strand of the literature, and accordingly we investigate whether model uncertainty is capable to account for the policy cautiousness that seems to characterize also the Greenspan era. To this end and in contrast to the sensitivity analysis, we assume that the Fed policy preferences are known with certainty, as given by the estimates above. Hence, the only source of uncertainty is now the policy makers' agnosticism about what model provides the best description of the 'true' economic dynamics.

It should be noticed that unlike previous studies, which assess the robustness of their results over alternative speci…cations of the economy and consequently of the policy rule, we propose a strategy to nest in a single reaction function the relevant information embodied in a given class of models. In so doing, we follow the 'thick' modeling proposed by Granger (2000) '...to keep all close speci…cations, …nd their outputs that relate to the design of optimal monetary policy [...] and pool these values. [...] A simple method of combining them is to give equal weights after removing a few outlayers'. The label 'thick', as opposed to 'thin', re‡ects the fact that if one estimates and plots each model-speci…cation she will get a 'thick' representation of the optimal monetary policy, that is, a curve whose width is made up of as many 'thin' curves as the number of speci…cations that survive the trimming of the outlayers.

Before discussing our 'thick' strategy, we consider worthwhile to describe how model uncertainty has been traditionally approached.

5.1 Traditional approaches

With uncertainty about the model structure, a reaction function, which is optimal under a single speci…cation, might perform quite poorly if that speci…cation does not capture properly the 'true' economic dynamics. Then, a safer alternative may be to search for a rule that, while not optimal in any given structural model, it may perform reasonably well over a range of plausible speci…cations (i.e. over a range of plausible economic scenarios). This consideration has motivated a growing empirical literature on monetary policy making under model uncertainty, which advocates the robustness of simple policy rules (see McCallum, 1998; Levine, Wieland and Williams, 1999; Taylor, 1999b; Rudebusch, 2001a). In particular, McCallum (1998), and Levine, Wieland and Williams (1999) show respectively that monetary-base instrument rules and first difference interest rate ones overperform optimal rules when uncertainty is added to the picture. Yet, in this framework model uncertainty, combined with data uncertainty, appears to be the source of cautiousness in the Fed's behaviour, although it alone is not enough to reconcile the optimal and historycal policies (see Rudebusch, 2001a).

An alternative approach to resolving model uncertainty is provided by the techniques of robust control (see Hansen and Sargent, 2001). This method specifies a risk function (that can be easily reinterpreted as the loss function in the monetary policy literature) and a minimax criterion needed to perturbate the policy makers' model. The latter is assumed to be an approximation that belongs to a potentially time varying and state dependent neighborhood of the 'true' model of the economy. Then, given the least favorable scenario, that is roughly speaking the maximum value that the loss function can take in that neighborhood, the robust optimal reaction function is chosen so as to minimize the maximum value function. Interestingly, Sargent (1999), Stock (1999), and Onatski and Stock (2002) show that this criterion implies robust policy rules more aggressive than those obtained without model uncertainty, in sharp contrast to the findings above.

5.2 A novel approach: 'thick modeling'

We implement now the 'thick' approach to model uncertainty developed in Granger (2000) by specifying a class of models for the structure of the economy and proposing an a priori criterion to pool into a single policy rule the information that relate to the design of monetary policy. To this end, we estimate by OLS the dynamics generated by the relevant combinations of a base set of eight regressors for the AS and nine for the AD whose richest specification takes the following form:

$$\pi_{t+1} = \alpha_1 \pi_t + \alpha_2 \pi_{t-1} + \alpha_3 \pi_{t-2} + \alpha_4 \pi_{t-3} + \alpha_5 y_t + \alpha_6 y_{t-1} + \alpha_7 y_{t-2} + \alpha_8 y_{t-3} + \varepsilon_{t+1} \quad (9)$$

$$y_{t+1} = \beta_1 y_t + \beta_2 y_{t-1} + \beta_3 y_{t-2} + \beta_4 y_{t-3} + \beta_5 \pi_t + \beta_6 \pi_{t-1} + \beta_7 \pi_{t-2} + \beta_8 \pi_{t-3} + \beta_9 (i_t - \bar{\pi}_t) + \eta_{t+1} \quad (10)$$

The selection of the relevant models is based on both empirical and theoretical arguments. First, we keep fixed across specifications the first lag of inflation and output gap in the AS and AD respectively. In so doing, we end up with the models that display a fairly good empirical fit. Moreover, we discard the specifications that do not allow monetary policy to have a direct impact on the economy through both equations. In particular, we take the real interest rate, $i_t - \bar{\pi}_t$, as a further fixed regressor and we constraint the AS to be dependent from, at least, one of the lagged values of the output gap. The latter amounts to cut off approximatively the five percent of the 2^7x2^7 models specified in the class. Then, we derive the optimal policy rules implied by all the retained AD-AS specifications and we let policy makers implement, at each point in time, the simple average of the optimal rates associated to those specifications. This describes the robust 'thick' policy rule that serves to evaluate whether model uncertainty helps to understand the conduct of monetary policy.

Our 'thick' strategy di¤ers in scope from the one proposed by Favero and Milani (2001), although we employ a similar family of models. Indeed, they use 'thick' modeling to interpret the observed inertia in policy rate behaviour, analogously to the arguments in Sack (2000) and Söderström (1999a) for parameter uncertainty. Our approach, instead, is meant to evaluate the potential of model uncertainty for explaining monetary policy cautiousness.

The empirical results are shown in Figure 5.

Insert Figure 5 about here

The 'thick' monetary policy designed with model uncertainty is less aggressive and volatile than the 'thin' one adopted with a single speci…cation of the constraints. In fact, by pooling into a single policy rule all the information embodied in the otherwise discarded models, we …nd that the responses of monetary authorities to in‡ation and output gaps are more moderate and gradual when alternative speci…cations are taken into account. These results are summarized in Table 2, which reports the …rst two moments of estimated and optimal policy rates, both with and without model uncertainty.

Insert Table 2 about here

The sample means and in particular the standard deviations of the estimated path and the optimal path incorporating model uncertainty are almost equal. In contrast, they both stand at odds with the …rst two moments of the optimal path derived under a single speci…cation of the constraints. This suggest that model uncertainty per sè can explain, at least partially, the cautiousness that seems to have characterized the Fed policy making from the past decade since it predicts a path of interest rates much closer than the 'thin' one to the estimated rule.

6 Conclusions

Monetary policy re‡ects central bank's preferences, thus to evaluate the former it is crucial to identify the latter. A simple way to do this is to go backward and, as a kind of revelation principle, to extract the relevant information from observed policy decisions. Since the estimated coe¢cients in a feedback rule are convolutions of the 'deep' parameters of the economy and those describing the policy makers' preferences, they are natural candidates for the purpose at hand. This paper develops a novel calibration method to recover the central bank's policy preferences from the reduced form estimates of a Taylor-type reaction function. To this end, we solve the intertemporal optimization of monetary authorities under the constraints provided by a small structural representation of the US economy. Then, we select among a fairly wide class of alternative targeting policies, the one that minimizes the sum of squared deviations between the associated optimal rule and the estimated one.

Our …ndings show that the Greenspan's tenure as Fed chairman is effectively described by a strict in‡ation targeting policy according to which the stabilization of in‡ation around its target has been the only concern of monetary authorities. Indeed, the feedback estimates show that the output gap has been important in policy making. However, since it is found to enter the policy rule but not the objective function, it can only be interpreted as a leading indicator for future in‡ation. Furthermore, our results are pretty stable over the Greenspan's era and particularly robust to alternative specifications of the relevant structure of the economy.

Once identified the Fed policy preferences, it is possible to evaluate the conduct of monetary policy by defining the optimal path of policy rates associated to those preferences. Accordingly, we compare simulated policy rates, given they were implemented over the entire tenure, with estimated ones. The results support the view that the US monetary policy from the past decade has been more cautious than the one recommended by the optimal rule. In particular, the estimated response of monetary authorities to the developments in the economy is found to be more moderate than the one suggested by the solution of the optimal control problem.

Lastly, we question whether model uncertainty may rationalize this timidity: our answer is yes. By employing a novel 'thick' modeling, we built up a robust monetary policy as the simple average of all optimal rules associated to the specifications of the economic dynamics in a given class of models. We find that much of the observed cautiousness can be explained by the lack of knowledge that policy makers face about the relevant structure of the economy. In other words, model uncertainty accounts for a sizable portion of the differences between estimated and optimal policy rule.

Appendix: the stochastic optimal linear regulator problem

For a discount factor δ, $0 < \delta < 1$, the central bank faces an intertemporal optimization problem of the form:

$$E_t \sum_{\tau=0}^{\infty} \delta^{\tau} LOSS_{t+\tau} \tag{11}$$

according to which it minimizes the expected discounted sum of future loss values. In particular, the objective function reads in each period:

$$LOSS_t = \lambda_{\pi}\pi_t^2 + \lambda_y y_t^2 + \lambda_{\Delta i}(i_t - i_{t-1})^2 \tag{12}$$

The loss function is quadratic in the deviations of output and inflation from their target values and embodies an additional term that is meant to penalize for an excessive volatility of the policy instrument, i_t. The parameters λ_{π} and λ_y represent the (potentially time-variant) central bank's policy preferences towards inflation and output stabilization respectively. The weights in the objective function are normalized to sum to one.

When the discount factor, δ, approaches unity, the intertemporal loss function in (11) approaches the unconditional mean of the period loss function:

$$E[LOSS_t] = \lambda_{\pi} Var[\pi_t] + \lambda_y Var[y_t] + \lambda_{\Delta i} Var[\Delta i_t] \tag{13}$$

The constraints of the optimization problem describe the structure of the economy, and they are specified by the AD-AS system in (1) and (2). This has a convenient state-space representation of the form:

$$X_{t+1} = AX_t + Bi_t + \varepsilon_{t+1} \tag{14}$$

where the elements of (14) are given by:

$$X_t' = \begin{bmatrix} \pi_t & \pi_{t-1} & \pi_{t-2} & \pi_{t-3} & y_t & y_{t-1} & i_{t-1} & i_{t-2} & i_{t-3} \end{bmatrix} \tag{15}$$

$$A = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{\beta_3}{4} & -\frac{\beta_3}{4} & -\frac{\beta_3}{4} & -\frac{\beta_3}{4} & \beta_1 & \beta_2 & \frac{\beta_3}{4} & \frac{\beta_3}{4} & \frac{\beta_3}{4} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{\beta_3}{4} \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{16}$$

$$\varepsilon_t' = \begin{bmatrix} \epsilon_t & 0 & 0 & 0 & u_t & 0 & 0 & 0 & 0 \end{bmatrix} \tag{17}$$

X_{t+1} is the 9 x 1 vector of state variables, i_t is the policy control (i.e. the federal funds rate) and ε_{t+1} is a 9 x 1 vector of supply and demand iid normally distributed shocks with mean vector zero and covariance matrix:

$$E\varepsilon_t\varepsilon_t' = \Sigma \tag{18}$$

Lastly, A and B are the matrices of the parameters that describe the strucutre of the economy.

The loss function in (12) can have a more compact representation by defining the 3 x 1 vector Y_t of goal variables. This vector reads:

$$Y_t = CX_t + Di_t \tag{19}$$

where the elements of (19) are given by:

$$Y_t = \begin{bmatrix} \bar{\pi}_t \\ y_t \\ i_t - i_{t-1} \end{bmatrix}, C = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{20}$$

Accordingly, the loss function can be rewritten as:

$$LOSS_t = Y_t^{\prime} R Y_t \tag{21}$$

where R is a negative semidefinite symmetric 3 x 3 matrix characterized by the weight λ_{π}, λ_y and $\lambda_{\Delta i}$ on the diagonal and zeros elsewhere.

The central bank's optimal control problem is to minimize over choice of $\{i_t\}_{t=0}^{\infty}$ the criterion:

$$\sum_{\tau=0}^{\infty} \delta^{\tau} \left\{ Y_{t+\tau}^{\prime} R Y_{t+\tau} \right\} \tag{22}$$

subject to the dynamic evolution of the economy described in (14) and given the current state of the economy X_t.

The quadratic objective function, the linear transition equation and the property $E\left(\varepsilon_{t+1} \mid X_t\right) = 0$ are convinient forms for the stochastic optimal linear regulator problem (see Ljungqvist and Sargent, Ch. 4, 2000). It follows that the feedback rule that solves the optimization is linear and independent from the problem's noise statistics, Σ, since the certainty equivalence holds. Then, the first-order necessary condition turns out to be:

$$\left(S + \delta B^{\prime} P B\right) i = -(V^{\prime} + \delta B^{\prime} P A) X \tag{23}$$

which implies the following feedback rule for the policy instrument:

$$i = f X \tag{24}$$

where f is given by:

$$f = -\left(S + \delta B^{\prime} P B\right)^{-1} (V^{\prime} + \delta B^{\prime} P A) \tag{25}$$

The 9 x 9 matrix P is the solution of the algebraic Riccati equation:

$$P = Q + \delta (A + Bf)' P (A + Bf) + f' S f + V f + f' V' \tag{26}$$

where Q, V and S are defined as:

$$Q = C'RC, \quad V = C'RD, \quad S = D'RD$$

The reaction function (24) resembles an augmented Taylor's rule according to which monetary authorities set the federal funds rate in every period as the optimal response to movements in the current and lagged values of the state variables, which include the lagged values of the fed funds rate itself.

Given this optimal feedback rule, the transition function of the economy can be rewritten as:

$$X_{t+1} = M X_t + \eta_{t+1} \tag{27}$$

where the 9 x 9 matrix M reads:

$$M = A + Bf \tag{28}$$

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Table 1
Estimated versus Simulated Optimal Taylor rule

Policy Rule Parameters		
$f_{ð}$	f_{y}	f_{i}
Panel A. Estimated Coefficients*		
0.21	0.34	1.26
(0.07)	(0.10)	(0.14)
Panel B. Simulated Optimal Coefficients		
0.57	1.08	0.60

* Standard errors in parenthesis.
Note: the policy rule is $i_t = fX_t$ where $X_t = [ð_t,\ ð_{t-1},\ ð_{t-2},\ ð_{t-3},\ y_t,\ y_{t-1},\ i_{t-1},\ i_{t-2},\ i_{t-3}]$. The first two columns refer to the coefficients of contemporaneous inflation and output gap respectively, whereas the third column refers to the coefficient of the first lag of the policy rate. These parameters are both statistically and quantitatively the most significant. The simulated optimal coefficients are obtained with the preference estimates $ë_{ð}=0.80$ and $ë_{y}=0.00$, after having imposed $ë_{Äi}=0.20$.

Table 2
Estimated versus Simulated Optimal Taylor rules with Model Uncertainty

Policy Rates	*Sample Mean*	*Standard Deviation*
Estimated	**-0.023**	**1.731**
Simulated optimal (thin*)	**0.449**	**3.709**
Simulated optimal (thick*)	**0.001**	**1.733**

Note: the policy rule is $i_t = fX_t$ where $X_t = [ð_t,\ ð_{t-1},\ ð_{t-2},\ ð_{t-3},\ y_t,\ y_{t-1},\ i_{t-1},\ i_{t-2},\ i_{t-3}]$. The simulated optimal coefficients are obtained with the preference estimates $ë_{ð}=0.80$ and $ë_{y}=0.00$, after having imposed $ë_{Äi}=0.20$.
* The label 'thick' refers to the simulated optimal policy rule derived under model uncertainty whereas the label 'thin' refers to the simulated optimal policy rule derived under a single specification of the economic dynamics.

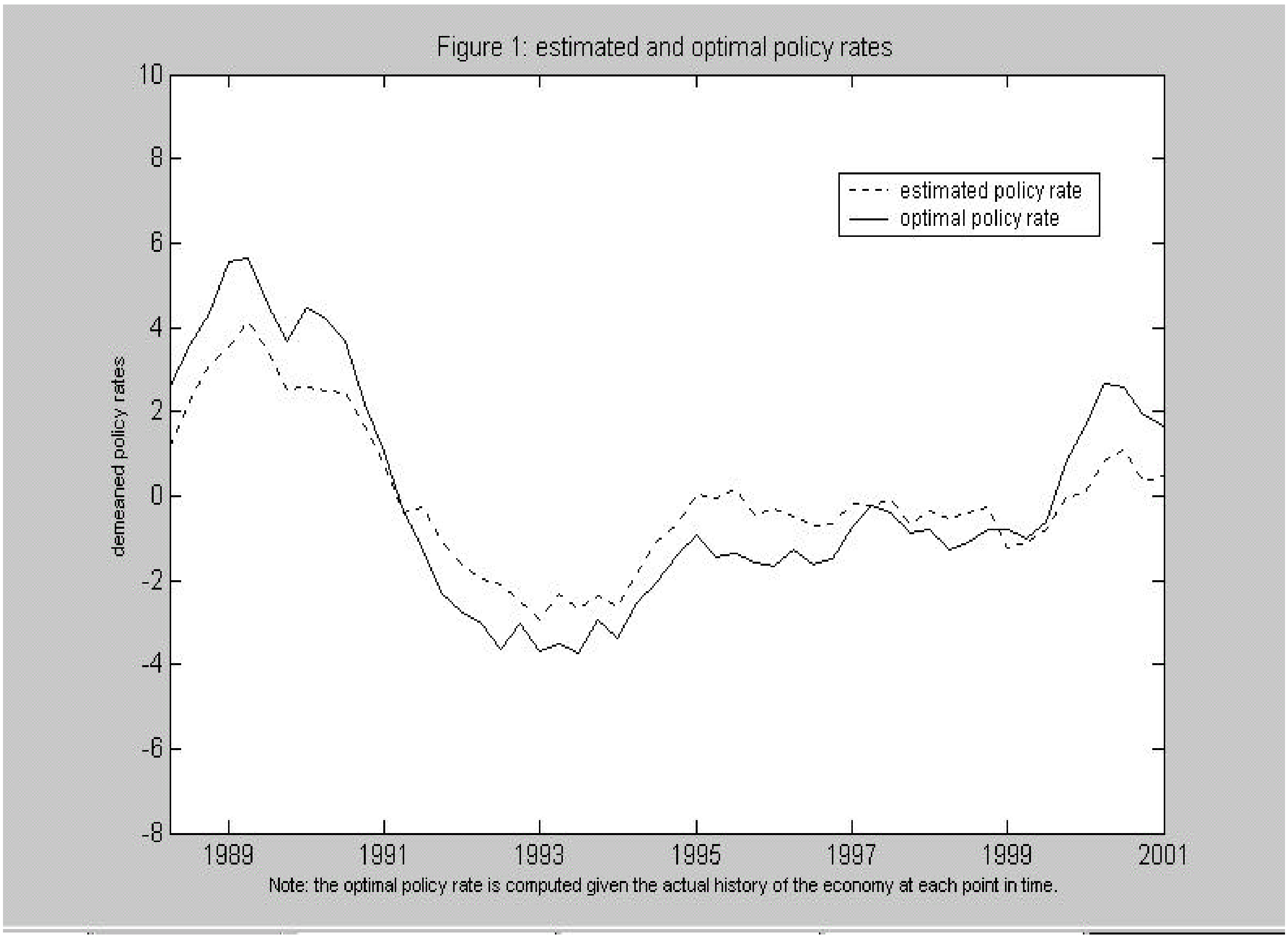


Figure 1: estimated and optimal policy rates
estimated policy rate
optimal policy rate
demeaned policy rates
10
8
6
4
2
0
-2
-4
-6
-8
1989
1991
1993
1995
1997
1999
2001
Note: the optimal policy rate is computed given the actual history of the economy at each point in time.

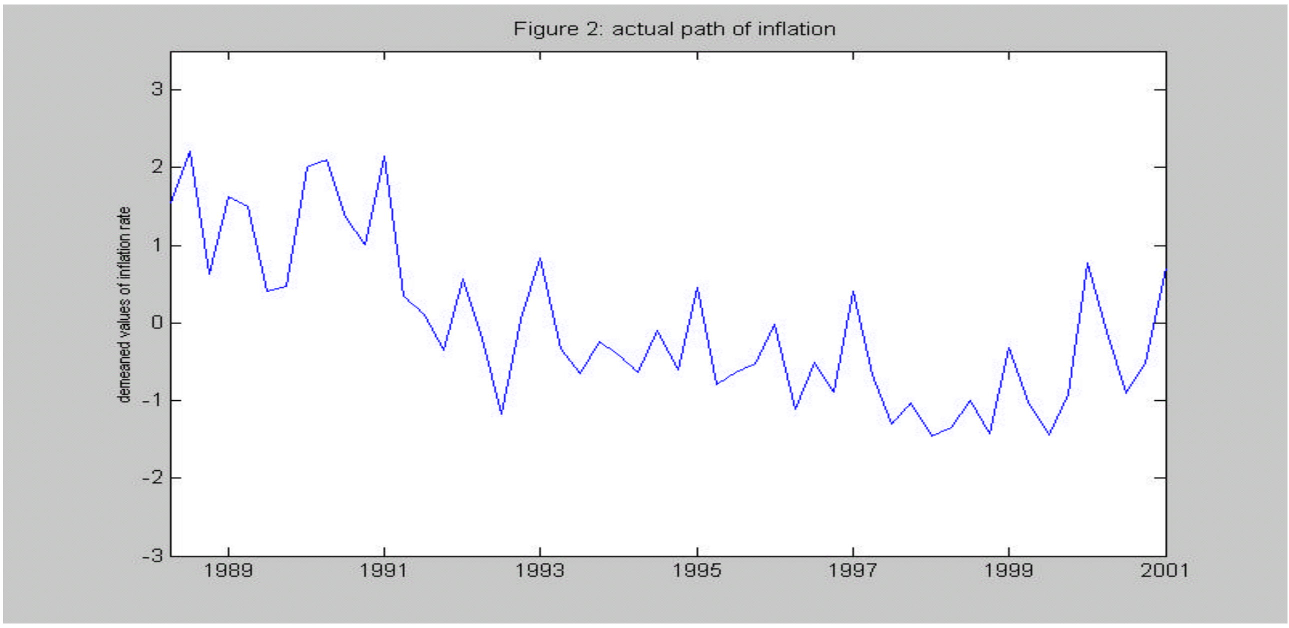


Figure 2: actual path of inflation
demeaned values of inflation rate
3
2
1
0
-1
-2
-3
1989
1991
1993
1995
1997
1999
2001

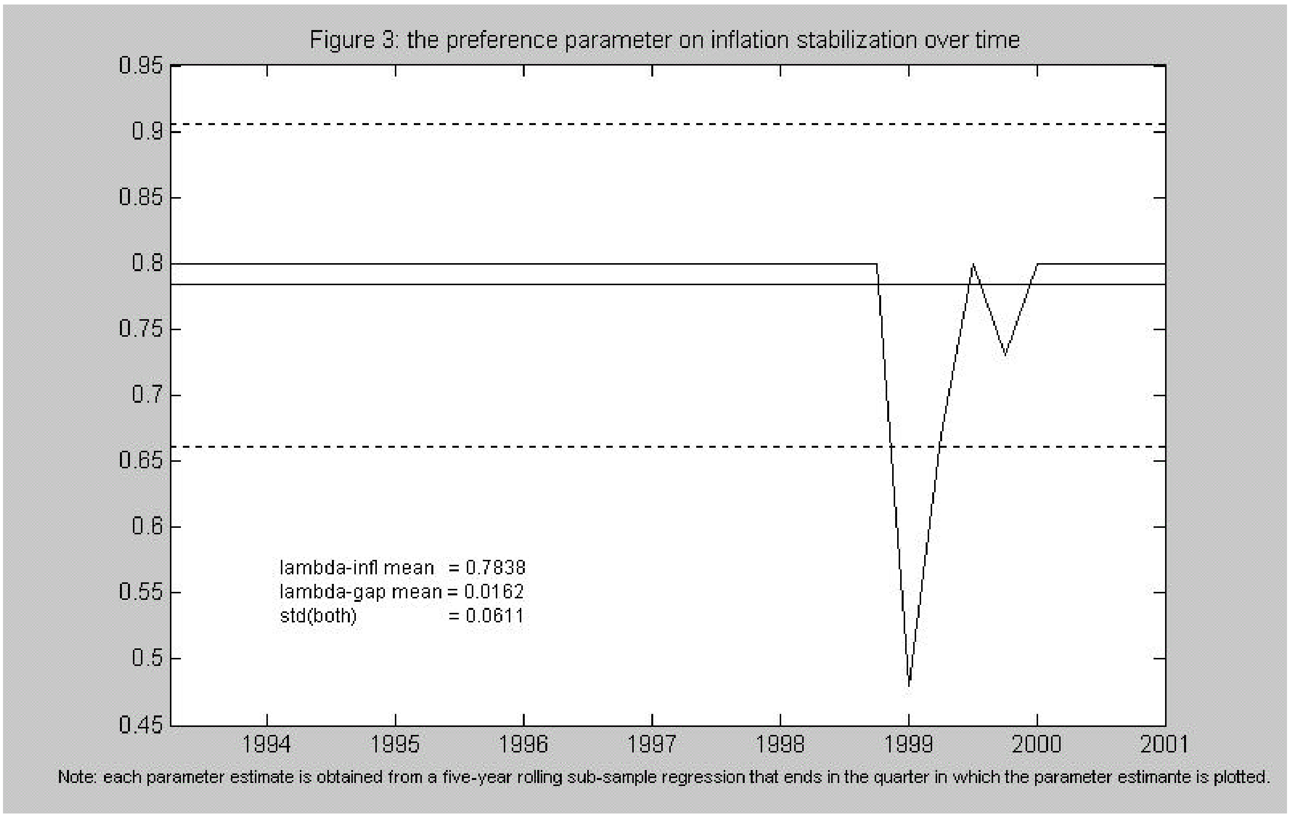
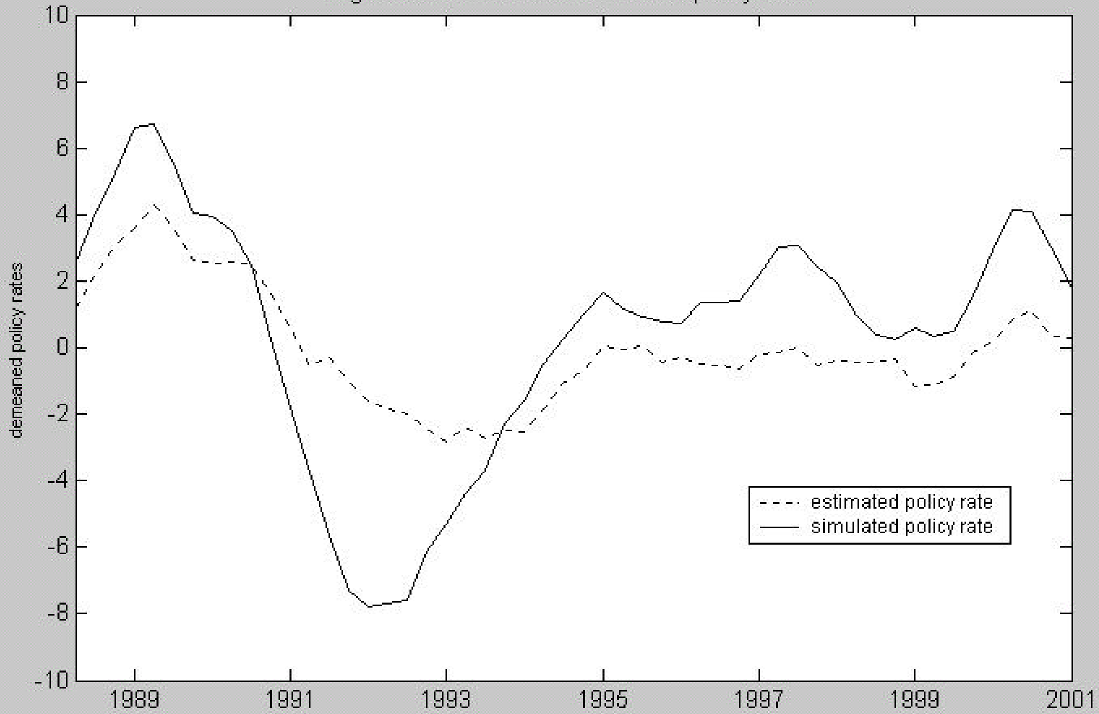


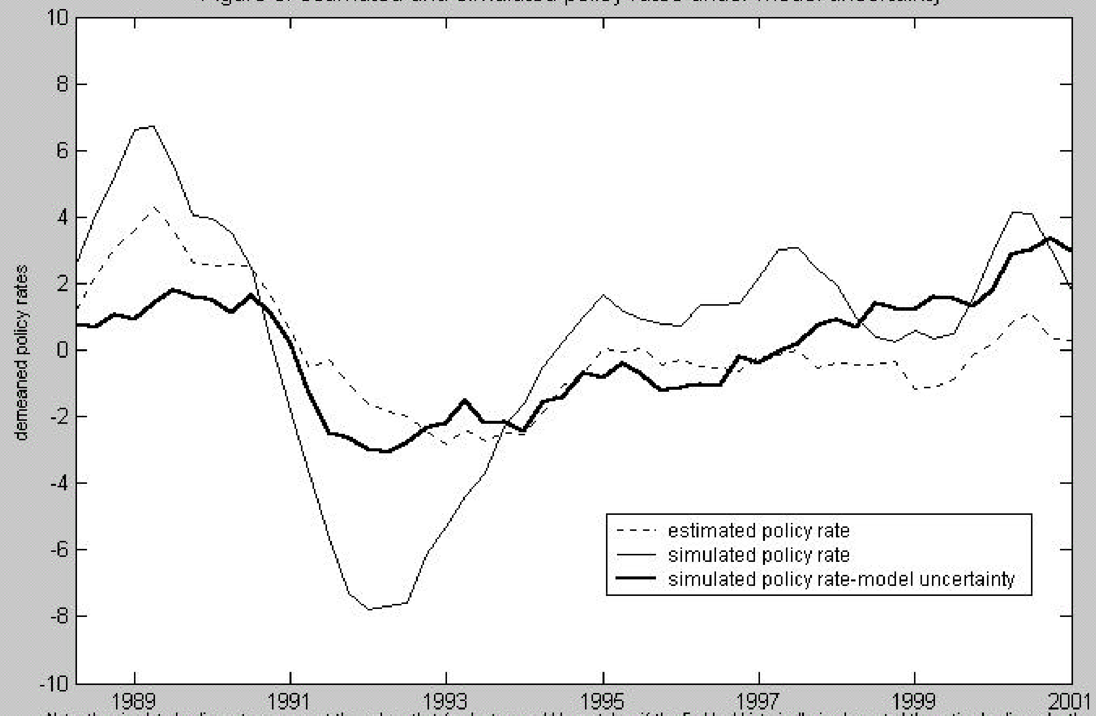
Figure 3: the preference parameter on inflation stabilization over time
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
lambda-infl mean = 0.7838
lambda-gap mean = 0.0162
std(both) = 0.0611
1994
1995
1996
1997
1998
1999
2000
2001
Note: each parameter estimate is obtained from a five-year rolling sub-sample regression that ends in the quarter in which the parameter estimante is plotted.

Figure 4: estimated and simulated policy rates



Note: the simulated policy rate represents the values that fund rate would have taken if the Fed had historically implemented the optimal policy rule; the policy preferences estimates are lambda-inflation = 0.8 and lambda-gap = 0.0, after having imposed lambda-smoothing = 0.2.

Figure 5: estimated and simulated policy rates under model uncertainty



Note: the simulated policy rates represent the values that fund rates would have taken if the Fed had historically implemented the optimal policy rule; the policy preferences estimates are lambda-inflation = 0.8 and lambda-gap = 0.0, after having imposed lambda-smoothing = 0.2. The simulated policy rate under model uncertainty is computed as simple average of all optimal rules in a given class of specifications of the relevant dynamics.