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Model Uncertainty, Optimal Monetary Policy and the Preferences of the Fed

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SUMMARY

Monetary policy in the US is characterized by a substantial degree of inertia. While in principle this may well be the outcome of an optimizing central bank behavior, the ability of any derived policy rule to match the data relies on so large weights for interest rate smoothing into policy makers' preferences as to be theoretically flawed. In this paper we investigate whether such a puzzle can be interpreted as resulting from the concern of monetary authorities for potential misspecifications of the macroeconomic dynamics. Accordingly, we propose a novel *thick modeling* approach that incorporates model uncertainty into the identification of central bank's preferences. The *thick* robust policy rule shows the kind of smoothness observed in the data without resorting to 'incredible' values for the preference parameters.

Keywords: Model uncertainty, interest rate smoothing, Fed policy preferences, optimal monetary policy

JEL: C61, E52, E58

CONTENTS

"Expectations about future economic developments overall inevitably play a crucial role in our policymaking. Because accurate point forecasts are extraordinarily difficult to fashion, we are forced also to consider the probability distribution of possible economic outcomes. Against these distributions, we endeavor to judge the consequences of various alternative policy scenarios, [...] *and the costs should those outcomes prevail. In short, our policy behavior is the result of examining the implications of the interaction of probability distributions and loss functions".*[1]

Alan Greenspan

1 Introduction

The US Federal Reserve tends to change short-term interest rates by small steps that move in a particular direction over sustained periods and reverse only infrequently (see Rudebusch, 1995, and Goodhart, 1997). This prominent feature of policy rates, which is interchangeably referred to as interest rate smoothing, policy gradualism or policy inertia, characterizes the Fed response to inflation and output gaps as having been more moderate than an optimizing central bank behavior would predict.

In a recent survey of evidence Sack and Wieland (2000) interestingly discuss several explanations to reconcile historical and optimal policy rules. A number of empirical studies find that uncertainty creates incentives to smooth policy rates, in the form of either parameter uncertainty or measurement error for inflation and output gap. Parameter uncertainty, which is the uncertainty on the monetary transmission mechanism, alters the knowledge of decision makers about the impact of policy action on the economy. Accordingly, a central bank that adjusted aggressively policy rates to the developments in the economy would be more likely to have unpredictable and therefore undesirable movements of output and inflation. Then, as shown in the VAR analyses by Sack (2000), Salmon and Martin (1999), and Söderström (1999), policy gradualism may be the optimal strategy to bring the relevant macroeconomic variables in line with the targets.

Another source of uncertainty comes from the measurement errors for inflation and output gap. Indeed, the evaluation of monetary policy in most empirical studies relies on the unrealistic assumption that policy makers know the state of the economy without error. However, monetary policy mainly involves decisions that are based on real-time available information, which are subject to frequent revisions after the initial release. Interestingly, Orphanides (1998) shows that whenever policy makers take data uncertainty into account

[1]"*Economic developments*", May 24, 2001. Before the Economic Club of New York, New York.

the estimated policy response to inflation and output gaps is more moderate, thereby preventing the possibility of wide interest rate fluctuations due to measurement errors. This attenuation turns out to be particularly relevant under simple policy rules, although it also emerges for optimal policy rules.

These explanations have each proved to be statistically significant, although none alone has resulted to be quantitatively satisfactory (see Sack and Wieland, 2000). Moreover, interest rate smoothing is derived as the optimal policy rule of a central bank whose only concerns are to stabilize output and inflation and the possibility that policy makers have an explicit preference to penalize policy rate fluctuations is ruled out by assumption.

On the positive side, the inclusion of an interest rate term into the policy makers' objective function can be theoretically justified on several grounds (see Woodford, 1999a and 1999b; Goodfriend, 1987; Walsh, 1998, and Svensson, 1999b). The empirical model proposed by Rudebusch and Svensson (1999 and 2001), which includes an explicit interest rate smoothing goal, has become by now a popular framework to analyze monetary policy under uncertainty (see Stock, 1999; Smets, 1999; Onatski and Stock, 2002; Onatski, 2000; Rudebusch, 2001a; Favero and Milani, 2001). For example, Rudebusch (2001a) argues that the interaction of several forms of uncertainty rather than a single one is likely to generate the kind of smoothness observed in the data and points towards measurement errors and model misspecifications as the most relevant candidates. In particular, the perturbation of some key structural relations such as the inflation dynamics and the output sensitivity to interest rate are shown, everything equals, to make smoother an otherwise volatile policy rate behavior, thereby being an excellent starting point for the present analysis.

On the negative side, the ability of any optimal policy to match the data badly relies on 'incredible' values for the preference parameters as the weights imposed to interest rate smoothing in the objective function are inconsistent with the theory. This suggests the potential for a strictly related issue, namely the identification of the Fed policy preferences. In fact, several pioneering studies have proposed alternative strategies to estimate the structural parameters in a small empirical model à la Rudebusch and Svensson (see Favero and Rovelli, 2001; Dennis, 2001; Ozlale, 2001). While extremely promising, these estimates have left the *interest rate smoothing puzzle* unsolved in that any plausible set of preferences implies an optimal path for policy rates much more volatile than the observed one.

In this paper we bring together the literature on model uncertainty and the one on central bank's preferences by using the progresses made in the former to solve the puzzle emerged in the latter. To this end, we incorporate model uncertainty in the simple calibration method we propose to identify the Fed policy preferences. In so doing, we investigate whether the concern for model misspecifications can explain the inertial behavior of policy rates without resorting to implausible weights for the interest rate smoothing objective.

The intuition for having more moderate policy responses when the model is misspecified comes from the policy makers' agnosticism about what model provides the most accurate description of the economy. Accordingly, a policy rule, which is optimal under a single specification, may turn out to perform quite poorly if that model does not capture properly the 'true' macroeconomic dynamics. Then, a concern for interest rate smoothing can simply reflect the choice of a policy rule that would perform reasonably well *on average* (i.e. over *various alternative policy scenarios* in the words of Alan Greenspan).

A general strategy to take model uncertainty into account is to calculate a global optimal policy as some combination of the policy rules derived separately for each of the possible specifications (see Stock, 1999). It is worthy to note that the *robust* rule we are interested in differs in scope from the one derived with robust control techniques. Indeed, here robustness has to be understood as a form of hedging against potential misspecifications of the macroeconomic dynamics rather than as a way of guarding against worst case scenarios. To this end, we follow the *thick* modeling proposed by Granger (2000) to nest into a single policy rule a large number of specifications in a given class of models. In particular, we first let policy makers implement, at each point in time, the simple average of the optimal rates for each of the relevant specifications. Then, we identify among a large number of targeting policies the set of preference parameters that makes such a *robust* rule matching the data.

Our results shed new lights as well as confirm conventional wisdoms on the conduct of monetary policy in the US. First, model misspecification is an important concern of the Fed such as to explain alone most of the observed inertial behavior of policy rates. Second, any identification method that neglects model uncertainty is likely to deliver a set of policy preferences that cannot be readily interpreted. Third, the stabilization of output over the cycle has not been a final concern of US monetary authorities whereas the stabilization of inflation has been a superior goal.

The paper is organized as follows. Section 2 sets up the model and presents the relative estimates. Section 3 identifies the preference parameters for the Greenspan's tenure and defines the *interest rate smoothing puzzle* from the comparison between our results and those obtained in several recent analyses. Model uncertainty is introduced in section 4 and then it is used in the following section to re-identify the Fed policy preferences. The last section concludes while the appendix provides a guideline to solve numerically the optimal control problem.

2 A small empirical model of the US economy

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 relations 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 behavior 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 methods, a backward-looking model is likely to be preferred to a forward-looking one as the former overperforms the latter in fitting the data (see Fuhrer, 1997).

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

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

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

where π_t is the quarterly inflation in the GDP chain-weighted price index, p_t, calculated at annual rate, that is $4\left(p_t - p_{t-1}\right)$, and $\bar{\pi}_t$ is four-quarter inflation constructed as $\frac{1}{4}\sum_{j=0}^{3} \pi_{t-j}$. The quarterly average federal funds rate, i_t, is expressed in percent per year whereas the four quarter average federal funds rate, $\bar{\imath}_t$, is computed as $\frac{1}{4}\sum_{j=0}^{3} i_{t-j}$; Supply and demand iid shocks are denoted by ε_t and u_t respectively. All variables are demeaned. All variables but the funds rate are in logs and rescaled upward on a 100 point basis such that the output gap, say, is $y_t = 100 * (\log(Q_t) - \log(Q_t^*))$ where Q_t and Q_t^* are respectively actual and potential GDP, both in levels. Therefore, no constants appear in the equations.

On the one hand, the aggregate supply equation in (1), AS henceforth, captures the inflation dynamics by relating inflation to its lagged values and to current and lagged output gaps. On the other hand, the aggregate demand equation in (2), AD henceforth, explicitly models the monetary transmission mechanism by relating output gap to its lagged values and most importantly to past real interest rate (see Rudebusch and Svensson, 1999 and 2001).

This empirical model of inflation and output, although parsimonious, embodies the minimal set of variables one may want to include for the analysis of monetary policy (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 report of the Bank for International Settlements for 11 central bank models, 1995). Moreover, monetary policy affects (through the instrument i_t) aggregate demand with one lag and aggregate supply with two lags, in the spirit of the specifications in Ball (1999) and Svensson (1997). Finally, such a dynamics can be interpreted either as structural relations, as we do, or as a reduced-form restricted VAR with impulse responses that are consistent with those of the FRB-US model.

The AD-AS system is backward-looking and therefore it is subject to the Lucas critique (1976). It follows that the selection of an inappropriate sample may undermine the stability of the structural parameters, which is an important condition for drawing inference. This consideration motivates our focus on the sample 1987:3 - 2001:1, which corresponds to the tenure of Alan Greenspan as Fed chairman. Indeed, one may argue that this period has been characterized not only by an increasing macroeconomic 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 (see Bernanke and Mihov, 1998), thereby reducing the significance of the Lucas critique[2].

[2] Moreover, the Andrews' test (1993) cannot reject the null of stability for both equations.

We estimate individually the equations (1) and (2) by OLS. 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:

$$\pi_{t+1} = \underset{(0.133)}{0.282}\pi_t - \underset{(0.134)}{0.025}\pi_{t-1} + \underset{(0.134)}{0.292}\pi_{t-2} + \underset{(0.136)}{0.385}\pi_{t-3} + \underset{(0.054)}{0.141}y_t + \hat{\varepsilon}_{t+1} \tag{3}$$

$$y_{t+1} = \underset{(0.136)}{1.229}y_t - \underset{(0.149)}{0.244}y_{t-1} - \underset{(0.078)}{0.073}\left(\bar{\imath}_t - \bar{\pi}_t\right) + \hat{u}_{t+1} \tag{4}$$

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[3]. All estimates have the expected sign but the second lag of inflation in the AS, although it has not explanatory power. Furthermore, the coefficient for the real interest rate is not statistically significant. While undesirable, this result confirms the evidence from several studies for the US and the UK over recent samples (see for instance Neiss and Nelson, 2001). Finally, although these estimates suggest a minor initial role for monetary policy, the impact of the lagged values of the output gap in the AD is large implying that the response of aggregate demand to policy rates is much greater in the long-run.

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)[4]. This corresponds to 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

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

[4] 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 Walsh (1998), Clarida, Galì and Getler (1999), Rudebusch and Svensson (1999), and Svensson (1999c).

makers since it embodies some degree of commitment (to a loss function) and some degree of discretion (through a state-contingent rule). 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[5]. Then, policy rates are set to minimize the following objective function:

$$Var\left[\bar{\pi}_t\right] + \lambda Var\left[y_t\right] + \mu Var\left[\Delta i_t\right] \tag{5}$$

The quarterly average short-term interest rate, i_t, is regarded as the instrument under policy makers' control whereas Δi_t stands for its first difference. The parameters λ and μ represent the central bank's policy preferences towards output stabilization and interest rate smoothing respectively and unlike in Rudebusch and Svensson (2001), who set them exogenously, they will be determined within the model. The coefficient on inflation stabilization is normalized to one such that λ and μ are expressed in relative terms. Finally, we constrain both parameters to be non negative meaning that the central bank values both any deviation of output from its potential and any jump in interest rates as a *bad*.

The specification in (5) is empirically attractive since, unlike alternative monetary models as the FRB-US, it is able to predict an interest rate path that exhibits the kind of smoothness observed in the data. Nevertheless, it has been criticized for being theoretically flawed. However, it can be shown not only that price stickiness may rationalize the output-inflation trade off (see Rotemberg and Woodford, 1997), but also that transaction frictions and/or a zero nominal interest-rate lower bound allow deriving a quadratic interest-rate term in the loss function (see Woodford, 1999b)[6]. Moreover, an interest-rate smoothing goal can be theoretically justified either as a part of an optimal delegation problem through which the central bank gains the opportunity of affecting aggregate demand by means of small changes in the policy rates (see Woodford, 1999a) or as a way of preventing the disruption of financial markets (see Goodfriend, 1991). Although the preference parameters to smooth policy rates in Woodford (1999a and 1999b) are calibrated

[5] 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).

[6] More precisely, these considerations justify a concern of monetary authorities to reduce the variability of the levels of interest rates around the target.

within a different model, we take these numerical values as a rough point of reference. In particular, it is shown that a coefficient for μ greater than 0.28 is not easy to rationalize in the context of an optimizing central bank behavior.

The optimal control problem described in (1), (2) and (5) has a convenient state space representation that is characterized by a quadratic objective and a linear transition law. This specification leads to the *stochastic optimal linear regulator problem* according to which the decision rule for interest rates is a linear function of the state variable vector:

$$X_t' = \begin{bmatrix} \pi_t & \pi_{t-1} & \pi_{t-2} & \pi_{t-3} & y_t & y_{t-1} & i_{t-1} & i_{t-2} & i_{t-3} \end{bmatrix} \tag{6}$$

In particular, the central bank minimizes the loss (5) 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]:

$$i_t = fX_t \tag{7}$$

The coefficients in the vector f represent some convolution of the central bank's preferences, λ and μ, and the behavioral parameters of the economy, αs and βs, such that for any given distribution of weights in (5) there exists a different optimal f in (7).

Then, we make the model consistent with our implementation by the timing assumption that the Fed sets policy rates after the realization of the state variables, which occurs at the beginning of the period. Hence, we estimate by OLS the stochastic version of the optimal rule derived in (7). The estimates yield the following results:

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

with an Adjusted R^2 of 0.96.[8] The coefficients show that monetary authorities adjust gradually the funds rate 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). Finally, the coefficients on the interest

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

[8]Neither the point estimates nor the standard errors change significatively using GMM.

rate lags sum up to 0.85 consistently with much of the literature on partial adjustment policy rules. This suggests that the observed policy inertia is greater than systematic responses to output and inflation fluctuations would imply.

3 The Fed policy preferences and the interest rate smoothing puzzle

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 that characterize the aversion of monetary authorities towards inflation, output and interest rate volatility. Then, a simple way to identify these preferences is to go backward and, as a kind of revelation principle, to extract the relevant information from the observed policy decisions. The optimization problem described above shows that the reaction function estimates can be interpreted as convolutions of the 'deep' parameters of the economy and those describing the central bank's preferences and therefore they are natural candidates for the purpose at hand. Accordingly, given the point estimates in (3) and (4), we calibrate the preference parameters $[\lambda, \mu]$ such as to minimize the distance between the optimal policy and the fitted path of interest rates in (8), where the distance is measured by the sum of squared deviations over time[9]. The optimal policy describes the path that the funds rates would have followed if the Fed had historically implemented the optimal rule and therefore, given the actual values of state variables at the beginning of the sample, it is derived by substituting, period by period, the simulated dynamics of the X into the reaction function (7). Our identification method applied to the sample 1987:3 - 2001:1, which corresponds to the Greenspan chairmanship, returns values of $\lambda = 1.00$ and $\mu = 8.00$ for the preferences on output stabilization and interest rate smoothing respectively. One may be tempted to conclude that while output and inflation stabilizations have received an equal concern, interest rate smoothing has been the major objective of the Fed. However, we show below that these results may be 'misleading' in that they miss an important feature of monetary policy making.

At this point, it is useful to relate our results to several recent studies since there

[9] 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. Moreover, our results do not change significantly when actual rates enter the calibration because of the good empirical fit of the feedback estimates.

exists interesting differences and similarities. Favero and Rovelli (2001) identify central bank's preferences by estimating via GMM the Euler equations for the solution of alternative specifications of the optimization problem. Cecchetti and Ehrmann (2001) and Cecchetti, McConnell and Perez-Quiros (1999) capture the dynamics of the economy in a VAR framework and then recover policy makers' preferences from the estimates of the output-inflation variability and those obtained via VAR. Dennis (2001) and Ozlale (2001) use respectively a full information approach and the Kalman filtering to jointly estimate with maximum likelihood the structural model of the economy and the loss function. These studies but the ones of Cecchetti and coauthors are built upon a common empirical model of inflation and output, namely the one by Rudebusch and Svennson (1999 and 2001), and therefore their findings turn out to be directly comparable to ours. Table 1 brings together our revealed preferences and the estimates from the different contributions. The reported values refer to the Greenspan's tenure, although Favero and Rovelli (2001) do not distinguish between the Volcker's and the Greenspan's chairmanship[10]. In particular, Panel A shows the first two moments of the fitted policy rates whereas Panel B displays in columns the Fed policy preferences, the first two moments of the optimal paths and the average distance between optimal and fitted rates. Figure 1 plots the optimal and the fitted path of policy rates for the four studies.

Insert Table 1 about here

Insert Figure 1 about here

The first two lines of Panel B in Table 1 refer to the present work and the one by Dennis (2001)[11]. On the positive side, these sets of policy preferences predict a path for policy rates capable to replicate the kind of smoothness observed in the data (see the top panels of Figure 1). Indeed, the first two moments are broadly consistent in both cases with those of the fitted path in Panel A and the average distance, which is computed on squared values, is fairly low. On the negative side, they rely upon 'incredible' parameters for interest rate smoothing such as the literature on optimal monetary policy cannot easily

[10] Understanding whether the two periods may be described by a single set of policy preferences is beyond the scope of this paper. However, to the extent that no monetary regime shifts have occured in the post-Volcker period (see Clarida, Galì and Gertler, 2000), the preference parameters in Favero and Rovelli (2001) can be taken as a rough approximation of those in the restricted sample for Alan Greenspan only. As we are interested only in a qualitative comparison between our optimal policy rule and those from other studies, we consider such an approximation only as a minor in the interpretation of the results.

[11] We thank Richard Dennis for having kindly offered the FIML estimates for the Greenspan's period.

rationalize (see Woodford, 1999a and 1999b). In contrast, the last two lines of Table 1, which refer to the works by Favero and Rovelli (2001) and Ozlale (2001), return more plausible weights for the inertial coefficient in the loss function. However, the bottom panels of Figure 1 show that this can be done only at the cost of an optimal policy rule that is so volatile as to contradict the evidence on the funds rate.

The results at this stage seem to call for a sort of *interest rate-smoothing puzzle*. A trade off between an inertial behavior of policy rates and a plausible value for the relative preference parameter seems to emerge, thereby suggesting that the source of interest rate smoothing has to be found elsewhere.

For example, Rudebusch (2001b) dismisses the idea of optimality and argues that policy inertia is only an illusion. The conclusion is drawn upon the evidence from financial markets as the large amount of predictable funds rate movements that policy gradualism would imply is not detected at multi quarter ahead horizons. In fact, the policy rule behavior appears to be driven by episodic, unforecastable, serially correlated shocks that may be due for instance to measurement errors or omitted monetary regime shifts in the reaction function estimates.

An alternative, which is back to an optimizing central bank behavior, is that either the empirical model or the objective function are misspecified in some important respect. In particular, the structure of the economy proposed by Rudebusch and Svensson (1999 and 2001), while empirically attractive, is indeed very simple and the omission of any relevant variable may turn out to be an issue for the results obtained so far. Moreover, as discussed in the introduction, the lack of knowledge about the 'true' model of the economy may lead policy makers to consider *various alternative policy scenarios*, each one corresponding to a different specification of the underlying macroeconomic dynamics. We explore such an alternative in the next section to assess the potential of model uncertainty to account for the observed interest rate smoothing.

4 Model uncertainty

A common observation across central banks is that interest rates are moved in a more moderate fashion than certain equivalent optimal monetary policies predict. The difficulty of standard models to rationalize policy inertia has led to incorporate various forms of model uncertainty into the policy makers' optimization problem. In practice, monetary authorities know far less about the dynamics of the economy than simple policy experiments presume and model parameters are likely to be better viewed as random. In particular, suppose that monetary authorities know the distribution of parameters but not the realization; then, uncertainty can be introduced at different levels. A Brainard-style multiplicative uncertainty (1967) considers parameter distributions that are centered around the estimates of a specific model. This means that policy makers know the parameter first moments on an ex ante basis, although they do not know the values that realize in any given quarter. Rudebusch (2001a), Estrella and Miskin (1999), and Peersman and Smets (1999) find that parsimonious structural models and simple policy rules predict only negligible attenuations of policy action in the context of parameter uncertainty. In contrast, the analyses in Sack (2000), Salmon and Martin (1999) and Söderström (1999) show that unrestricted VARs and unrestricted policy rules may result in a moderate conduct of monetary policy, although it alone is not enough to replicate the kind of smoothness observed in the data[12].

Another way to think of model uncertainty is to regard also the parameter mean as unknown. In fact, if policy makers fear that a small structural model is misspecified, they would have no reason to believe that the 'true' parameters coincide, even on average, with the least square estimates. A valuable robustness check is then to vary the values of some key model parameter to understand whether this is the relevant form of uncertainty that central banks face. Rudebusch (2001a) shows that the slope coefficients on inflation and the output gap are indeed crucial as the perturbation of each of them, everything equals, results in a significant, but not exhaustive, attenuation of the policy stance.

These results altogether are very promising in that they point towards model uncertainty, in a *broad* sense, as the relevant source of the observed policy gradualism. Moreover, they suggest that the policy preference shown above may be 'misleading' as no identification method takes such an uncertainty into account and only the point estimates of the structural parameters enter the analyses. In contrast, this section incorporates model specification uncertainty into the calibration of the Fed policy preferences. In so doing, we attempt to solve for the *interest rate smoothing puzzle* by assessing the potential of a *broad* type of uncertainty for explaining the inertial behavior of policy rates.

[12] As argued in Rudebusch (2001a), such a result may simply reflect the rich parametrization of the VAR which includes the small-sample estimates of numerous econometrically superflous regressors for the analysis of monetary policy making.

Our approach departures from previous studies along three lines. First, we regard the point estimates of our benchmark model only as one set of possible realizations. In other words, we allow the average value of the distributions being different from the estimated parameters. Moreover, rather than assuming that these distributions are known ex-ante, we let them be shaped ex-post by the point estimates obtained for each of the possible models. Lastly, in addition to the kind of slope coefficient uncertainty in Rudebusch (2001a), we also allow for simultaneous perturbations of all parameters as potentially omitted variables are likely to affect each of the point estimates in the model.

In practise, we follow the 'thick' modeling proposed by Granger (2000) and we *'keep all close specifications, find 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 outliers'.* The label 'thick', as opposed to 'thin', reflects the fact that if one estimates and plots each model-specification 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 specifications that survive the trimming of the outliers.

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

4.1 Traditional approaches

The robustness of monetary policy to model uncertainty has been the focus of a number of recent empirical studies. The goal has been to assess the performance of optimal rules moving from the model in which they are derived to a set of alternative specifications as well as to establish the efficiency of simple policy rules (see Taylor, 1999). For example, McCallum (1998) shows that monetary-based instrument rules overperform optimal ones over a range of possible macroeconomic dynamics. Moreover, simple partial adjustment policy mechanisms and simple forecast-based instrument rules responding to an inflation horizon no longer than one year are found to efficiently stabilize inflation and output in a variety of forward-looking models (see Levine, Wieland and Williams,1999 and 2001). Essentially, these rules set the change in the funds rate rather than the level as the optimal value of the lagged policy rate coefficient is close to one. The intuition is that the central bank, which has established a reputation of conducting monetary policy in a gradual manner, can achieve its goals while maintaining a low level of interest rate volatility through the expectations of policy inertia (see Goodfriend, 1991 and Woodford, 1999a).

An alternative approach to solve for 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 literature on monetary policy) and a minimax criterion that serve to form a non-parametric set of perturbations around the policy makers' model. The latter is assumed to be an approximation that belongs to a potentially time varying and state dependent bounded 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 rule is chosen so as to minimize the maximum value function. Interestingly, Sargent (1999), Stock (1999), Onatski and Stock (2002), and Tetlow and von zur Muehlen (2001) show that model uncertainty may call for a more activist policy stance, although the worst possible models for the kind of historical Fed policy rule may not describe plausible structures of the economy (see Onatski, 2000). The intuition for this result comes from the fact that the central bank plays a game against a malevolent nature in which only worst case scenarios matter for policy making. This implies that an aggressive rule may be the optimal response of monetary authorities to large departures of inflation and output from the target values.

4.2 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:

$$\begin{aligned}\pi_{t+1} = \alpha_1\pi_t + \alpha_2\pi_{t-1} + \alpha_3\pi_{t-2} + \alpha_4\pi_{t-3} + \\ \alpha_5 y_t + \alpha_6 y_{t-1} + \alpha_7 y_{t-2} + \alpha_8 y_{t-3} + \xi_{t+1}\end{aligned} \tag{9}$$

$$\begin{aligned}y_{t+1} = \beta_1 y_t + \beta_2 y_{t-1} + \beta_3 y_{t-2} + \beta_4 y_{t-3} + \beta_5\pi_t + \\ \beta_6\pi_{t-1} + \beta_7\pi_{t-2} + \beta_8\pi_{t-3} + \beta_9\left(\bar{\imath}_t - \bar{\pi}_t\right) + \eta_{t+1}\end{aligned} \tag{10}$$

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, $\bar{\imath}_t - \bar{\pi}_t$, 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 approximately the five percent of the 2^7x2^7 models specified in this class. Finally, we derive the optimal policy rules for each of 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 policy rule that we use in the next section to evaluate the ability of model uncertainty to account for interest rate smoothness. Our *thick* strategy is in the spirit of Favero and Milani (2001), although we take two important departures. First, we analyze a different sample according to the reasoning that policy preferences are Chairman-specific. Second, we endogenously determine these preferences rather than simply imposing them.

5 The Fed policy preferences with model uncertainty

We use our identification method to recover the preference parameters for the Greenspan's tenure in the presence of model uncertainty. It is worthy to note that in contrast to the analysis in section 2, which considers a single specification of the economy and thus a single optimal rule, the calibration is based here on the distance between fitted and *thick* policy rates, where the latter are computed as the simple average of the optimal rules for each of the possible models. In so doing, we incorporate model uncertainty into the identification of policy preferences. In other words, we investigate whether the Fed cares about model specification by assessing the ability of a *robust* rule to match the data without resorting to 'incredible' values for the interest rate smoothing parameter. Indeed, the revealed policy preferences for the Greenspan's chairmanship are now $\lambda = 0.00$ and $\mu = 0.11$, while the first two moments of the associated optimal path are consistent with those of the historical path, as shown in Table 2. Moreover, the average distance is still fairly low.

Insert Table 2 about here

Figure 2 compares the two optimal paths associated to the preferences $\lambda = 0.00$ and $\mu = 0.11$ with and without model uncertainty respectively.

Insert Figure 2 about here

The *robust thick* policy rule effectively describes the main features of funds rate movements throughout the sample, although there are some differences in magnitude. While this suggests that other source of uncertainty such as measurement errors for inflation and output gap may also be relevant, we find that by considering model misspecifications most of the *interest rate smoothing puzzle* seems to vanish, as the relative preference parameter take now only a modest value. Model uncertainty is eventually crucial because whenever neglected the optimal policy rule looses its ability to match the data.

We interpret such a result as the evidence that model misspecification is an important concern of the Fed. Hence, any identification method that did not take this form of uncertainty into account would miss an important part of the story, thereby delivering a set of policy preferences that would be not sensibly interpretable. Moreover, the revealed policy preferences show 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). According to this, the stabilization of output around its potential value is not a final concern of the central bank (i.e. $\lambda = 0.00$). However, we do not mean that the output gap has been unimportant in policy actions. Indeed, as argued by Favero and Rovelli (2001) and Dennis (2001), it may well be that the output gap has been regarded as a leading indicator for future inflation rather than as a goal variable per sè (i.e. as an argument in the reaction function rather than in the loss). An alternative, in the spirit of the evidence in Smets (1999), Estrella and Mishkin (1999), and Wieland (1998) on output gap uncertainty, is that monetary authorities have placed less weight on the most poorly measured target.

6 Conclusions

Actual policy rates appear to be smoother than an optimal monetary policy would predict. Policy rules derived as the solution of an optimal control problem under the constraints provided by a small empirical model of inflation and output can match the data only by introducing interest rate smoothing into central bank's preferences. However, since the relative parameter should be imposed at 'incredible' values, this choice alone turns out to be unsatisfactory. While there may well be other rationales for the observed policy inertia, this paper shows that such a behavior can be interpreted as resulting from the concern of monetary authorities for potential misspecifications of the economic dynamics. Indeed, a Granger-style model uncertainty combined with plausible calibrated values for the policy preferences appears to solve most of the observed *interest rate smoothing puzzle*. Moreover, the preference parameters show that the Greenspan's tenure as Fed chairman is effectively described by a *strict inflation targeting* policy according to which the stabilization of inflation around its target has been the only concern of monetary authorities.

We take these results as a promising deal for future research and the calibration exercise we propose proves these potentialities. Intriguing identification strategies for the preference parameters have been found to return unattractive results in that they display either implausible values for the inertial coefficient or extremely volatile paths for the policy rates whenever model uncertainty is neglected. In contrast, our revealed preferences move to sensible values when the calibration incorporates a wide number of possible specifications. This suggests that model uncertainty may play a major role also for other identification strategies reconciling eventually inertial policy rate movements with sensible values for the preference parameters.

Appendix: the optimal control 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:

$$LOSS_t = \bar{\pi}_t^2 + \lambda y_t^2 + \mu \left(i_t - i_{t-1}\right)^2 \tag{12}$$

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 and μ represent the relative policy preferences of the central bank towards output stabilization and interest rate smoothing respectively. The inflation stabilization weight in the objective function is normalized to one.

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

$$E\left[LOSS_t\right] = Var\left[\bar{\pi}_t\right] + \lambda Var\left[y_t\right] + \mu Var\left[\Delta i_t\right] \tag{13}$$

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:

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

where the elements of (14) are given by:

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

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

$$\eta_t' = \left[\begin{array}{ccccccccc} \varepsilon_t & 0 & 0 & 0 & u_t & 0 & 0 & 0 & 0 \end{array}\right] \tag{17}$$

X_{t+1} is the $9x1$ vector of state variables, i_t is the policy control (i.e. the federal funds rate) and η_{t+1} is a $9x1$ vector of supply and demand iid normally distributed shocks with mean vector zero and covariance matrix $E\eta_t\eta_t' =$. Lastly, A and B are the matrices of behavioral parameters.

The loss function in (12) can be represented in a more compact form by defining the $3x1$ vector Y_t of goal variables. This vector reads:

$$Y_t = CX_t + Di_t \tag{18}$$

where the elements of (18) are given by:

$$Y_t = \left[\begin{array}{c} \bar{\pi}_t \\ y_t \\ i_i - i_{t-1} \end{array}\right], \quad C = \left[\begin{array}{cccccccc} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{array}\right], \quad D = \left[\begin{array}{c} 0 \\ 0 \\ 1 \end{array}\right] \tag{19}$$

Accordingly, the loss function can be rewritten as:

$$LOSS_t = Y_t'RY_t \tag{20}$$

where R is a negative semidefinite symmetric $3x3$ matrix characterized by the weight 1, λ and μ on the main diagonal and zeros elsewhere. Then, the central bank optimal control problem is to minimize over choice of $\{i_t\}_{t=0}^{\infty}$ the criterion:

$$\sum_{\tau=0}^{\infty} \delta^{\tau} \left\{Y_{t+\tau}'RY_{t+\tau}\right\} \tag{21}$$

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 $E\left(\eta_{t+1} \mid X_t\right) = 0$ are convenient 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, , as the certainty equivalence holds. Then, the first-order necessary condition turns out to be:

$$\left(S + \delta B'PB\right) i = -(V' + \delta B'PA)X \tag{22}$$

This implies the following feedback rule for the policy instrument

$$i = fX \tag{23}$$

where f is given by:

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

The $9x9$ matrix P is the solution of the algebraic Riccati equation:

$$P = Q + \delta \left(A + Bf\right)' P \left(A + Bf\right) + f' S f + V f + f' V' \tag{24}$$

where Q, V and S are defined as $C'RC$, $C'RD$ and $D'RD$ respectively.

The reaction function (23) 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 as well as lagged values of the fed funds rate itself.

Given this optimal feedback rule, the transition law of the economy can be rewritten as $X_{t+1} = MX_t + \eta_{t+1}$ where the $9x9$ matrix M is equal to $A + Bf$.

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Table 1 - Historical policy rule vs. optimal policy rules: a quantitative comparison of empirical evidence

Panel A: Descriptive statistics of the fitted policy rule, 1987:3 – 2001:1

Mean	*Standard deviation*
-0.0233	1.7307

Panel B: Descriptive statistics, policy preferences and average distance of the optimal policy rules

Author/s	*Estimates*	*Mean*	*Standard deviation*	*Average distance*
Castelnuovo and Surico (present paper)	$\lambda = 1.000$ $\mu = 8.000$	0.4913	1.9100	1.4459
Dennis (2001)	$\lambda = 0.815$ $\mu = 6.181$	0.4888	1.9797	1.4894
*Favero and Rovelli (2001)**	$\lambda = 0.00125$ $\mu = 0.00850$	0.3564	16.9932	271.198
Ozlale (2001)	$\lambda = 0.525$ $\mu = 0.975$	0.5563	2.4752	2.8621

* The estimates in Favero and Rovelli are based on the Volcker-Greenspan period, 1980:3 1998:3, rather than on the Greenspan tenure only, from the 1987:3 onwards. As discussed in the main text, this does not affect our conclusions.

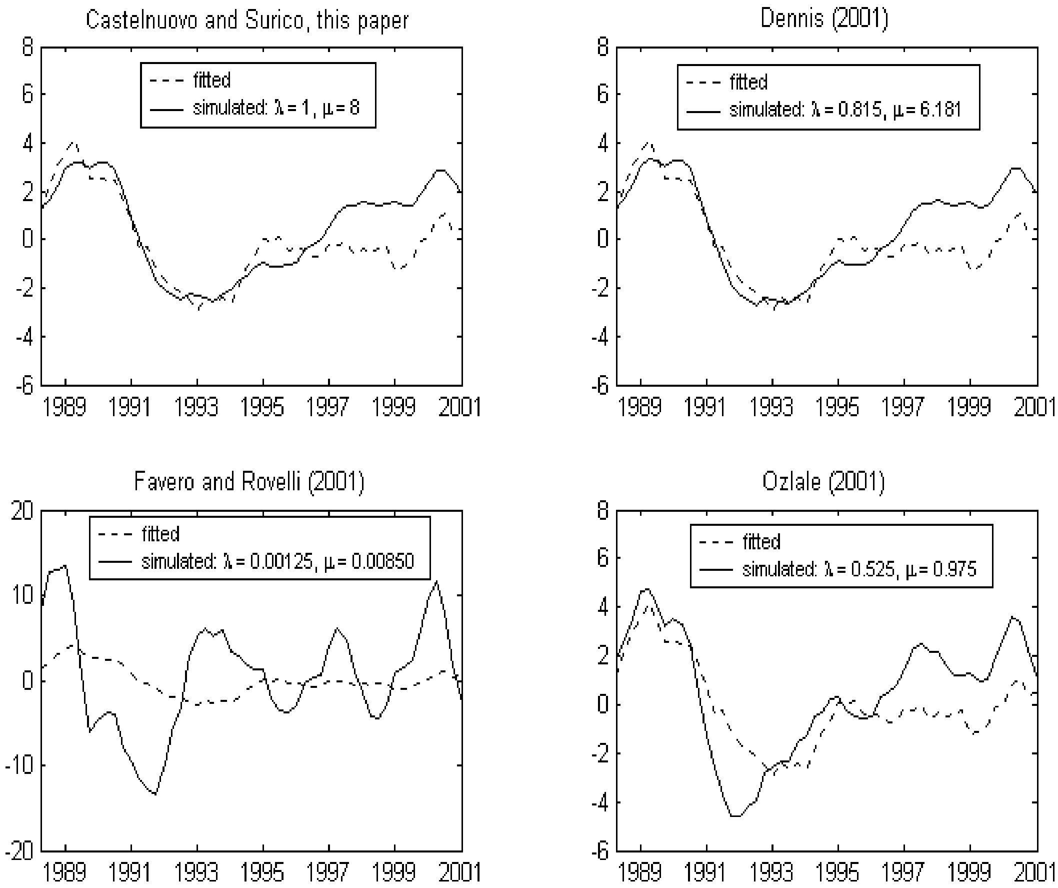
Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. The average distance is measured as the mean of the sum of the squared deviations between optimal and fitted policy rates at each point in time.

Table 2 – Optimal thick, optimal thin and fitted policy rules: descriptive statistics

Author/s	*Estimates*	*Mean*	*Standard deviation*	*Average distance*
Thin policy rule	λ = 0.000 μ = 0.111	0.4635	4.2493	11.4717
Thick robust policy rule	λ = 0.000 μ = 0.111	0.0087	1.8024	2.0385
Fitted policy rule	- -	-0.0233	1.7307	-

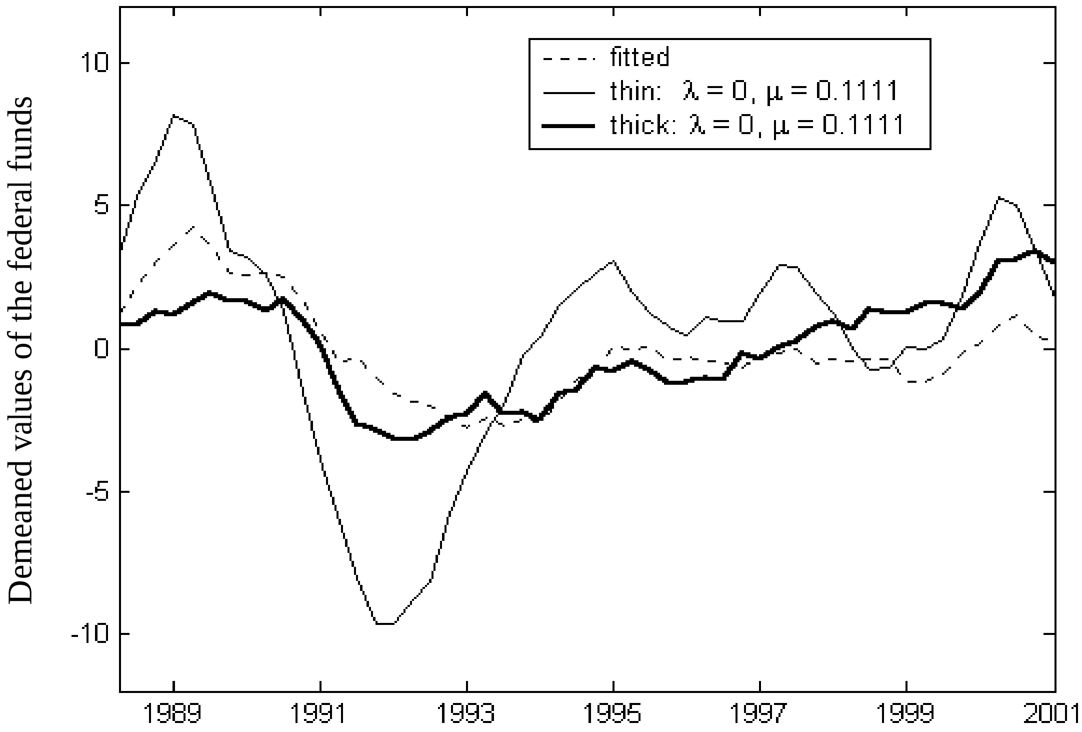
Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. The average distance is measured as the mean of sum of the squared deviations between optimal and fitted policy rates at each point in time. The thick robust policy rule is computed as the simple average at each point in time of the optimal rates for each of the possible specifications.

Figure 1 - Historical policy rule vs. optimal policy rules: a graphical comparison of empirical evidence



Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. Each optimal path shows the values that the funds rate would have taken if the Fed had historically implemented that optimal policy rule. Demeaned values of the federal funds rate are on the vertical axis.

Figure 2 - Thick robust policy rule vs. thin policy rule



Note: The preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. The optimal paths show the values that the funds rate would have taken if the Fed had historically implemented the optimal policy rule. The thick robust policy rule is computed as the simple average at each point in time of the optimal federal funds rates for each of the possible specifications.

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